APPLICATION OF GEOSPATIAL TECHNIQUES IN ASSESSING SUPPLEMENTAL IRRIGATION FOR SORGHUM AND MAIZE PRODUCTION IN KARAMOJA REGION

BY

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DECLARATION

Declaration by Candidate

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To my dear wife Martha Calton Mugisha, my daughter Mischella and my faithful Parents, without whose love and support the completion of this project would not have been possible.

ABSTRACT

Karamoja region is situated in north-eastern Uganda. Over 80% of the population in this region is moderately food insecure, and this has oftenly prompted relief agencies to engage in humantarian relief especially food aids for atleast the last three decades. The main objective of this study was to apply geospatial techniques in determining supplemental irrigation requirements for Maize and Sorghum production in this region. To achieve this goal, a land suitability analysis employing the use of spatial Multi-Criteria Evaluation (SMCE) tool in Integrated Land and Water Information System (ILWIS) was carried out. This involved the development of relevant geospatial datasets for the study area. The generated datasets were structured, standardized and weighted in ILWIS, from which the respective suitability maps for Maize and Sorghum production were calculated. The SMCE results showed 85.3% and 45.4% of the area in the region as being at least moderately suitable for Maize and Sorghum production, respectively. An irrigation suitability analysis was then conducted by initially establishing the average decadal effective rainfall maps for each of the designed three (3) seasons across the set scenarios i.e. wet, normal and dry scenarios. Average decadal net irrigation requirement (NIR) maps, as a deficit of the respective calculated average decadal crop water requirements and the effective rainfall maps earlier developed, were then determined and classified using set NIR ranges and logical-IFF condition commands in ILWIS. Finally cropping and irrigation alternatives to guide effective land utilization were determined following an inferential approach in which statistic information summarizing specific acreages and percentages at varying suitability index for each crop across all scenarios was collated. It was observed for Season-1 (running from March to June) that significant areas are highly suitable for both crops particularly in the wet year scenario. This is majorly attributed to the relatively higher effective rainfalls in the region around this time of the year, thus eliminating the need for irrigation. Season-2 (running from July to October) showed significant areas falling in the marginally suitable class. The region was particularly observed to have up to 57% of the area marginally suitable for Sorghum production in the dry year scenario. The increase in marginal suitability is majorly attributed to the relatively high NIR during this season. Season-3 which runs from November to February coincides with the driest spell in this region with average decadal rainfall ranging from 0-26 mm as compared to the 10-54 mm in Season-1. This statistic calls for relatively more irrigation water supply across all three scenarios of Season-3 in order to guarantee effective crop production. The results of this study show the extent of supplemental irrigation required to sustain effective crop production in the various areas of Karamoja region. The study recommends that a more detailed soil water balance analysis, at a relatively higher spatial resolution be conducted in the future in order to ascertain the specific contribution of other ambient factors to supplemental irrigation estimation within the study area.

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May the Almighty LORD grant you beyond your heart's desires

....

Mugisha Moses

ACRONYMS AND ABBREVIATIONS

ACF	Action Contre La Faim (Action against Hunger)
AHP	Analytic Hierarchy Process
CI	Consistency Index
DEM	Digital Elevation Model
DFID	Department for International Development
DLCI	Dry lands Learning and Capacity Building Initiative
DWD	Directorate of Water Development
FAO	Food and Agriculture Organization
GIS	Geographical Information System
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
GOU	Government of Uganda
GPS	Global positioning systems
GTS	Global Telecommunication System
IFPRI	International Food Policy Research Institute
ILWIS	Integrated Land and Water Information System
IPC	Integrated Food Security Phase Classification
IRIN	Investor Relations Information Network
IWR	Irrigation Water Requirement
JAXA	Japan Aerospace Exploration Agency
KAPFS	Karamoja Action Plan for Food Security
KPAP	Karamoja Productive Assets Programme
LUT	Land Utilization Type
MAAIF	Ministry of Agriculture, Animal Industry and Fisheries
MCE	Multi-Criteria Evaluation
MLH	Ministry of Lands and Housing
MW	Micro-wave
MWE	Ministry of Water and Environment
NOOA-CPC	National Oceanographic and Atmospheric Administration’s climate prediction center
NARO	National Agricultural Research Organization
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index

NIR	Net Irrigation Requirement
NUSAF	Northern Uganda Social Action Fund
REGLAP	Regional Learning and Advocacy Project
RS	Remote Sensing
SAARI	Serere Agricultural and Animal Research Institute
SCS	Soil conservation service
SRTM	Shuttle Radar Topographic Mission
SMCE	Spatial Multi-Criteria Evaluation
TIR	Thermal infra-red
US	United States
UBOS	Uganda Bureau of Statistics
USACE	US Army Corps of Engineers
USAID	United States Agency for International Development
USBR	United States Bureau of Reclamation
USCS	United States Conservation Service
USDA	United States Division for Agriculture
WFP	World Food Programme
WMO	World Meteorological Organization

CHAPTER ONE: INTRODUCTION

1.1 Background Information

Karamoja is the driest region in Uganda, much of it being semi-arid, with the dry season prevailing winds originating from the very dry areas of Northern Kenya (GOU, 2009). The region is a land of contrasts. Hot dry savannas in the east and central parts of the region provide seasonal grazing for cattle, small stock and game, and precarious farming. To the west, more fertile conditions prevail, with good land for maize, sorghum, groundnuts and pigeon peas, and valuable dry season grazing. But for most of the farmers in Karamoja, drought and famine are frequent realities (Sean, 2014). The main crops grown in Karamoja are sorghum (70%), maize, fingermillet, cowpeas, and groundnuts, and these are supplemented by wild fruits, and vegetables (Chow, 2011).

Unlike the rest of the country with two rainy seasons and two planting seasons, Karamoja has only one rainy season and one planting season. Cyclical droughts and erratic rainfall have affected crop production and pasture for livestock, thereby having a direct negative effect on the livelihoods of the population (GOU, 2009).

This study therefore is aimed at assessing the supplemental irrigation required for Sorghum and Maize production in this region as a means of generating information that could guide all stake holders in planning for sustainable Sorghum and Maize production and also determine appropriate cropping and irrigation alternatives to guide effective land utilization. It is then envisaged that this could improve food security, improve farmers' income through its increased production and productivity in the long run.

1.2 Statement of the Problem

In Karamoja region, over 80% of the population is reported to be ‘moderately food insecure’. This situation has oftenly prompted a diverse range of relief agencies to engage in humantarian relief especially food aids/donations for atleast the last three decades (Levine, 2010).

This situation is exacerbated by the region having cyclical droughts and inadequate rainfall that significantly affect crop production and productivity, thereby having a direct negative effect on the livelihoods of the population (GOU, 2009).

Because of this inadequacy in rainfall amounts, there is need to ascertain the amounts of extra water (supplemental irrigation) for each of the areas in this region something that is tedious and relatively expensive if field experiments are to be done through the entire region.

This study therefore aims at applying geospatial technology majorly Geographical Information System (GIS), and Remote Sensing (RS) to ascertain the extent of supplemental irrigation required for each area within the region.

1.3 Justification

Irrigation is viewed as a key factor in progress towards achieving food security in Africa (FAO, 1997). Knowledge of extent of supplemental irrigation specific for each area within Karamoja region is unavailable and if generated could guide the government, NGOs, donors, and private sector prior to investing in the Agricultural development of the region. This knowledge also could guide all stakeholders in planning for sustainable food production and also in determining appropriate cropping and irrigation alternatives to guide effective land utilization.

Furthermore, information from this research could steer up the farming spirits of the natives whose inclination is more on pastoralism hence making them self-reliant especially from food aids/donations. The World Food Program (WFP) in 2009 cut down their food aids/donations support to only 150,000 people in extremely vulnerable households, down from about 970,000 people (GOU, 2009).

Lastly but equally important, use of geospatial tools majorly GIS and RS provide a relatively cheaper, less tedious and quicker analysis especially for large areas (Lynn, 2009).

1.4 Research Objectives

1.4.1 Overall Objective

The main objective of the study was to apply geospatial techniques in assessing supplemental irrigation for Sorghum and Maize production in Karamoja region, Uganda.

1.4.2 Specific Objectives

The specific objectives of the study are to:

i. Carry out a land suitability analysis using Spatial Multi-Criteria Evaluation.
ii. Determine the irrigation suitability analysis based on Net Irrigation Requirement.
iii. Determine the cropping and irrigation alternatives for effective land utilization.

1.5 Description of the Study Area

1.5.1 General information

Karamoja Region (Latitude: 1° 23.6231‘S, Longitude: 30° 9.276‘E) is situated in the north-east corner of Uganda, encompassing an area of 27,200 km^2 (Figure 1.1), which constitutes 11.3% of the total surface area of Uganda (Sean, 2014). It is bordered to the east by the Rift Valley escarpment that drops down into the Turkana territory of Kenya. To the north lies the Republic of South Sudan and to the south are the Mt. Elgon highlands. In the west, Karamoja is bordered by the home territories of the Teso, Lango and Acholi ethnic communities. The mountain areas of Karamoja are inhabited by the Tepeth Teuso and Nyangwe, while the semi-arid lands of Karamoja are inhabited by pastoralist and agro-pastoralist communities (GOU, 2009).

Karamoja’s human population is approximately 1.4 million people which is about 3.4% of the Uganda’s population (GOU, 2013). The region comprises of seven (7) districts i.e. Kaabong, Kotido, Abim, Moroto, Napak, Nakapiripirit, and Amudat Districts as shown in Figure 1.1.

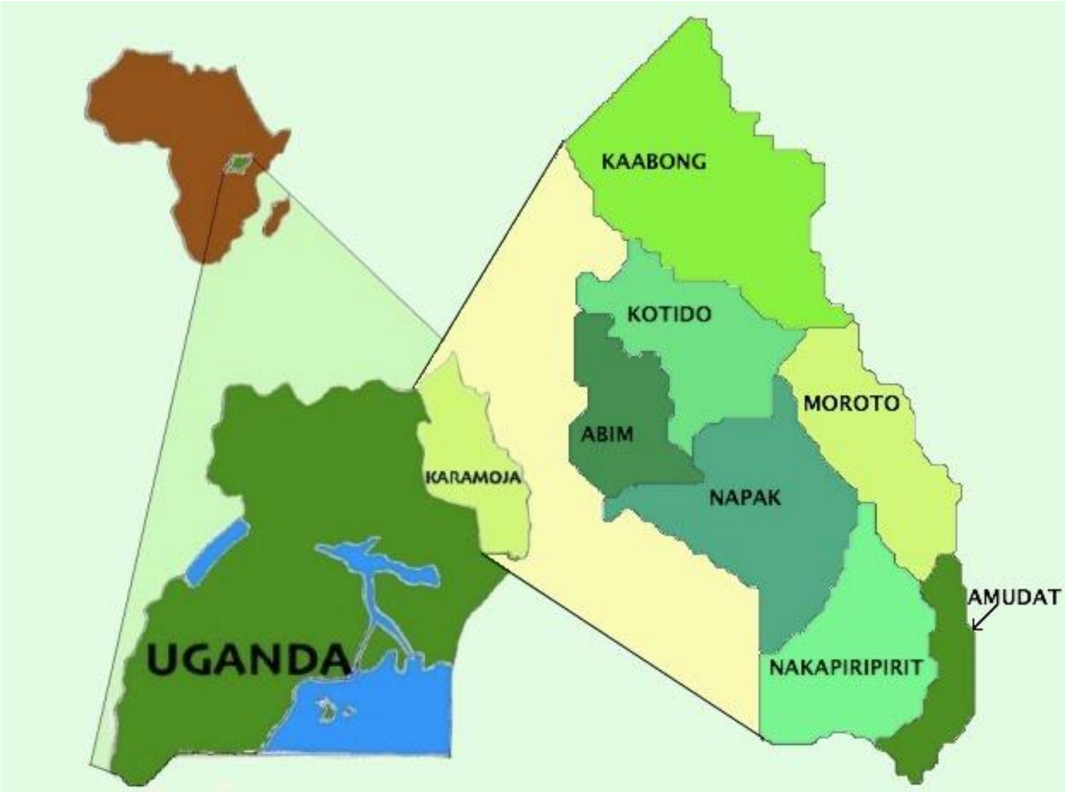


Figure 1.1: Map of Karamoja Region showing the major districts (Chow, 2011)

1.5.2 Topography, climate, hydrology and soils

The topography of the Karamoja sub-region is characterized by low elevation in the west and higher elevation in the east (Mbogga et. al., 2014). The average elevation of the plain of Karamoja lies at around 1400 meters (4500 feet) above sea level (GOU, 2009) and over 80% of the region is flat to gently sloping land with average slope of 3.41% (Kyagulanyi et.al., 2016b)

The weather in Karamoja is generally hot and dry. The average annual temperature is 21.5^{o}C; February and March are the hottest and July and August are the coolest months. The area receives about 760 mm to 1000 mm of rainfall with a dry season from December- March (GOU, 2011) which is longer than the average length of dry season (less than three months) in Uganda (Kyagulanyi et.al. 2016a).

The length of this dry season introduces a break in the food production cycle of the region and often supplementary irrigation is required to enable crops with longer growth periods to complete their growth cycle. The Karamoja region majorly has two soil types of sandy clay loams and black clays. (Sean, 2014)

The first objective of this study is to conduct a land suitability analysis to further more analyze the effect of the above soil types on Maize and Sorghum production.

1.6 Scope and Limitation of the Study

The scope of this study was limited to the application of geospatial techniques such as GIS modeling in ILWIS 3.6 and data analysis of remote sensed data. Spatial Multi-Criteria Evaluation (SMCE) tool in ILWIS was very pivotal in assessing the level of arability within the study area applying the Pair-wise Comparison originating from the Analytical Hierarchical Process (AHP) (Saaty, 2008).

A significant limitation to this study was scarcity of requisite climatic data especially daily humidity, wind speed, radiation for the last 20-30 years which contribute to better accuracy in determination of crop evapotranspiration. Only Temperature data was readily available and therefore used for this study.

CHAPTER TWO: LITERATURE REVIEW

2.1 Karamoja's Food Insecurity Cases and Interventions

Karamoja stands out as the least developed region in Uganda and consistently registers the lowest human development indicators in the country (GOU, 2009). About 970,000 people were in need of food aid in 2009 after a series of concurrent drought and flooding in 2006, 2007, and 2008. The region has always been a focal point of humanitarian assistance efforts in Uganda, having suffered from chronic food shortages, drought, and famine for decades (Sean, 2014).

The World Food Program (WFP) has been feeding people in the Karamoja region for more than 40 years has recently significantly scaled down and changed the dynamics of its Karamoja operations (Levine, 2010). They cut down their support to only 150,000 people in extremely vulnerable households, down from about 970,000 people in 2009 (GOU, 2009). Increasingly, WFP and other NGOs in the region are moving away from food donations to cash-and-voucher-based food assistance programmes, in line with the government's World Bank-funded Northern Uganda Social Action Fund (NUSAF), which aims to improve the region's infrastructure and create employment in the construction, health and agriculture sectors among others.

2.2 Maize and Sorghum Production in Karamoja Region

2.2.1 Sorghum Production

Sorghum (*Sorghum bicolor*) is the third most important staple cereal food crop in Uganda after maize and millet occupying 285,000 ha of arable land (GOU, 2009). However for Karamoja region, Sorghum is the most grown crop followed by maize, millet, potatoes, and cassava, respectively (GOU, 2011).

In an attempt to improve food security and incomes among the rural poor households, Serere Agricultural and Animal Research Institute (SAARI) generated a number of technologies among which are Sekedo and Epuripur improved sorghum varieties released in 1995 (Sean, 2014). These improved varieties are early maturing i.e. within three months or 100 days implying they can be grown more than once in a year, and equally important they are drought resistant, giving them an edge over climatic change (GOU, 2011).

2.2.2 Maize Production

Maize (*Zea mays* L.) is one of the major staple foods in Uganda. Its production has increased over the years as people change their consumption trends. It has evolved from a purely subsistence to a successful commercial crop. Farmers have improved maize yields from 1,000 kg/ha to 3,000 - 5,000 kg/ha using the recommended technologies (GOU, 2007).

Climatically, maize can be produced in most parts of the country except in the most arid parts of Karamoja. However, with on-going research, suitable early maturing varieties have been developed to suite this area (Sean, 2014).

2.3 Maize and Sorghum Growth Requirements

2.3.1 Sorghum Growth Requirements

According to Plessis (2008), Sorghum requires the following recommendation in order to guarantee high yields:

i. **Planting time:** the most effective time should be at the onset of rains i.e. March, April or August, September. Late planting leads to high disease attack.

ii. **Spacing:** sorghum should be planted at a spacing of 60 cm between rows and 20 cm between plants. 5-10 seeds should be planted per hole and thinned to two plants per hole when the plants are about 6 inches tall.

iii. **Soil Requirement:** Sorghum is mainly cultivated in drier areas, especially on shallow soils with high clay content. Other observations include the following:

a) Soils with a clay percentage of between 10 and 30 % are optimal for sorghum production.

b) Sorghum usually grows poorly on sandy soils, except where heavy textured subsoil is present.

c) Sorghum is more tolerant of alkaline salts than other grain crops and can therefore be successfully cultivated on soils with a pH (KCl) of between 5.5 and 8.5.

d) Sorghum can better tolerate short periods of waterlogging compared to maize.

e) Sorghum is more tolerant of wet soils and flooding than most of the grain crops-an interesting phenomenon in relation to its drought tolerance

f) If no soil impediments occur, roots can reach a lateral distribution of 1 meter and a depth of up to 2 meters early in the life of the plant.

iv. **Climate Requirement:** the climatic requirements for the production of sorghum are divided into temperature, day length and water needs.

(a) *Temperature:* the minimum temperature for germination varies from 7 to 10 °C. At a temperature of 15 °C, 80 % of seed germinate within 10 to 12 days. The best time to plant is when there is sufficient water in the soil and the soil temperature is 15 °C or higher at a depth of 10 cm. A temperature of 27 to 30 °C is required for optimum growth and development. Exceptionally high temperatures cause a decrease in yield (Carter et.al, 1989).

(b) *Water requirements:* Sorghum is produced on a wide range of soils, and under fluctuating rainfall conditions of approximately 400 mm in the drier areas to about 800 mm in the wetter areas.

2.3.2 Maize Growth Requirements

According to Mason and Nora (2002), Maize requires the following recommendations in order to guarantee high yields.

a) **Planting time:** planting is generally recommended to be done at the onset of rain but since maize is a robust crop, dry planting can be done when rain is expected. Dry planting is advantageous because it spread out the planting duration hence enabling the farmers to open more land. Delayed planting in relation to the onset of rains will lead to reduced yield. However, time to plant is not such a critical factor when one is using irrigation.

b) **Soil Requirement:**

i. **Soil Textural requirement:** Maize can be grown on a wide variety of soils, but performs best on well-drained, well-aerated, deep warm loams and silt loams containing adequate organic matter and well supplied with available nutrients. Although it grows on a wide range of soils, it does not yield well on very sandy soils, very heavy dense clay except with heavy application of fertilizers on heavy clay soils, deep cultivation and ridging is necessary to improve drainage. Maize is moderately sensitive to salinity.

ii. **Soil pH:** Maize can be grown successfully on soils with a pH of 5.0 - 7.0 but a moderately acid environment of pH 6.0 - 7.0 is optimum. Outside the range results in nutrient deficiency and mineral toxicity.

c) **Climate Requirement:** Maize is grown in climates ranging from temperate to tropic. When mean daily temperatures, during the growing season, are greater than 20°C, early grain varieties take 80 to 110 days and medium varieties 110 to 140 days to mature.

i. *Temperature:* The optimum temperature for plant growth and development ranges from 30°C - 34°C. The cool conditions at high altitude lengthen the cycle or growing period. Temperatures below 5°C and above 45°C result in poor growth and death of the maize plant. In general, temperatures in Uganda are favorable for maize production as long as appropriate varieties are grown in areas for which they were bred. For example highland maize is suitable for highland areas. The minimum temperature for germination is 10˚C and at a soil temperature of 16-18˚C, maize normally emerges within a week of planting. Maize does not tolerate waterlogging, so good drainage is essential, especially in temperate regions and on heavier soils.

ii. *Water requirements:* for maximum production, a medium maturity grain crop requires between 500 and 800 mm of water depending on climate. Maize appears relatively tolerant to water deficits during the vegetative and ripening periods. Greatest decrease in grain yields is caused by water deficits during the flowering period. Where rainfall is low and irrigation water supply is restricted, irrigation scheduling should be based on avoiding water deficits during the flowering period, followed by yield formation period.

Under conditions of marginal rainfall and limited irrigation water supply, the number of possible irrigation applications may vary between two and five (FAO, 1998).

2.4 Procedure for Assessment of Supplemental Irrigation within an Area

Irrigation is the practice of artificially maintaining root zone moisture at levels necessary to ensure optimal growth conditions for a given crop at a particular stage of growth when soil moisture would otherwise be inadequate (FAO, 2006).

According to FAO, (2005), there are two (2) general classifications of irrigation:

i. *Complementary irrigation,* if there is no rainfall, and all the water that the crops need has to be supplied by irrigation.

ii. *Supplementary irrigation,* if there is some rainfall, but not enough to cover the water needs of the crops, and irrigation water has to supplement the rain water in such a way that the rain water and the irrigation water together cover the water needs of the crop.

Because Karamoja region receives about 760mm to 1000mm, supplementary irrigation is most suited for this area.

2.4.1 Land Evaluation for Irrigated Agriculture

An optimal use of land and water resources by the development of irrigation facilities could lead to substantial increases in food production in many parts of the world. According to FAO, (1985), the process whereby the suitability of land for specific uses such as irrigated agriculture is assessed is called *land evaluation*.

Land evaluation provides information and recommendations for deciding 'which crops to grow where' and their respective suitability indices as shown in Table 2.1. Land evaluation is the selection of suitable land, and suitable cropping, irrigation and management alternatives that are physically and financially practicable and economically viable. The main product of land evaluation investigations is a land classification that indicates the suitability of various kinds of land for specific land uses, usually depicted on maps with accompanying reports (FAO, 1985).

Table 2.1 Structure of the land suitability classification (FAO, 1985)

ORDER	CATEGORIES CLASS	SUBCLASS
S - Suitable	S1	
	S2	S2t
		S2d
		S2td
	S3	
N – Not Suitable	N1	N1y
		N1z
		etc.
	N2	

Legend:
S1 *Highly Suitable*
S2 *Moderately Suitable*
S3 *Marginally Suitable*
N1 *Marginally Not Suitable*
N2 *Permanently Not Suitable*

Lower case letters in the subclass shown in Table 2.1 indicate the nature of a requirement of limitation (e.g. t and d for topography and drainage). Land suitability units (subdivisions of subclasses) may also be used to indicate minor differences in management.

Comparison between the FAO and USBR Land Evaluation Frameworks

There are currently two globally recognized frameworks for Land evaluation for Irrigated Agriculture:

i. United States Bureau of Reclamation (USBR) Framework.
ii. Food and Agriculture Organization (FAO) framework.

FAO uses provisionally-Irrigable and Irrigable land classifications while USBR uses Arable and Irrigable classifications for the same classifications. Secondly, USBR does not use the water supply as a class determining factor whereas FAO includes water supply in terms of water quality, quantity and seasonality as one of the factors.

Table 2.2 shows a comparison between the FAO Framework classification structure and the USBR classification system as carried out by FAO in 1985.

Table 2.2 Comparative Land Suitability classification for FAO and USBR frameworks (FAO, 1985)

SUITABILITY CATEGORY	FAO FRAMEWORK	USBR CLASSIFICATION		
ORDERS	S - Suitable	-		
	N – Not Suitable	-		
CLASSES	S1 – Highly Suitable	Class 1		
	S2 – Moderately Suitable	Class 2		
	S3 – Marginally Suitable	Class 3		
		Class 4 Special Uses 4.1, 4.2, 4.3		
		Class 5 (requiring further study to determine whether suitable or not)		
	N1 – Marginally Not Suitable	-		
	N2 – Permanently Not Suitable	Class 6		
SUB-CLASS	Class	Subclass	Class	Subclass
	S2	S2m	Class 2	2s
		S2d		2d
		S3md		2sd
		etc.		etc.
UNITS	Subclass	Unit		
	S2d	S2d Special study areas (informative appraisal areas) (for which management and development recommendations are given)		

Notes: *(1) Subclasses, reflecting a requirement or limitation are denoted by a letter suffix (see Table 2)- in the USBR system these are s, t or d indicating a soil, topographic or drainage deficiency respectively; (2) See text for use of Sc (Conditionally Suitable) in the FAO system; (3) Special use lands (USBR Class 4) are classified 1, 2 and 3 to reflect relative payment capacity with a letter designating the land use (crop); and (4) Class 5 land (USBR) requires further study to determine whether it is suitable or not. Class N1 (FAO) is marginally not suitable at present (FAO, 1985).*

Because FAO framework uses water supply in terms of water quality, quantity and seasonality on top of land characteristics majorly used by the USBR framework, it is widely acceptable and therefore was adopted for this study classification (FAO, 1985).

2.4.2 Estimation of Irrigation water requirement

Irrigation water requirement entails the determination of the deficit between the crop water requirement and the effective rainfall within an area. For each of the crops grown on the different sites, the crop water needs can be estimated according to Eq.2.1 (FAO, 1997).

$$IR = ET_c - P_e \quad (2.1)$$

where: IR is the irrigation water requirement; ET_c is the crop water requirement in mm/unit time and P_e is effective rainfall which is a portion of the received rainfall within a given area.

Determining the Crop Water Requirement (ET_c)

The Crop water requirement (ET_c) is the amount of water required by the crop for its effective growth and is estimated according to Eq.2.2 (FAO, 1998).

$$ET_c = ET_o * K_c \quad (2.2)$$

where: ET_o is the reference evapotranspiration in mm/unit time, and K_c is the crop factor.

Depending on the crop of choice, the crop factors (K_c) for the Initial, Mid and End stages are obtained from FAO (1998) and shown in Appendix I.

The other value of crop coefficients other than the ones specified is obtained by the numerical determination of K_c formula in Eq.2.3 (FAO, 1998).

$$Kc_i = Kc_{prev} + \left[\frac{i - \sum(L_{prev})}{L_{stage}}\right](Kc_{next} - Kc_{prev}) \quad (2.3)$$

where: Kc_i is the crop factor on a particular day e.g. Kc_{20} referring to the crop factor on the 20th day of crop growth; Kc_{prev} is the crop factor for the previous stage; Kc_{next} is the crop factor for the next stage; L_{prev} is the length of the previous stage and the L_{stage} is the length of the current stage.

2.4.3 Techniques for estimating Effective Rainfall

Not all the rain that falls is available for the crop to take up. Rain may be lost from run-off, drainage below the root zone of the crop, or interception by foliage, leaf litter or mulch. Effective rainfall is the proportion of any rainfall event that is stored within the crop root zone and available for use by the crop. It can be roughly estimated by the following methods as described by Raes (2004).

a) **Fixed percentage method:** Effective rainfall is a fixed percentage of actual rainfall, being calculated according to Eq.2.4

$$P_e = \text{Fixed percentage} * P \quad (2.4)$$

P = total measured rainfall as received within a given area. The fixed percentage is always an estimate by the user to account for the losses due to runoff and deep percolation and is an arbitrary based on the user's experience and observations within the study area.

b) **Dependable rainfall (FAO/AGLW formula)**: Based on an analysis carried out for different arid and sub-humid climates, an empirical formula was developed in the Water Service of FAO to estimate the dependable rainfall, the combined effect of dependable rainfall (80% probability of exceedance) and estimated losses due to Runoff (RO) and Deep Percolation (DP). This formula may be used for design purposes where 80% probability of exceedance is required. The dependable rainfall is calculated as shown in Eqn.2.5 and 2.6 for available monthly data steps and decadal rainfall data steps respectively:

Monthly step:

$P_e = 0.6 * P - 10$ for $P_{month} <= 70$ mm

$P_e = 0.8 * P - 24$ for $P_{month} > 70$ mm……………………..……..…......(2.5)

where P_{month} is the recorded monthly total rainfall

Decadal rainfall data:

$P_e = 0.6 * P_{dec} - 10$ for $P_{dec} <= (70 / 3)$ mm

$P_e = 0.8 * P_{dec} - (24 / 3)$ for $P_{dec} > (70 / 3)$ mm…………………..……... (2.6)

where P_{dec} is the recorded decadal total rainfall.

c) **Empirical formula:** This formula is similar to that for dependable rainfall but with the possibility to change the parameters, which may be determined from an analysis of local climatic records:

Monthly step:

$P_e = a * P_{month} - b$ for $P_{month} <= z$ mm

$P_e = c * P_{month} - d$ for $P_{month} > z$ mm…………………………………..… (2.7)

Decadal step:

$P_e = a * P_{dec} - (b / 3)$ for $P_{dec} <= (z / 3)$ mm

$P_{e\ (dec)} = c * Pdec - (d / 3)$ for $Pdec > (z / 3)$ mm………………………… (2.8)

where: values for a, b, c, d and z are correlation coefficients.

d) **United States Division for Agriculture (USDA) Method :** Formula developed by United States Conservation Service (USCS), where effective rainfall can be calculated according to:

Monthly step:

$P_e = P_{month} * (125 - 0.2 * P_{month}) / 125$ for $P_{month} <= 250$ mm

$P_e = 125 + 0.1 * P_{month}$ for $P_{month} > 250$ mm………………….............. (2.9)

Decadal step:

$P_e = (P_{dec} * (125 - 0.6 * P_{dec})) / 125$ for $P_{dec} <= (250 / 3)$ mm

$P_e = (125 / 3) + 0.1 * P_{dec}$ for $P_{dec} > (250 / 3)$ mm…………………….…. (2.10)

e) **Zero effective rainfall method:** In this method, rainfall is not considered in irrigation calculations and it will be ignored as in the case of complementary irrigation

Seasonal effective rainfall estimates in this particular study were calculated using the USDA Equation 2.10 as shown above. This was used because of its accurate estimation (80-90%) for most rainfall values below/above the 100 mm/month in comparison to the actual field observations (Raes, 2004).

2.4.4 Frequency Analysis of Historical Rainfall Data

Frequency analysis outlines a statistically approved technique to estimate in this case, rainfall depths that can be expected for selected probabilities or return periods (Raes, 2004). With the help of a frequency analysis on historical rainfall data, the magnitude of the rainfall depths can be estimated. The estimates are required for the design and management of irrigation and drainage projects.

Rainfall variability in time

Because of the strong variability of rainfall in time, the design and management of irrigation water supply and flood control systems are not based on the long-term average of rainfall records but on particular rainfall depths that can be expected for a specific probability or return period. These rainfall depths can only be obtained by a thoroughly analysis of long time series of historic rainfall data and form a basis of subsequent design procedure (Raes, 2004).

Estimates of rainfall depths (X_P) or intensities that can be expected for a specific probability during a specific reference period (hour, day, week, 10-day, month, year) are required for the management and design of irrigation and drainage projects. In this note the probability refers to the probability of exceedance and it specifies the likelihood that the actual rainfall during that period will be equal to or higher than the estimated rainfall depth X_P. Since the rainfall depth X_P is the amount of rain that can be expected or might be exceeded in a given period for a specific probability, it refers to the minimum amount of rain one can rely on during the reference period, and therefore is often denoted as '*dependable rainfall*' in irrigation sciences (Raes, 2004).

Probability of exceedance

The probability of exceedance refers to the probability of the occurrence of a rainfall depth greater than some given value X_P. The probability of exceedance (P_X) is expressed as a fraction (on a scale ranging from zero to one) or as a percentage chance with a scale ranging from 0 to 100% (Raes, 2004).

Information on the rainfall depth that can be expected in a specific period under various weather conditions is required for management and planning purposes. Smith, (1992) uses the following rules for the determination of dry, normal and humid weather conditions:

i. The weather condition in a period is called dry if the rainfall received during that period will be exceeded 4 out of 5 years, i.e. having a probability of exceedance of 80%.

ii. The rainfall in a period is normal, if the rainfall received during that period will be exceeded in 1 out of 2 years. The probability of exceedance is equal to 50%;

iii. The weather condition in a period is called humid if the rainfall received during that period is exceeded 1 out of 5 years, i.e. having a probability of exceedance of 20%.

In this study, the above conditions were used to develop scenarios to assess their respective impact on estimation of supplemental Irrigation and how each of them can influence specific Cropping and Irrigation alternatives.

Estimation of the probability of exceedance

This can be done graphically or numerically depending on the available datasets (Raes, 2004).

a) ***Graphical Method:*** The graphical methodology for estimating the probability of exceedance is summarised in the following steps.

Step 1: The first step is the ranking of the rainfall data in either ascending or descending order.

Step 2: After the rainfall data are ranked, a serial rank number (r) ranging from 1 to n (number of observations) is assigned. Subsequently the probability have to be determined that should be assigned to each of the rainfall depths. If the data are ranked in descending order, the highest value first and the lowest value last, the probability is an estimate of the probability that the corresponding rainfall depth will be exceeded.

Step 3: When data are ranked from the lowest to the highest value, the probability refers to the probability of non-exceedance. Hence the probabilities are estimates of cumulative probabilities. They are formed by summing the probabilities of occurrence of all events greater then (probability of exceedance) or less than (probability of non-exceedance) some given rainfall depth. Since these probabilities are unknown the probabilities of exceedance have to be estimated by one or another method.

Step 4: Several methods such as Weibull, Sevruk and Geiger, and the Gringorten methods are theoretically better. The probabilities will be the plotting positions of the ranked rainfall data in the probability plot.

b) ***Numerical Method:*** When annual rainfall is completely normally distributed, the data in a probability plot will fall perfectly on the normal line. On this line the mean rainfall ($\overline{X}$) corresponds with the 50 % probability of exceedance, the $\overline{X}$ +s (standard deviation) corresponds with 15.87 % and the $\overline{X}$ -s with the 84.13 % probability of exceedance. Since the normal distribution is completely characterized by its average and standard deviation, they can be used to estimate rainfall for selected probabilities or return periods according to the following formula;

$$X_P = \overline{X} \pm k\, s \qquad (2.11)$$

where: X_P is the rainfall depth having a specific probability of exceedance; $\overline{X}$ is the sample mean; s is the standard deviation and k is a frequency factor. The sign and magnitude of the frequency factor vary according to the selected probability of exceedance as summarised in the Table 2.3 below (Raes, 2004).

Table 2.3 Frequency factor k for various probabilities of exceedance (Raes, 2004)

Probability of exceedance (%)	+ k	Probability of exceedance (%)	- k
5	+ 1.64	50	- 0.000
10	+ 1.28	55	- 0.125
15	+ 1.04	60	- 0.255
15.87	+ 1.00	65	- 0.39
20	+ 0.84	70	- 0.53
25	+ 0.66	75	- 0.66
30	+ 0.53	80	- 0.84
35	+ 0.39	84.13	- 1.00
40	+ 0.255	85	- 1.04
45	+ 0.125	90	- 1.28
50	+ 0.000	95	- 1.64

The Numerical method was used in this study because of its simplicity while working with spatial datasets.

2.4.5 Experimental Design

The design of experiments (DOE, DOX, or experimental design) is the design of any task that aims to describe or explain the variation of information under conditions that are hypothesized to reflect the variation (Creswell, 2013). It differs from an *observational study*, which involves collecting and analyzing data without changing existing conditions.

In its simplest form, an experiment aims at predicting the outcome by introducing a change of the preconditions, which is reflected in a variable called the *predictor (independent variable)*. The change in the predictor is generally hypothesized to result in a change in the second variable, hence called the *outcome (dependent variable)*.

DOE is an efficient procedure for planning experiments so that the data obtained can be analyzed to yield valid and objective conclusions. Because the validity of an experiment is directly affected by its construction and execution, attention to experimental design is extremely important (Campbell et.al, 1963). Major concerns in experimental design include the establishment of validity, reliability, and replicability. For example, these concerns can be partially addressed by carefully choosing the predictor, reducing the risk of measurement error, and ensuring that the documentation of the method is sufficiently detailed.

Categories of experimental designs

There are three broad categories of experimental designs **(**Montgomery, 2013):

1. Independent measures where different participants are used in each condition of the independent variable. This means that each condition of the experiment includes a different group of participants. This should be done by random allocation, which ensures that each participant has an equal chance of being assigned to one group or the other. This type of design is also known as *between groups*.
2. Repeated measures where the same participants take part in each condition of the independent variable. This means that each condition of the experiment includes the same group of participants. This type of design is also known as *within groups*.
3. Matched pairs where each condition uses different participants, but they are matched in terms of important characteristics, e.g. gender, age, intelligence etc. One member of each matched pair must be randomly assigned to the experimental group and the other to the control group.

The Matched pairs category was used in this study because of its appropriateness. It was very relevant because each condition of cropping and/or irrigation alternative is determined using different participants i.e. varying set NIR ranges, yet they are matched in terms of one important characteristic which is their supplemental Irrigation assessment.

Variables in experimental design

There are three different kinds of variables i.e. the independent variable, the dependent variable, and controlled variables.

i. Independent Variable (IV): this is the variable that is changed to examine its effect on the dependent variable. The IV must be operationally defined (in terms of the experiment) and empirically defined (in general for future variations of the experiment), and a minimum of 3 different levels must be listed excluding the control level.
ii. Dependent Variable (DV): the dependent variable is what is affected by the independent variable. It should be defined in units. The dependent variable must be operationally and empirically defined, and levels are unnecessary because that is what will be determined through the experiment.
iii. Controlled Variables (CV): Controlled variables are factors which could affect the dependent variable but are kept constant throughout the experiment. Several controlled variables should be listed (usually four is a good amount).

2.5 Overview of Geospatial Techniques and their Applications

Geospatial technology refers to set of tools and methods used in acquiring, managing, interpreting, integrating, displaying, and analyzing data in the geographic, temporal, and spatial contexts (Lynn, 2009). They include Geographic Information Systems (GIS), satellite remote sensing of the environment, surveying techniques, digital mapping and Global Positioning Systems (GPS).

The effectiveness of geospatial technologies as data and information management, and decision-making tool depends on people who know the theory and applications of those technologies and can be resourceful in identifying and collecting spatial data, determining the quality of the data, processing it, and asking the right kind of questions to get right answers to aid decision-making (Lynn, 2009).

2.5.1 Geographic Information System

A Geographic Information System (GIS) is a computer-based information system that supports capture, modeling, manipulation, retrieval, analysis, and presentation of spatial data. GIS has become an increasingly important means for understanding and dealing with the pressing problems of water and related resources management in the world. Information about water resources and the environment is inherently geographic. GIS concepts and technologies help in collection and organization of the data about such problems and understand their spatial relationships. An example of new mapping technology is satellite imagery from which detailed terrain models (DTM) can be created. Examples of fields where it is actively used include: land use planning where GIS is used to evaluate the consequences of different scenarios in the development of a region; geology where GIS is used to find the most suitable places for mining; or to determine areas subject to natural hazards; pollution monitoring using GIS functions; City planning based on analysis of many spatial and temporal patterns; Water shed hydrologic and groundwater modeling; water and wastewater demand forecasting, pipe network modeling, floodplain delineation, etc.

Geospatial applications in irrigation

Irrigation is one of the most important inputs for an efficient and sustainable agricultural production (Chandra and Ghosh, 2015). Water availability for irrigation purposes for any area is vital for crop production in that region. Irrigation experts are seeking the ways in which the water is used very efficiently and among these are geospatial interventions that include land use mapping; irrigated area mapping; irrigation requirement assessment; Remote Irrigation water monitoring and Management; Satellite data based identification of the water supply source (surface and subsurface); Satellite data based identification of the irrigation infrastructure: canals, dams, pipelines, weir etc; GIS based identification of water flow direction, area, slope and drainage; Smart Sensors for measuring Soil Moisture; Aerial application of pesticides, guided by satellite navigation and Drone based monitoring of crop type and yield.

In this study, Geospatial techniques were used to assess supplemental irrigation requirements of Maize and Sorghum by considering land suitability analysis, evapotranspiration estimation, Net Irrigation Requirement computation, and designing Irrigation alternatives all performed in GIS environment.

GIS Software

A large number of GIS software options are available as open-source or commercial products. These include ArcGIS^{R}, AutoCAD, ERDAS IMAGINE, GRASS (Geographic Resource Analysis Support System), AQUASTAT, ILWIS (Integrated Land and Water Information System). As a GIS and Remote Sensing package, ILWIS allows one to input, manage, analyze and present geo-graphical data. From the data, it is possible to generate information on the spatial and temporal patterns and processes on the earth surface.

Due to its advantages over similar software, ILWIS 3.6 was the main GIS software used for this study.

2.5.2 Integrated Land and Water Information System

Integrated Land and Water Information System (ILWIS) is a geographic information system (GIS) and remote sensing software for both vector and raster data processing. Its features include digitizing, editing, analysis and display of data, and production of quality maps. ILWIS was initially developed and distributed by ITC Enschede (International Institute for Geo-Information Science and Earth Observation) in the Netherlands for use by its researchers and students. Having been used by many students, teachers and researchers for more than two decades, ILWIS is one of the most user-friendly integrated vector and raster software programmes currently available.

ILWIS has some very powerful raster analysis modules, a high-precision and flexible vector and point digitizing module, a variety of very practical tools, as well as a great variety of user guides and training modules all available for downloading. Similar to the GRASS GIS in many respects, ILWIS is available natively only on Microsoft Windows. However, a Linux Wine manual has also been released (Hendrikse, 2000).

ILWIS Operations Relevant to the Study

The following operations as explained below played a significant role in the attainment of the overall objective of this study.

i. **Mask operation:** A mask is a simple query to find (retrieve), display or use only those points, segments or polygons in a map that have certain class names, identifiers or values. It allows the user to selectively copy Part of an input Vector map into a new output vector map. The user has to specify a mask to select and retrieve the class names, IDs or values of the polygons that are to be copied. By specifying a mask, one can search for points, segments or polygons with a certain class name, ID or value.

ii. **Attribute-map operation:** by creating an attribute map of a raster map, the class name or ID of each pixel in the original map is replaced by the value, class or ID found in a certain column in an attribute table. A raster map using a Class or ID domain can have extra attribute information on the classes or identifiers in the map. These attributes are stored in columns in an attribute table. The attribute table can be linked to the map to which it refers, or to the domain of the map. One can check whether an attribute table is linked to the raster map or to its domain through the properties dialog box of the map or the domain.

iii. **Rasterize operation:** this operation is used to convert a Vector map i.e. Polygon, Point or Segment map into a raster map. The class names, IDs, or values in the Vector map are also used in the raster map, i.e. the domain of the polygon map is also the domain of the raster map however the user has to select or create a georeference for the output raster map**.**

iv. **Cross operation:** The Cross operation performs an overlay of two raster maps: pixels on the same positions in both maps are compared; the occurring combinations of class names, identifiers or values of pixels in the first input map and those of pixels in the second input map are stored. These combinations give an output cross map and a cross table. The cross table includes the combinations of input values, classes or IDs, the number of pixels that occur for each combination and the area for each combination.

v. **Resample operation:** This operation resamples a raster map from the map's current georeference to another target georeference. The coordinate of each output pixel is used to calculate a new value from close-by pixel values in the input map. Three resampling methods are available: nearest neighbor, bilinear, and bicubic. In raster operations (e.g. MapCalc, Cross), all input raster maps must have the same georeference. Thus, prior to such operations, you can use resample to combine raster maps obtained from various sources (different projections, pixel size); to combine satellite imagery of different dates or resolutions; to combine satellite images or scanned photographs with existing rasterized vector data and to rectify scanned aerial photographs.

vi. **Fill-Sinks operation;** before using the Flow Direction operation, the user may wish to clean up the Digital Elevation Model (DEM), so that local depressions (sinks) are removed from your DEM. The “Fill sinks” operation will 'remove' from a DEM; depressions that consist of a single pixel, i.e. any pixel with a smaller height value than all of its 8 neighboring pixels and depressions that consist of multiple pixels, i.e. any group of adjacent pixels where the pixels that have smaller height values than all pixels that surround such a depression

The resulting output map of the Fill sinks operation is a so-called sink-free or depression-free DEM. This means that for every pixel in the DEM, a flow direction will be found towards the edges of the map. In this way, it is ensured that, when using the Flow direction operation on the output DEM of the Fill sinks operation, and a subsequent Flow accumulation operation on the output map of the Flow direction operation: outlets will always be found towards the edges of the map; Lakes and flat areas will not act as 'consuming' reservoirs of water but will still discharge towards an outlet.

vii. **Flow-direction Operation:** this operation determines into which neighboring pixel any water in a central pixel will flow. Flow direction is calculated for every central pixel in input blocks of 3 by 3 pixels, each time comparing the value of the central pixel with the value of its 8 neighboring pixels. The output map contains flow directions as N (to the North), NE (to the North East), etc.

viii. **Flow-accumulation operation:** this operation performs a cumulative count of the number of pixels that naturally drain into outlets. The operation can be used to find the drainage pattern of a terrain. As input the operation uses the output map of the flow direction operation and contains cumulative hydrologic flow values that represent the number of input pixels which contribute any water to the outlets (or sinks if these have not been removed).

ix. **Filter operation:** Filtering is a process in which each pixel value in a raster map is replaced with a new value. The new value is obtained by applying a certain function to each input pixel and its direct neighbors. These neighbors are usually the 8 adjacent pixels (in a 3 x 3 filter) or the 24 surrounding pixels (in a 5 x 5 filter). It is used for example to sharpen an image, to detect line features, to remove noise from an image, etc. In this particular study, DFDX and DFDY filters were majorly used to detect slope differences in x and Y-directions respectively.

x. **Slice operation**: Slicing classifies the values of a raster map. Ranges of values of the input map are grouped together into one output class. A domain group should be created beforehand; it lists the upper boundaries of the groups and the group names. With slicing, a map with for example slope values ranging from 0 to 100% can be grouped into relief classes: Flat (0-2%), Undulating (2-8%), Rolling (8-16%), Hilly (16-30%), Mountainous (>30%). Also, a map containing Green Vegetation Index values (combination of satellite bands), can be sliced into user-defined intervals. This can be considered as a first classification.

xi. **Glue-raster maps:** The *Glue raster maps* operation glues or merges two or more georeferenced input raster maps into one output raster map. The output map then comprises the total area of all input maps. The domains of the input maps are merged when needed. Resampling is performed when needed. With the Glue raster maps operation, you can thus merge two or more adjacent or partly overlapping raster maps (i.e. make a mosaic), or glue smaller raster maps onto a larger one.

xii. **Import-map Operation**: this operation is used to import a map in the format of another software package into ILWIS.

2.5.3 Suitability analysis in GIS

The concept of *Suitability analysis* describes the search for locations or areas that are characterized by a combination of certain properties. Often, the result of a suitability analysis is a suitability map. It shows which locations or areas are suitable for a specific use in form of a thematic map such as a ground water suitability map (Saaty, 2008).

Suitability analysis in GIS is achieved by a principle called **weighted overlay** which involves assigning weights to influencing factors (Pourghasemi et.al, 2012). In this approach, a numerical weighting factor is assigned to each thematic layer according to its relative importance compared to all other layers. After that, the weighted layers are overlaid on to one thematic layer. This approach of weighted overlay is possible with raster and vector data sets.

The weighted layers are overlaid on to one thematic layer with the weighted overlay tool accepting only discrete rasters (integer values) as input. Continuous rasters must be reclassified to discrete rasters before they are overlaid. As an example, two input rasters as shown in figure 2.1 have been reclassified to an evaluation scale of 1 to 3. Each raster is assigned a percentage influence. The influence of the first raster is 75 percent and the influence of the second is 25 percent. The cell values are multiplied by their influence percentages, then added together to create the output raster. Taking the top left cell (2 * .75) = 1.5 and (3 * .25) = .75. The sum of 1.5 and .75 is 2.25. Because the output raster is discrete, the value is rounded to 2.

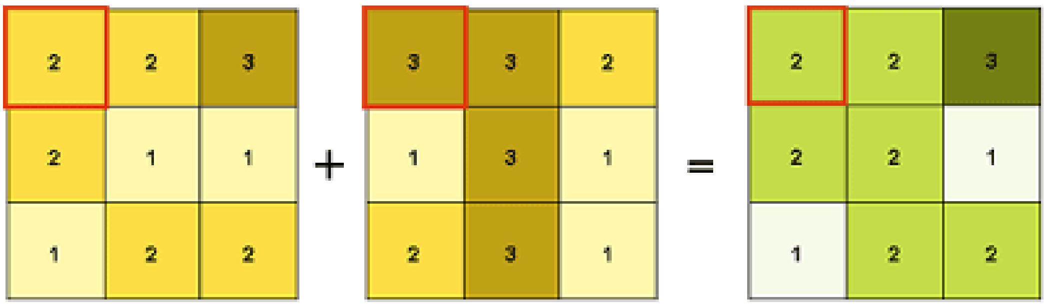


Figure 2.1 Principle of Weighted overlay of raster datasets (Saaty, 2008)

The following weighting methods are available (Zuccaa, 2008):

a) ***Direct:*** the user specifies a value for the relative importance of each factor himself. Weights are normalized automatically within the software

b) ***Rank Order:*** the user specifies the rank-order of the relative importance of all factors, either using the rank sum method or the expected value method. From the specified rank-order, normalized weights are calculated.

c) ***Pairwise Comparison:*** the user goes through all unique pairs and assigns the Saaty weights, i.e. user specifies the relative importance for each pair of factors in fixed phrases or with a slide bar. From these weights, normalized weights are calculated. This method stems from the Analytic Hierarchy Process (AHP), a famous decision-making framework developed by the American Professor of mathematics (Saaty, 2008).

Analytic Hierarchy Process (AHP)

AHP is one of the most widely applied Multi-Criteria Evaluation (MCE) techniques whose main strength lies in its impartial and logical grading system as well as its flexibility to be combined with other techniques such as Linear Programming, Genetic Algorithm, and Fuzzy Logic. It enables the decision-makers to structure a complex problem in the form of a simple hierarchy and to evaluate a large number of quantitative and qualitative factors in a systematic manner under multiple criteria environment in confliction (Cheng, 1999).

The AHP is a powerful and flexible multi-criteria decision-making tool for dealing with complex problems where both qualitative and quantitative aspects need to be considered. The AHP helps analysts to organize the critical aspects of a problem into a hierarchy rather like a family tree (Saaty, 2008).

The application of the AHP to the complex problem usually involves four major steps (Cheng, 1999).

1. Break down the complex problem into a number of small constituent elements and then structure the elements in a hierarchical form.
2. Make a series of pair wise comparisons among the elements according to a ratio scale.
3. Use the eigenvalue method to estimate the relative weights of the elements.
4. Aggregate these relative weights and synthesize them for the final measurement of given decision alternatives.

An advantage of the AHP is that it is designed to handle situations in which the subjective judgments of individuals constitute an important part of the decision process.

Steps taken in assigning weights

1) Completion of the pairwise comparison matrix; Two criteria are evaluated at a time in terms of their relative importance. Index values from 1 to 9 are used. If criterion A is exactly as important as criterion B, this pair receives an index of 1. If A is much more important than B, the index is 9. All gradations are possible in between. For a "less important" relationship, the fractions 1/1 to 1/9 are available: if A is much less important than B, the rating is 1/9. The values are entered row by row into a cross-matrix. The diagonal of the matrix contains only values of 1. First, the right upper half of the matrix is filled until each criterion has been compared to every other one. If A to B was rated with the relative importance of n, B to A has to be rated with 1/n. If the vegetation cover is a little more important than slope (index 3), the slope is a little less important than vegetation cover

(index 1/3). For reasons of consistency, the lower left half of the matrix can thus be filled with the corresponding fractions.

Table 2.4 Weighting system for AHP (Saaty, 2008)

Definition	Index	Definition	Index
Equally important	1	Equally important	1/1
Weak or slightly important	2	Equally or slightly less important	1/2
Moderately important	3	Slightly less important	1/3
Moderate to Strongly important	4	Moderate to Strongly less important	1/4
Strongly important	5	Strongly less important	1/5
Strongly to Very strongly important	6	Strongly to Very strongly less important	1/6
Very strongly important	7	Very strongly less important	1/7
Very, very strongly more important	8	Very, very strongly less important	1/8
Extremely more Important	9	Extremely less important	1/9

2) Calculating the criteria weights; the weights of the individual criteria are calculated. First, a normalized comparison matrix is created: each value in the matrix is divided by the sum of its column. To get the weights of the individual criteria, the mean of each row of this second matrix is determined. These weights are already normalized; their sum is 1.
3) Assessment of the consistency matrix; A statistically reliable estimate of the consistency of the resulting weights is made. An important consideration in terms of the quality of the ultimate decision relates to the consistency of judgments that the decision maker demonstrated during the series of pairwise comparisons.

It should be realized perfect consistency is very difficult to achieve and that some lack of consistency is expected to exist in almost any set of pairwise comparisons

Implementing the Analytic Hierarchy Process

The numbers odd numbers 3, 5, 7, and 9 correspond to the verbal judgments "moderately important", "strongly more important", "very strongly more important", and "extremely more important" and 2, 4, 6, and 8 for compromise between the previous values. Reciprocal values are automatically entered in the transpose position. In order to compute the weights for the different criteria, the AHP starts creating a pairwise comparison matrix **A**. The matrix **A** is a m×m real matrix, where m is the number of evaluation criteria considered. Each entry a_{jk} of the matrix **A** represents the importance of the j_{th} criterion relative to the k_{th} criterion. If $a_{jk} > 1$, then the j_{th} criterion is more important than the k_{th} criterion, while if $a_{jk} < 1$, then the j_{th} criterion is less important than the k_{th} criterion. If two criteria have the same importance, then the entry a_{jk} is 1. The entries a_{jk} and a_{kj} satisfy the following constraint.

$$a_{jk} \times a_{kj} = 1 \qquad (2.12)$$

Obviously, $a_{jk} = 1$ for all j. The relative importance between two criteria is measured according to a numerical scale from 1 to 9, where it is assumed that the j_{th} criterion is equally or more important than the k_{th} criterion. The phrases in the "Interpretation" may be used to translate the decision maker's qualitative evaluations of the relative importance between two criteria into numbers. It is also possible to assign intermediate values which do not correspond to a precise interpretation. The values in the matrix **A** are by construction pairwise consistent. On the other hand, the ratings may in general show slight inconsistencies. However, these do not cause serious difficulties for the AHP.

Table 2.5 Relative scores in AHP

Value of a_{jk}	**Interpretation**
1	j and k are equally important
3	j is slightly more important than k
5	j is more important than k
7	j is strongly more important than k
9	j is absolutely more important than k

Once the matrix **A** is built, it is possible to derive from **A** the normalized pairwise comparison matrix, $\mathbf{A}_{normal}$ by making equal to 1 the sum of the entries on each column. Each entry a_{jk} of the matrix $\mathbf{A}_{normal}$ is computed as;

$$\bar{a}_{jk} = \frac{a_{jk}}{\sum_{i=1}^{m} a_{jk}} \quad \text{.......... (2.13)}$$

Where $\bar{a}_{jk}$ is the computed entry of the matrix $\mathbf{A}_{normal}$

Finally, the criteria weight vector **w** (that is an m-dimensional column vector) is built by averaging the entries on each row of $\mathbf{A}_{normal}$ computed as;

$$w_j = \frac{\sum_{i=1}^{m} \bar{a}_{ji}}{m} \quad \text{.......... (2.14)}$$

For a matrix **A**, a_{ji} denotes the entry in the i_{th} row and the j_{th} column of **A**. For a vector **v**, v_i denotes the i_{th} element of **v**.

Consistency Index (CI)

The consistency index is an indicator of the degree of consistency in pairwise comparisons and should range between 0 and 0.1 (Cheng, 1999). A value of 0 indicates complete consistency; a value larger than 0.1 indicates inconsistency and implies that the pairwise comparison should be adjusted (Cheng, 1999).

Estimating CI

Step 1: Multiply each value in the first column of the pairwise comparison matrix by the relative priority of the first item considered and then sum up the values across the rows to obtain a vector of values labeled "weighted sum".

Step 2: Divide the elements of the vector of weighted sums obtained in Step 1 by the corresponding priority value labeled "weight priority".

Step 3: Compute the average of the values computed in step 2. This average is denoted as $\lambda_{\max}$

Step 4: Compute the consistency index (CI):

$$CI = \frac{\lambda_{\max} - m}{m - 1} \quad \text{.......} \quad (2.15)$$

Standardization of input maps

Most values in the various input maps have different meanings, and are expressed in different units of measurement (e.g. distance maps, costs, age, etc.). In order to compare criteria with each other, all values need to be standardized, i.e. transformed to the same unit of measurement (from 0 to 1) (Zuccaa, 2008). Different standardization is applied for different types of maps as summarized in Pourghasemi et.al (2012).

a) For "value maps", standardization is done by choosing the proper transformation function from a set of linear and non-linear functions. The outcome of the function is always a value between 0 and 1. The function is chosen in such a way that pixels in the map that are highly suitable for achieving the objective result in high standardized values, and unsuitable pixels receive low values. ILWIS' SMCE module provides a number of linear and nonlinear functions. Possible standardization methods for value maps in the developed SMCE module are e.g. “Maximum”, “Interval” and “Goal”. Together with the “cost/benefit” property of the criterion, this information is sufficient for applying the selected standardization method in the correct way.

b) For “classified maps”, standardization is done by matching a value between 0 and 1 to each class in the map. This can be done directly, but also by pair wise comparison or rank ordering the classes.

Pairwise comparison was used in this study because of its easy and more reliable justification of priorities (Saaty, 1977) and it is from this analysis respective saaty weights for the above factors were calculated as shown in Table 4.2. The advantage of this method is that decision makers can express qualitative priorities and that more priority assessments are made, which allows for a check on consistent assessment. The disadvantage of this method is that it is rather time consuming.

Determination of output map(s)

The calculation of output maps also known as composite index maps in ILWIS is only possible when all input data is defined and no values are out of range. When only one 'alternative' is used, the output map for the main goal will be calculated, as well as underlying maps for optional sub goals.

When multiple alternatives are used, output maps will be calculated for every alternative, as well as underlying map(s) for optional sub goals. They contain the accumulated suitability for all criteria, standardized and weighted as specified in the criteria tree and have values between 0 and 1 (domain NIL to 1).

Pixels with values near 0 represent unsuitable areas whereas pixels with values near 1 represent highly suitable areas. The output map is a combination of all inputs. In other words, the output map is the result of the weighted-sum formulas and the standardization formulas. However, areas that were classified as 'impossible' in constraints are propagated to the resulting composite index map: these areas will obtain suitability 0.

Classifying or slicing the composite index maps

The first phase in this classification is inspecting the values in the Composite Index maps using respective histogram or aggregate values followed by classifying or slicing the values in the SMCE output maps into a user-defined number of classes guided by the user's desired boundary values and adapted output class names.

2.5.4 Remote Sensing for rainfall monitoring

Remote sensing is the science and art of obtaining information about an object, area, or phenomenon through the analysis of data acquired by a device that is not in contact with the object, area, or phenomenon under investigation (Lynn, 2009). Using various sensors such as Micro-wave (MW), Thermal infra-red (TIR), etc., about earth characteristics such as surface temperature, cloud cover, Vegetation index and even areal rainfall. The sensors are mounted at satellites that can remain stationed vertically above a particular point on the earth's surface (Geostationary satellites) or Polar orbiting satellites where these particular ones follow the pattern of the sun (Cecccato and Dinku, 2010) .

Remotely sensed data is comparatively advantageous over data from the rain gauges in terms of cost, area coverage, better/ relatively consistent spatial and temporal coverage but can however be unreliable given environmental factors (like clouds) that may obscure correct data. This observations call for interpretation of skilled operators and emphasis of calibration/validation against ground-based data (Ymeti, 2007).

Merging Satellite rainfall estimates from different sensors

According to Cecccato and Dinku, (2010), rainfall estimates from TIR sensors offer global coverage, higher spatial resolution and more repeat time but their accuracy is very limited. On the other hand, Microwave (MW) sensors offer a more accurate rainfall estimate but have limited area coverage, coarse spatial resolution and very low repeat frequency.

Consequently, there are techniques which make the best use of the better accuracy of MW sensors and the better spatial and temporal coverage of TIR sensors by optimally combining the two products. Different statistical techniques are employed by different agencies to accomplish this. Another approach towards better satellite rainfall products is blending the satellite rainfall estimates with available gauge measurements. Generally this is accomplished in two stages. In the first stage the gauge data is used to adjust satellite rainfall estimates for bias errors. Then the satellite product is blended with the gauge observation. The quality of the final product depends on the quality, number, and distribution of the gauges used.

Remotely sensed Rainfall Products

There are a number of internationally recognized remotely sensed rainfall products with most of them generated by the National Oceanographic and Atmospheric Administration's climate prediction center **(**NOAA-CPC, U.S.), with satellites being flown by the National Aeronautics and Space Administration (NASA, U.S.) and Japan Aerospace Exploration Agency (JAXA, Japan) (Ymeti, 2007). Some of these products include the following:

i. African Rainfall Estimation (RFE)

This is a product produced by NOAA-CPC specifically for Africa. The current version, RFE version 2.0 (RFE2), started in January 2001. Meteosat geostationary satellite infrared data is acquired in 30-minute intervals, and areas depicting cloud top temperatures of less than 235K are used to estimate convective rainfall.

World Meteorological Organization (WMO) Global Telecommunication System (GTS) data taken from approximately 1000 stations provide accurate rainfall totals, and are assumed to be the true rainfall near each station. RFE2 obtains the final daily rainfall estimation using a two part merging process, then sums daily totals to produce decadal estimates at about 10km spatial resolution.

ii. African Rainfall Climatology (ARC)

ARC is also produced by NOAA-CPC at 10km spatial resolution daily. It is very similar to RFE except that 3-hourly TIR data is used instead of 30-minute and it does not include microwave observations. Its objective is to create 1982-present climatology of daily precipitation over Africa. Currently ARC data is available starting from 1995.

iii. Global Precipitation Climatology Project (GPCP)

The Global Precipitation Climatology Project (GPCP) combines the precipitation information available from each of several sources into a final merged product, taking advantage of the strengths of each data type. The microwave estimates are based on Special Sensor Microwave/Imager (SSM/I) data from the Defense Meteorological Satellite Program satellites that fly in sun-synchronous low-earth orbits. The infrared precipitation estimates are obtained primarily from geostationary satellites and secondarily from polar orbiting satellites. Additional low-Earth orbit satellite estimates also come from instruments onboard the NOAA series satellites. The gauge data are assembled and analyzed by the Global Precipitation Climatology Centre. The current products include global monthly 2.5^o and daily 1^o rainfall estimates. The monthly data extends from 1979 to current, while the daily product is from 1996 to present. Both products are made available with some time delay.

iv. CPC Merged Analysis of Precipitation (CMAP)

CMAP is produced by NOAA-CPC at a spatial resolution of 2.5^o with pentad (five-day) and monthly aggregations. This technique produces global precipitation in which observations from rain gauges are merged with precipitation estimates from several satellite-based algorithms and is very similar to that of GPCP.

Remotely sensed rainfall data of RFE version 2.0 was used in this study because of relatively higher accuracy merging three sets of data i.e. available data, TIR-sensed data and Micro-wave sensed data.

CHAPTER THREE: MATERIALS AND METHODS

3.1 Land Suitability Analysis Using Spatial Multi-Criteria Evaluation

This was done using the SMCE tool in ILWIS as explained in Section 2.5.2. Under this section, four datasets i.e. the soil pH map, soil clay content map, slope map and the protected areas map of Karamoja region were developed as shown in section 4.2. These four datasets were then subjected to SMCE in ILWIS where they were standardized, weighted and later assigned Saaty weights using Pairwise Comparison in AHP.

The FAO's Land Evaluation Framework as described in section 2.4.1 was adopted for this study because it considers more parameters in its assessment i.e. the water quality, quantity and seasonality on top of land characteristics majorly used by the USBR framework (FAO, 1985).

3.2 Methodology for Development of SMCE Input Maps

3.2.1 Current boundary map

This boundary map shown in section 4.2.1 below was developed using the *Mask* operation in ILWIS as explained in section 2.5.2. This output was very important in the development of the other datasets.

3.2.2 Slope map

Before calculating the slope map, the Digital Elevation Model (DEM) of the study area was derived after a "cross" operation between the boundary map developed earlier on and a 90m resolution DEM for the entire area of Uganda obtained from Shuttle Radar Topographic Mission (SRTM).

The following procedure was then used for the slope map generation:

i. Calculation of height differences in X-direction using the Filter operation as explained in section 2.5.2. A linear filter *DFDX* was used to compute a map showing the first derivative in X-direction (df/dx) per pixel. The calculated Map using this filter was named "Kara_DX".

ii. Calculation of height differences in Y-direction using the same Filter operation but instead using a different linear filter *DFDY* to compute the first derivative in Y-direction (df/dy) per pixel. The calculated Map for this study using this filter was named "Kara_DY".

iii. A slope map in percentages was then derived using an ILWIS command line operation as shown in Equation 3.1.

*Kara_Slope = 100 * HYP(Kara_DX,Kara_DY)/ PIXSIZE(Kara_DEM)*. (3.1)

where *Kara_Slope* is the calculated slope map in percentages, *HYP* is an internal Mapcalc/Tabcalc function in ILWIS, *Kara_DX* and *Kara_DY* are maps showing pixel by pixel height differences in X and Y direction respectively, and PIXSIZE is an internal function that returns the pixel size of a raster map in this case 90m.

iv. The slope map in percentages was then converted to degrees to simplify the subsequent analysis using the command line function shown in Equation 3.2.

Kara_SlopeDEG = RADDEG(ATAN(Kara_Slope/100))……………..…… (3.2)

where *Kara_SlopeDEG* is calculated slope map in degrees, *ATAN* and *RADDEG* are internal MapCalc/TabCalc functions in ILWIS used in this conversion.

3.2.3 Soil map

Two maps for pH and soil clay content were calculated as attribute maps of the raster soil map of Karamoja region *Kara_Soils* using respective attribute map windows as illustrated in Figure 3.1. The Soil map of Karamoja region was an extract from the original 90m resolution map obtained from National Agricultural Research Organisation (NARO).

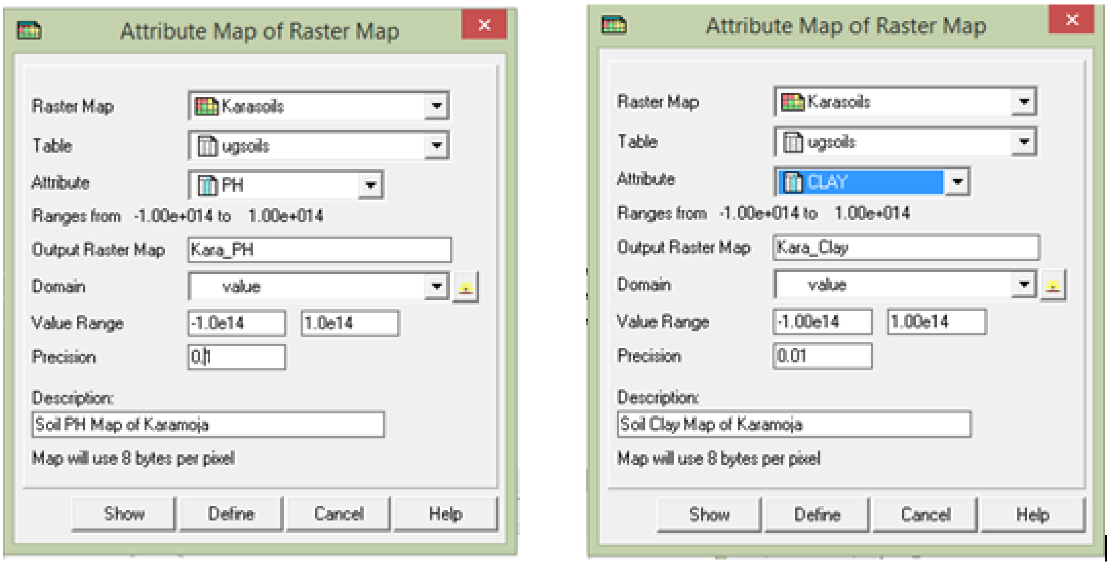


Figure 3.1 Attribute map windows for calculating pH and soil clay content maps

The two windows shown in Figure 3.1 summarize an operation in which pH and soil clay content maps are derived from the soil map of Karamoja region where pH and soil clay content data is stored for each pixel. Soil clay content and pH were used in this study because they are among the most significant factors affecting Maize and Sorghum growth as explained in section 2.3.

3.2.4 Protected areas map

The *protected areas* map was developed using the *Cross* operation in ILWIS as explained in section 2.5.2. This map was very crucial in delineating the permanently-not-suitable areas for irrigation as areas gazetted for National parks, and Central

Forest Reserves. This was clipped from the original *protected areas* map of Uganda developed by the National Forestry Authority (NFA).

3.3 SMCE Methodology for Land Suitability Analysis

The SMCE process was very useful in computing maps that indicate respective areas with varying suitability indices for both Maize and Sorghum production. To achieve the analysis, the following procedure was adopted:

3.3.1 Problem Structuring phase

It is within this phase that factors and constraints affecting the analysis were defined with all the necessary conditions set as enumerated below:

a) ***Problem:*** **land suitability analysis for Maize and Sorghum**

b) ***Constraints:*** The suitable area should not be a national park, or central forest reserve.

c) ***Suitability Factors***

  i. The arable area for both Maize and Sorghum should preferably be located on a terrain with a slope less than 20º (FAO, 1985).

  ii. Both Maize and Sorghum are significantly affected by clay and pH levels present in the soil as explained in section 2.3. However, effective Sorghum production requires significant soil clay content (at least have 20%) in contrast to effective Maize production which requires very low levels of Soil clay. Sorghum is more pH tolerant i.e. 5.5-8.5 as compared to Maize's tolerance of 5.0 to 7.0.

3.3.2 Standardization (Partial valuation) of factors

Each criterion was represented by a map of a different type, i.e. one classified map (*Protected areas* map) and three (3) value maps (slope, soil pH, and soil clay).

For decision analysis, the values and classes of all the maps had to be converted into a common scale, called "utility" relating to its value/worth (measured in a scale 0 to 1).

3.3.3 Weighting

After all input maps were standardized; weights showing the relative importance of each input map were then computed using the Pairwise comparison technique as explained in section 2.5.3. Equations 2.13 – 2.15 were used to develop the pair wise comparison matrix, the normalized matrix and also and the consistency ratio respectively for both Maize and Sorghum as shown in Tables 3.1 – 3.3.

Table 3.1: Pairwise Comparison Matrices for Sorghum and Maize Land suitability analysis

Sorghum				Maize			
	CLAY	pH	SLOPE		CLAY	pH	SLOPE
CLAY	1	9	9	CLAY	1	4	9
pH	1/9	1	7	pH	1/4	1	9
SLOPE	1/9	1/7	1	SLOPE	1/9	1/9	1
Total	**1.22**	**10.14**	**17**		**1.36**	**5.11**	**19**

Soil clay is extremely more important (Index 9 as explained in Tables 2.4 and 2. 5) in land suitability analysis for Sorghum as compared to that in maize owing to the relevance of clay content in effective Sorghum production (*refer to section 2.3*).

On the other hand, Soil pH is extremely more important (Index 9) in Land Suitability analysis for Maize as compared to that in Sorghum owing to the limited PH range to enhance effective Maize production (*refer to section 2.3*). This limited PH range made a critical factor in the analysis

Table 3.2: Normalized Pairwise Comparison Matrices for Sorghum and Maize Land suitability analysis

Sorghum					Maize				
	CLAY	**pH**	**SLOPE**	**WEIGHT PRIORITY**		**CLAY**	**pH**	**SLOPE**	**WEIGHT PRIORITY**
CLAY	0.818	0.887	0.529	**0.75**	**CLAY**	0.735	0.783	0.474	**0.66**
pH	0.091	0.099	0.412	**0.20**	**pH**	0.184	0.196	0.474	**0.29**
SLOPE	0.091	0.014	0.059	**0.05**	**SLOPE**	0.082	0.022	0.053	**0.05**
Total				**1**					**1**

Table 3.2 shows the procedure for computation of the respective weight priority for Sorghum and Maize. This was obtained using Equation 2.14 after calculating individual normalized entries using Equation 2.13.

The consistency index was finally computed in Table 3.3 using Equation 2.15 to ascertain the level of consistency of judgment following the criteria in section 2.5.3. It was found that the CI index for Sorghum and Maize was 0.08 and 0.09 respectively which is within the acceptable range.

Table 3.3: Computation of Consistency Index (CI) for Sorghum and Maize Land suitability analysis

Sorghum						
	CLAY	**pH**	**SLOPE**	**SUM**	**WEIGHT PRIORITY**	**SUM//WEIGHT**
CLAY	0.74	1.80	0.49	3.04	0.74	3.12
pH	0.08	0.20	0.38	0.67	0.20	3.16
SLOPE	0.08	0.03	0.05	0.17	0.05	3.20
λ_{max}						**3.18**
				CI for Sorghum = 0.08		
Maize						
	CLAY	**pH**	**SLOPE**	**SUM**	**WEIGHT PRIORITY**	**SUM/WEIGHT**
CLAY	0.66	1.14	0.47	2.27	0.664	3.30
pH	0.17	0.28	0.47	0.92	0.284	3.11
SLOPE	0.07	0.03	0.05	0.16	0.052	3.15
λ_{max}						**3.19**
				CI for Maize = 0.09		

This technique was adopted for this study because of its detailed procedure and criticality in weights calculation (Zuccaa, 2008). From this analysis respective Saaty weights for the above factors were calculated as shown in Table 4.2.

3.3.4 Suitability assessment/ derivation of overall attractiveness

a) After partial valuation and identification of the relative importance of each criterion, the next step was to obtain the overall attractiveness (suitability) of each point (pixel) ranging between 0 and 1 with a higher index correlating to increased suitability (Figures 4.4 and 4.5). Each of these derived maps was further “crossed” with the protected areas map to integrate the Permanently-

Not-Suitable class as those areas that are located in a national park, central forest reserve, or game reserve.

b) The final suitability maps were reclassified in ILWIS using the Slice Operation (*section 2.5.2*) into four classes according to FAO (1985) guidelines. These classes include: the Highly Suitable class, Moderately Suitable class, Marginally Suitable class, and the Permanently Not Suitable.

3.4 Irrigation suitability analysis based on Net Irrigation Requirement

This section was aimed at classifying areas based on their suitability for irrigation. The basis for this was the relative pixel Net Irrigation Requirement (NIR) obtained as a deficit between the respective average decadal crop water requirement and the average decadal effective rainfall. This analysis followed the Matched Pairs category of experimental design as explained in Section 2.5.3.

The first step was to calculate rainfall maps for the three designed seasons i.e. Season-1, Season-2, and Season-3 (Table 2.4). Remotely sensed rainfall data of RFE version 2.0 was used in this study because of relatively higher accuracy merging three sets of data i.e. available data, TIR-sensed data and Micro-wave sensed data. This data comprises of aggregated 10-day (decadal) rainfall maps respectively for each season active period. These rainfall maps were then resampled using Karamoja georeference to produce maps capturing rainfall data per decade for each season only within the region.

The derivation of average decadal effective rainfall maps for each season using resampled rainfall maps earlier developed followed. This was computed using the USDA method for calculation of effective rainfall and this resulted into three maps representing the Normal (50% probability of exceedance) scenario. It was then that six (6) other maps were calculated using the numerical method for estimating probability of exceedance to model the other two scenarios i.e. the Wet Year scenario (20% probability of exceedance) and Dry (80% probability of exceedance) scenario. This made a total of nine (9) effective rainfall maps i.e. one of 20%, 50%, and 80% probability of exceedance for each of the three seasons.

After derivation of effective rainfall maps for each season, NIR for each season across each scenario was then calculated as the deficit between the computed average decadal crop water requirement (ET_c) and the respective effective rainfall earlier computed. The crop water demand for both Maize and Sorghum were computed for each day after which an average decadal ET_c was calculated *(Refer to Figures 4.13-4.18).*

Finally for each pixel of the 9 effective rainfall maps, a value of seasonal NIR per pixel was calculated bringing to a total of 18 Maps all together i.e. 9 maps for each crop across all seasons and across all scenarios.

3.4.1 Methodology for effective rainfall and NIR maps computation

This section details the procedure for calculation of seasonal effective rainfall maps from which the Net Irrigation Requirement (NIR) maps were derived.

Seasonal effective rainfall maps

Seasonal effective rainfall depicts the available rainfall for agricultural use after initial losses are subtracted. To estimate this, 10-day remotely sensed rainfall data for the period 2001-2015 covering the entire Horn of Africa was obtained from Uganda National Meteorological Authority (UNMA). The first task was to conduct a preliminary validation of the acquired data which involved comparison of these maps with samples of the locally available data for the study area. Average rainfall for each decade over the 15-year period was then computed by averaging the decade rainfall estimates for each year.

Resampling of these broad rainfall maps (section 2.5.2) was then done using Karamoja georeference inorder to interact exclusively with only the area of interest. In consultation with Agronomists from the parastatal incharge of Agricultural research and development within Karamoja Region (Nabuin Zonal Agricultural and Development Institute), three (3) seasons each 90 days were designed for this research as shown in Table 3.4. Varieties *MM3* and *SESO3* for Maize and Sorghum respectively were selected for this research because they have been designed specifically for this region and relatively have early maturing properties.

Table 3.4: Designed seasons to ensure Year round Maize and Sorghum productivity

Proposed Season	Period of the year	Duration	Proposed Season
Season 1	March 21st – June 18th	90 days	Season 1
Rest	June 20th – July 19th	30 days	Rest
Season 2	July 20th – Oct 17th	90 days	Season 2
Rest	Oct 18th – Nov 16th	30 days	Rest
Season 3	Nov 17th – Feb 14th	90 days	Season 3
Rest	Feb 15th – March 20th	30 days	Rest
CYCLE BEGINS AGAIN			

Maize Variety: *MM3 requiring 90 days to full maturity*

Sorghum Variety: *SESO3 requiring 90 days to full maturity*

The above Season-1 start date was zeroed at after the study area reconnaissance and in consideration with Maize and Sorghum growth requirements as stated in Section 2.3. The average decadal rainfall estimates per pixel were then obtained by averaging the respective decadal estimates for each season.

Average decadal effective rainfall estimates maps factoring in the several rainfall losses were finally calculated using the USDA Soil conservation Service formula as illustrated in Section 2.4. This was adopted because of its accurate estimation (80-90%) for most rainfall values below/above the 100 mm/month in comparison to the actual field observations (Raes, 2004).

These seasonal effective rainfall maps were calculated to model the Wet Year scenario (20% probability of exceedance), a normal year (50% probability of exceedance) and Dry (80% probability of exceedance) scenarios as explained in section 2.4.4.

Seasonal Net Irrigation water requirement Maps

The first step under this was to calculate seasonal Reference Evapotranspiration (ET_o) *(Refer to APPENDIX II)*. This was calculated using CROPWAT 8.0 software using available average monthly minimum and maximum temperature data for 10 years (2005-2015) obtained from Uganda National Meteorological Authority (UNMA).

Crop factors (K_c) for Maize and Sorghum for the different stages of growth were obtained from Table 12 (FAO, 1998) and these were used to calculate the individual crop factors for each day of the season according to Equation 2.3

Daily crop water requirements (ET_c) for the entire growth period for Sorghum and Maize were calculated using Equation 2.2 as shown in APPENDIX III and IV. These daily crop water requirements were then summed to yield both seasonal and average decadal crop water requirements for each crop.

The average decadal irrigation requirement was finally obtained as a deficit between the average decadal water requirement and the average decadal effective rainfall estimates and this was calculated for each pixel in the entire area (*refer to Equation 2.1*). A total of eighteen (18) maps for average decadal NIR were generated throughout this section i.e. 9 maps for each crop across all seasons and across all scenarios.

3.4.2 Irrigation suitability analysis using set NIR ranges

After the development of eighteen (18) maps for seasonal NIR, this section was aimed at reclassifying the different areas within the study area based on their land suitability class for the respective crop and the calcualted relative NIR for each crop across all seasons and across all scenarios.

The *cross* operation in ILWIS, explained in section 2.5.2, was used where each of the eighteen (18) average decadal NIR maps was crossed with the respective land suitability map developed in Section 3.1.

The respective cross maps were subjected to logical-IFF condition statements with set NIR ranges as follows:

i. Highly suitable NIR range from -20mm to 0mm

ii. Moderately suitable NIR range from 1mm to 21mm

iii. Marginally suitable NIR range from 22mm to 43mm

The above NIR ranges were designed by taking into account the difference between the maximum and minimum NIR (-20mm and 43mm respectively) from the average decadal NIR values tabulated in Table 3.4. The negative values of NIR indicate an excess of rainfall as compared to the amount of water required by the crop.

This information was input into ILWIS and calculations done within the software from which Figures 4.17- 4.22 were determined showing varying suitability index for Maize and Sorghum production within the study area.

A total of eighteen (18) maps each depicting the varying levels of irrigation suitability within the region was developed i.e. 9 maps for each crop across all seasons and across all scenarios.

3.5 Determination of Cropping and Irrigation Alternatives

Following the matched pairs category of experimental design as explained in section 2.4.5, an inferential approach was adopted to guide on the most appropriate times each crop (Maize and Sorghum) would be grown under the specific suitability class.

This was done by extracting summary data of number of pixels per crop per class across each scenario and converting the same to hectares (Ha) by multiplying by the number of pixels by the square of the individual pixel size in this case 90 meters.

To further study the variations in a more clear and precise way, the converted areas per crop per class across each scenarios were now computed as percentages of the total area within the study area. This step would then give a clear conclusion of the cropping and irrigation alternatives at any given time of the year within the study area.

3.6 Summarized Methodological Approach

Figures 3.2 - 3.4 summarizes the sequential procedure followed in achieving the three (3) specific objectives of this study.

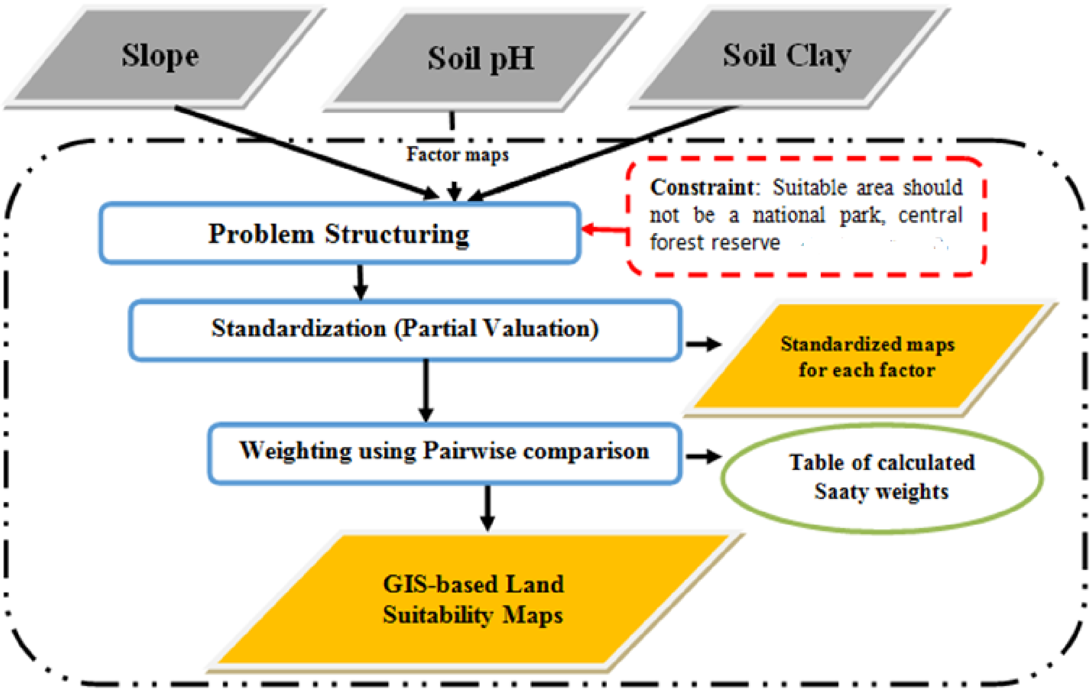


Figure 3.2: Methodological approach for Objective one

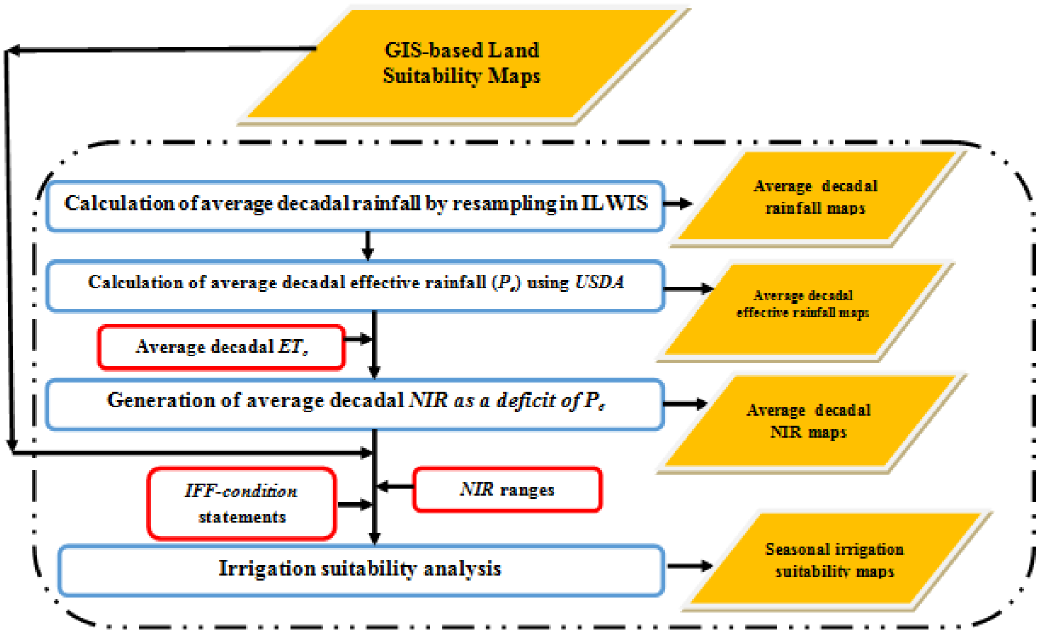


Figure 3.3: Methodological approach for Objective Two

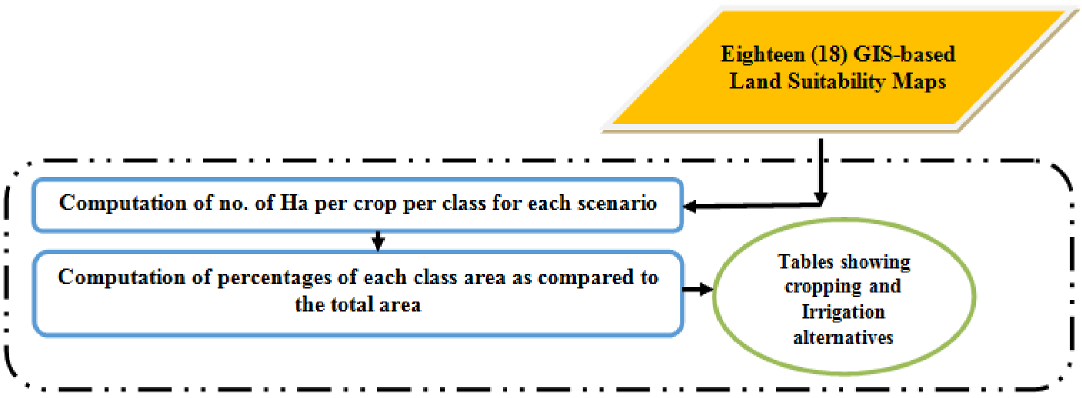


Figure 3.4: Methodological approach for Objective Three

CHAPTER FOUR: RESULTS AND DISCUSSION

4.1 Land Suitability Analysis Using Spatial Multi-Criteria Evaluation

This section presents step by step results that contributed to subsequent suitability analysis of specific areas suitable for Maize and Sorghum production within Karamoja Region.

4.2 Developed Geospatial and Hydrological Datasets for the Study Area

The following data sets were very important in the final analysis building on the overall objective of the study.

4.2.1 Boundary Map of Karamoja region

Figure 4.1 shows the seven (7) districts within Karamoja region. This map formed the basis for clipping out the rest of the datasets used in this study.

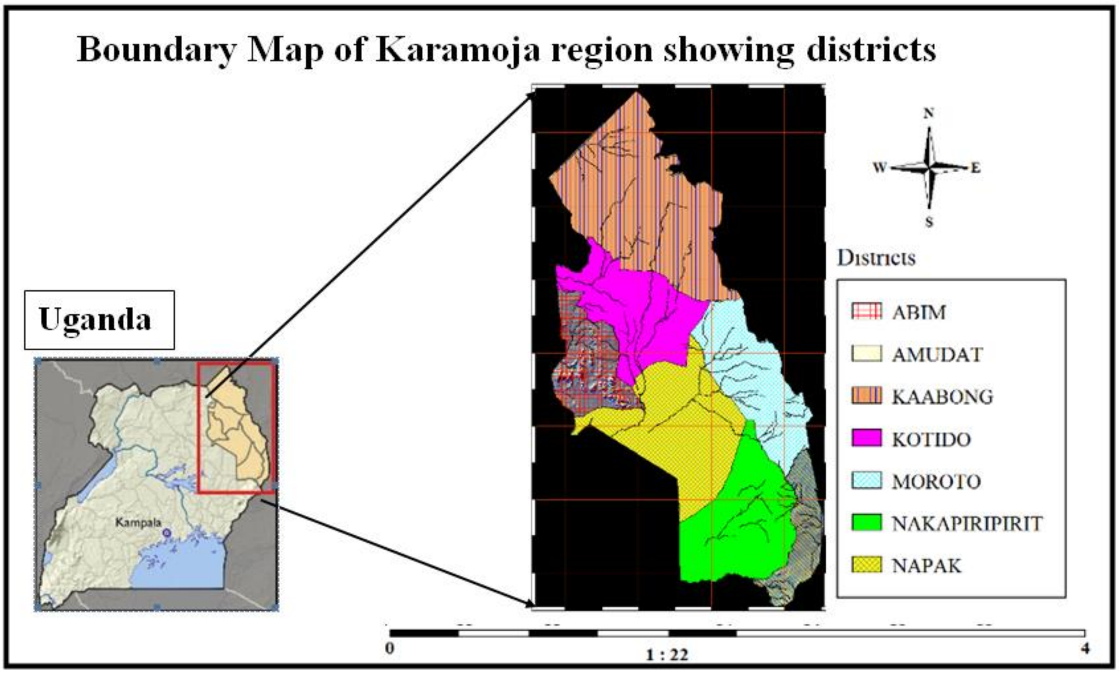


Figure 4.1: Boundary map of Karamoja Region, Uganda

4.2.2 Slope Map

Before calculating the Slope Map, the Digital Elevation Model (DEM) of the study area was extracted as shown in the Figure 4.2.

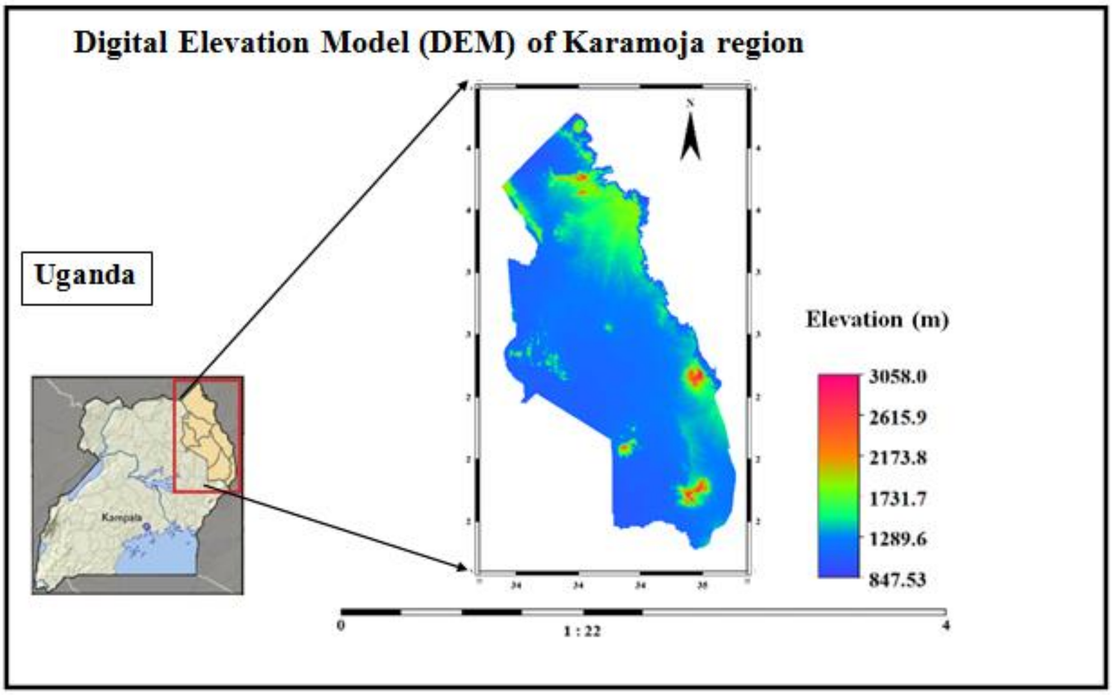


Figure 4.2: Digital Elevation Model (DEM) for Karamoja, Uganda

Most areas within Karamoja region range between 800-1100m above sea level (A.S.L) as clearly shown by this extracted DEM. The few areas with elevation of above 2200m A.S.L include the terrains around Mt.Moroto in Moroto District, Mt.Kadam in Napak District, among others.

After extracting the DEM, the procedure as discussed in section 3.2.2 guided in the computation of the slope map, shown in Figure 4.3.

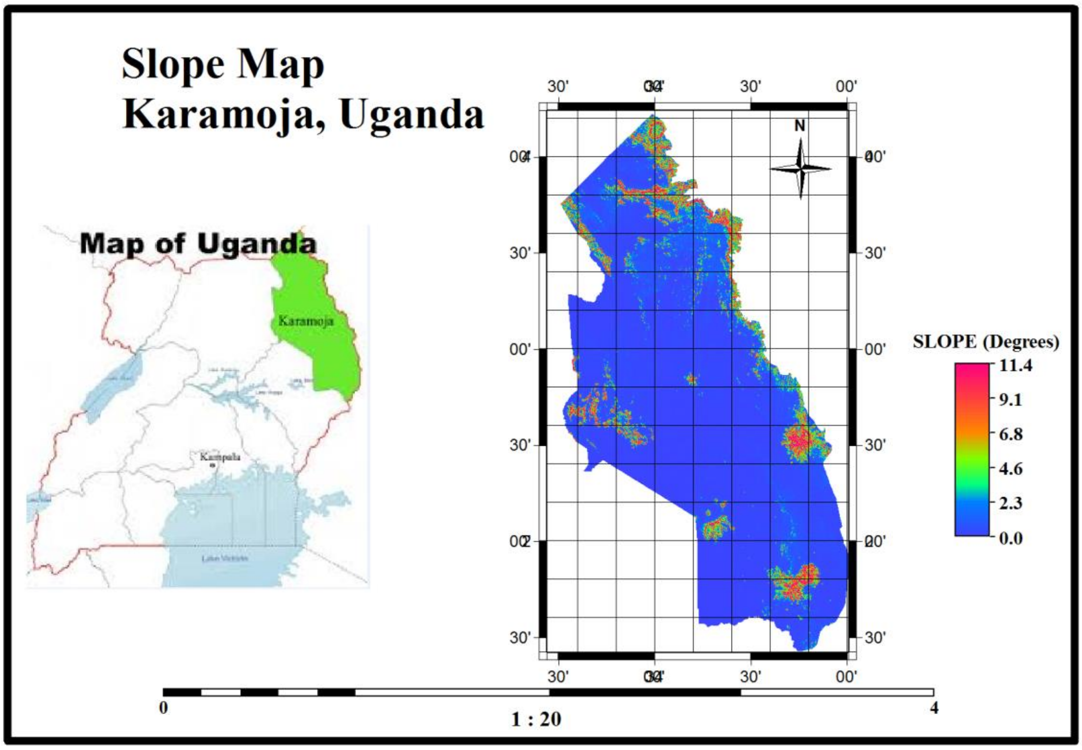


Figure 4.3: Slope map for Karamoja, Uganda

The slope map summarises the slope in degrees of each pixel within the study area and this forms a basis for the viability of irrigation and also serves as factor input in the SMCE process. It was observed that majority of the areas in Karamoja are relatively flat as indicated by their low slope which favors most types of irrigation.

4.2.3 Soil Maps

Figures 4.4 and 4.5 show unclassified and classified *soil clay content* and *pH* maps which summarise information recorded data for each pixel within the study area. The maps are classified as a procedure in the SMCE process to achieve the standardization objective. The reclassification was done in ILWIS guided by the crops' growth requirements (section 2.3) and the two parameter maps served as factor inputs in the SMCE process (*refer to Figure 4.5*).

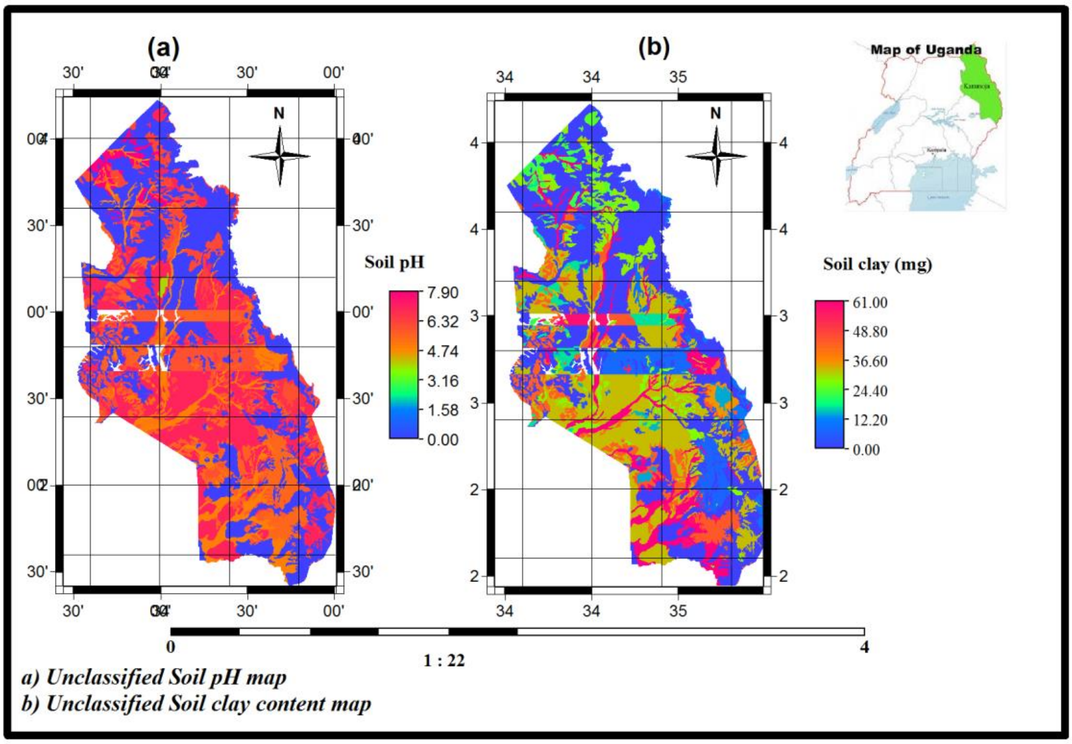


Figure 4.4: Unclassified soil pH and clay maps of Karamoja, Uganda

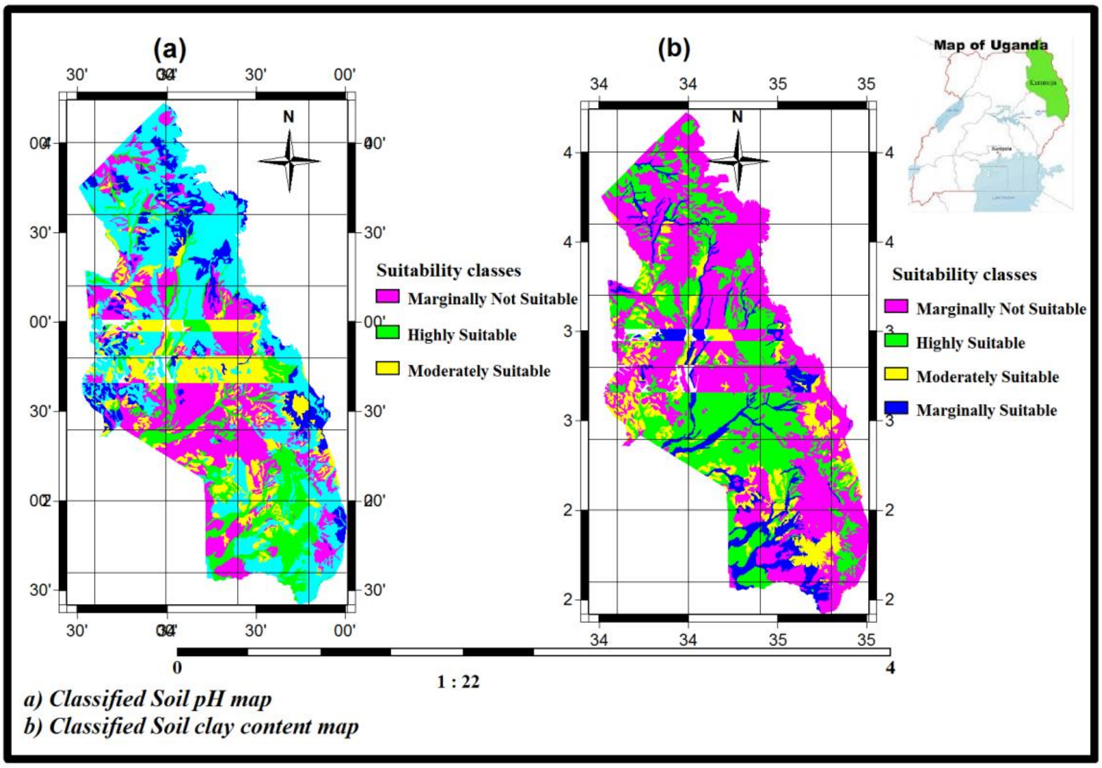


Figure 4.5: Classified soil pH and clay maps of Karamoja, Uganda

4.2.4 Protected Areas Map

This map shown in Figure 4.6 was developed using the *Cross* operation in ILWIS as explained in section 2.5.2. This map was very significant in delineating the Permanently- Not-Suitable areas for Irrigation i.e. areas gazetted for National parks and Central Forest Reserve.

Protected areas even when favorable for Agriculture were marked out and not considered arable in order to reserve them for their mentioned purpose.

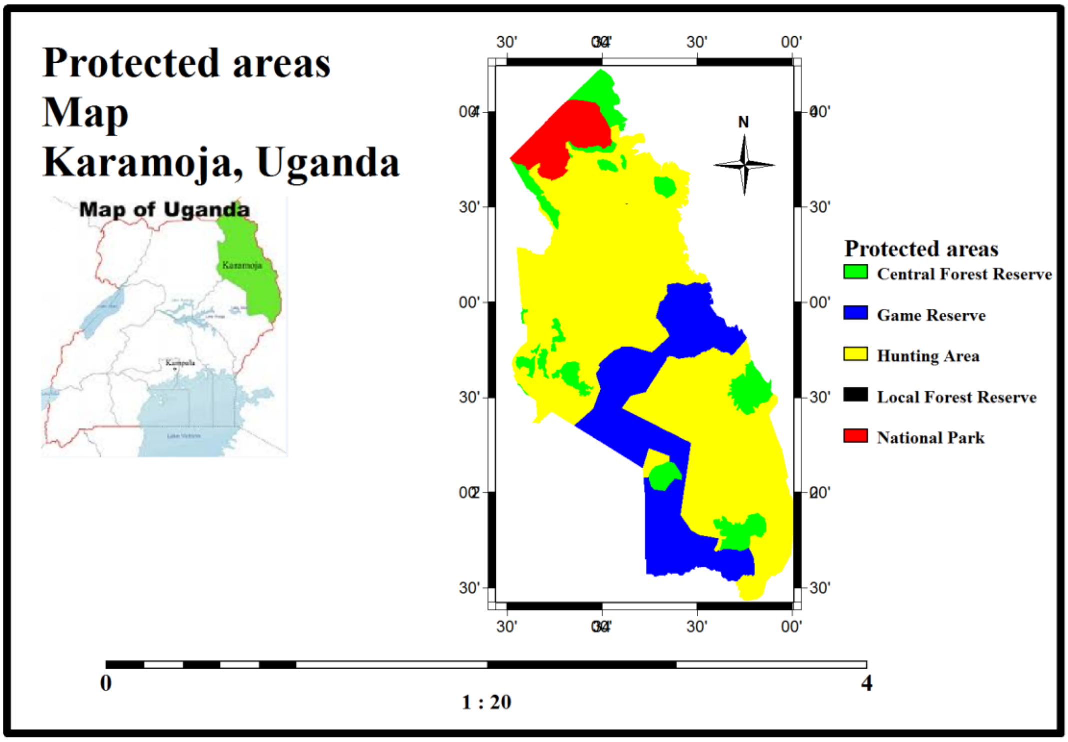


Figure 4.6: Protected areas Map of Karamoja, Uganda

4.2.5 Land Suitability Maps

Following the procedure of the AHP in section 3.3, Standardized values were computed as shown in Table 4.1, weights computed as shown in Table 4.2, and finally Land suitability maps developed for both Maize and Sorghum as shown in Figures 4.7 and 4.8.

Standardized factors

Table 4.1: Computed standardized factors in the SMCE Process

Crop	Sorghum				Maize				Maize & Sorghum	
Suitability Class	Soil Clay		Soil PH		Soil Clay		Soil PH		Slope	
	Range (mg/pixel area)	Utility	Range	Utility	Range (mg/pixel area)	Utility	Range	Utility	Range (Degrees)	Utility
Highly Suitable (HS)	81 and above	1	<5.5	0.2	<= 35	1	< 5.0	0.2	<= 10	1
Moderately Suitable (MS1)	56-80	0.8	5.5-6	0.8	36-55	0.8	5-6	0.8	10-15	0.8
Marginally Suitable (MS2)	36-55	0.6	6.1-7	1	56-80	0.6	6.0-7	1	15-20	0.6
Marginally NOT Suitable	<= 35	0.2	>7	0.2	81 and above	0.2	>7	0.2	>20	0.2

These standardized values were very relevant to simplify subsequent analysis within ILWIS.

Calculated Saaty weights

Using the pair wise comparison in ILWIS, the weights in Table 4.2 were calculated as explained in section 3.3.3.

Table 4.2: Calculated weights in ILWIS

Calculated Saaty Weights		Factor(s)		
		Soil Clay	Soil pH	Slope
		Calculated Weight on a scale of 0 - 1		
Crops	Sorghum	0.75	0.20	0.05
	Maize	0.66	0.29	0.05

Soil clay carried a higher weight in land suitability analysis for Sorghum as compared to that in maize owing to the relevance of clay content in effective Sorghum production (*refer to section 2.3*).

Soil pH carried a higher weight in Land Suitability analysis for Maize as compared to that in Sorghum owing to the limited PH range to enhance effective Maize production (*refer to section 2.3*). This limited PH range made a critical factor in the analysis.

Land Suitability Maps for Sorghum and Maize

After partial valuation and identification of the relative importance of each criterion, a composite index map for each of the crops was computed as shown in Figures 4.7 and 4.8. These figures respectively show in Map (a), the unclassified land suitability map direct from ILWIS and in Map (b), the reclassified map using the slice operation (*refer to section 2.5.3*) into four classes according to FAO (1985) guidelines. These classes include the Highly Suitable class, moderately suitable class, Marginally Suitable class, and the Permanently Not Suitable class as shown in figures 4.7 (b) and 4.8 (b) respectively.

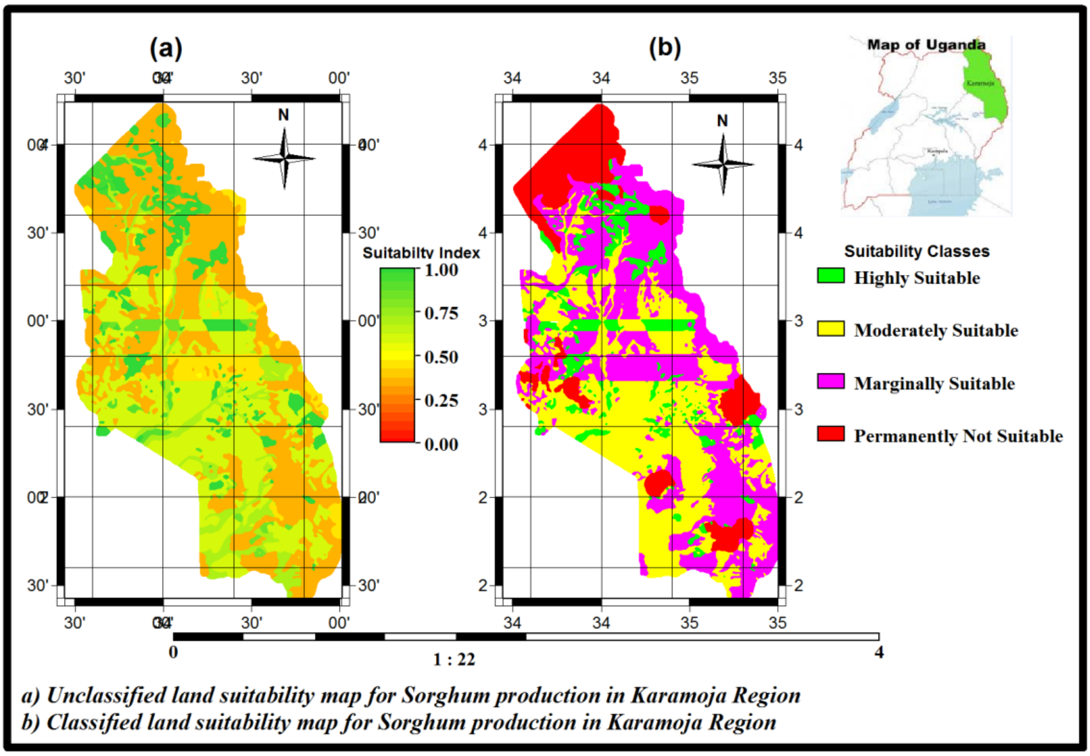


Figure 4.7: Land suitability maps for Sorghum production in Karamoja Region, Uganda

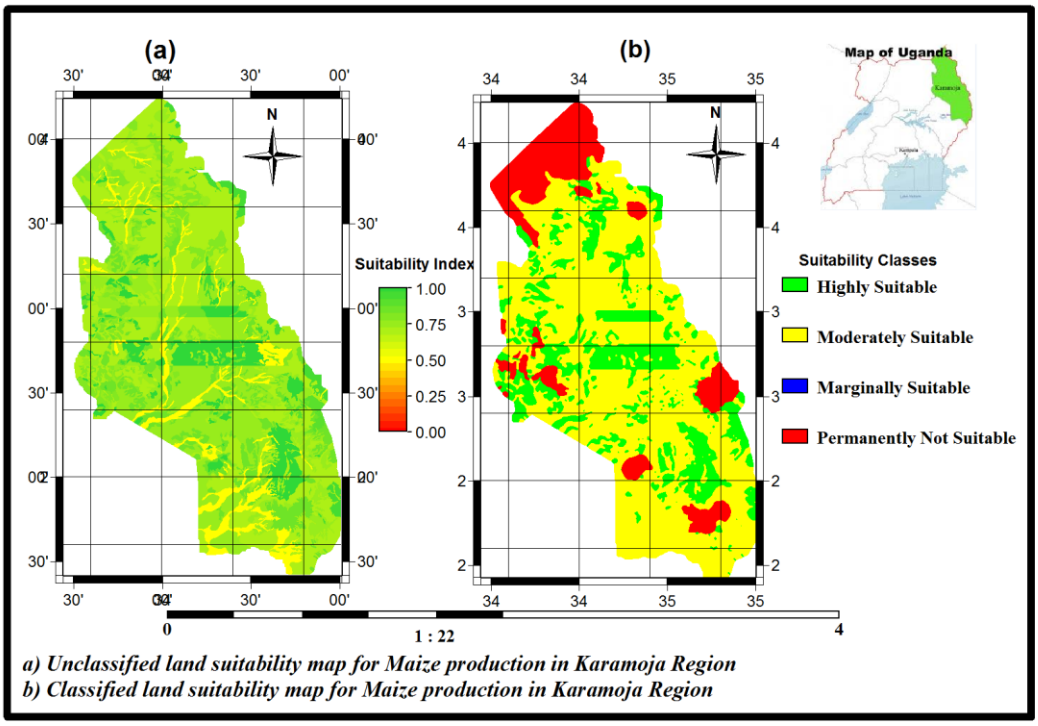


Figure 4.8 Land suitability maps for Maize production in Karamoja Region, Uganda

Table 4.2 summarizes the respective acreage per class for the Maize and Sorghum as derived from Figures 4.7 and 4.8. This table provides information regarding the specific areas that are best suited for Maize and Sorghum Production in varying suitability indices.

Table 4.3: Respective acreage resulting from land suitability analysis for Maize and Sorghum

Crop	Maize		Sorghum	
CLASS	**Area (Ha)**	**% of Total area analyzed**	**Area (Ha)**	**% of Total area analyzed**
Highly Suitable	612,631	22.4	256,848	9.4
Moderately Suitable	1,745,867	63.6	1,062,108	38.8
Marginally Suitable	0	0	1,039,541	37.8
Permanently NOT Suitable	382,314	14	382,314	14
TOTAL	**2,704,811**	**100.0**	**2,740,811**	**100.0**

From Table 4.2, it is observed that the study area has relatively more areas suitable for Maize production with up to 85.3% at least moderately suitable as compared to 45.4% areas suitable for Sorghum production. This is attributed to Maize's tolerance to minimal clay content prevalent in Karamoja region, a factor that affects effective Sorghum production (*refer to section 2.3*)

4.3 Irrigation Suitability Analysis Based on Net Irrigation Requirement

Irrigation suitability analysis guided reclassifying the different areas within the study area based on their land suitability class for the respective crop and the calculated relative NIR for each crop across all seasons and across all scenarios. This procedure led to computation of eighteen (18) maps showing varying irrigation suitability index for Maize and Sorghum across the three (3) seasons and across the three (3) scenarios are illustrated in Figures 4.17- 4.22. As stated in section 3.4.1, computations of these maps required a requisite calculation of seasonal average decadal rainfall maps, seasonal average decadal effective rainfall maps, average decadal crop water requirement and average decadal NIR as presented below.

4.3.1 Developed geospatial datasets for irrigation suitability analysis

This section presents step by step results that contributed to subsequent analysis for areas of specific areas best suited for supplemental irrigation.

Seasonal total rainfall maps

These seasonal rainfall estimates per pixel were calculated by averaging the decade rainfall estimates for each of the designed seasons as explained in Section 3.4.1 and are illustrated in Figure 4.9.

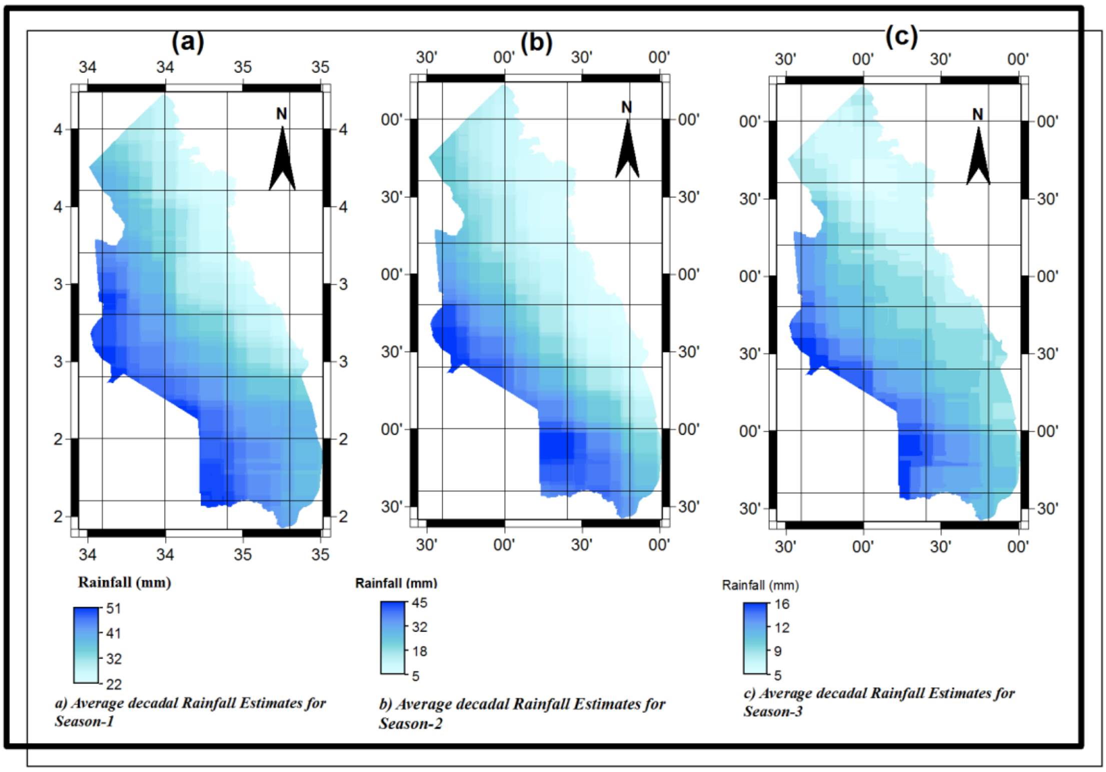
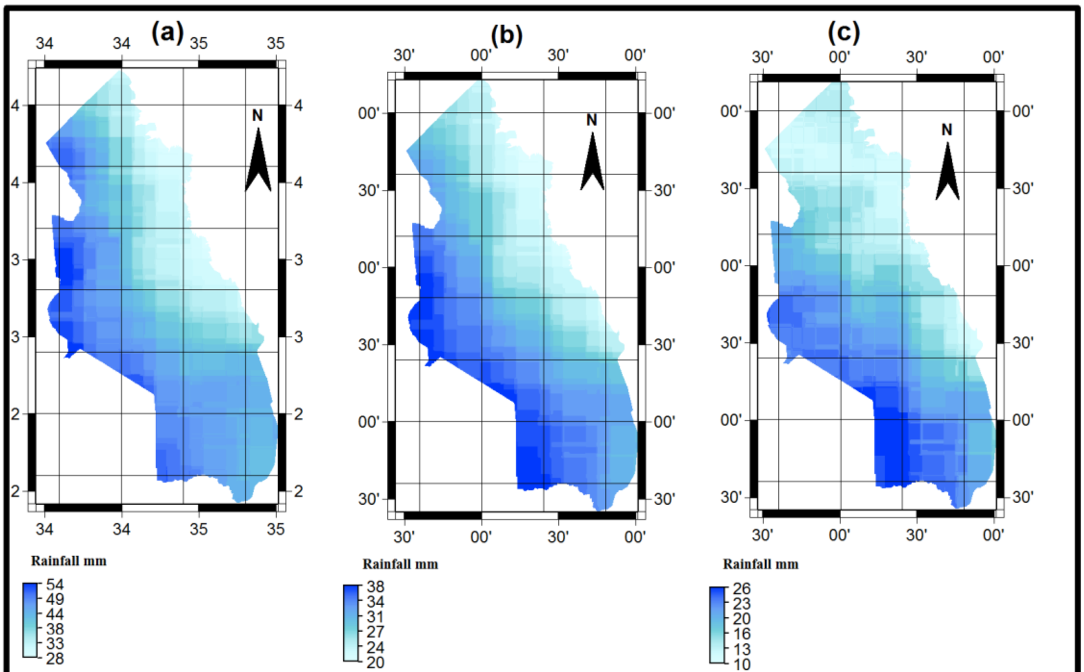


Figure 4.9: Maps showing Average decadal rainfall received per season in Karamoja, Uganda

It is clearly seen here that the region receives more rainfall in Season-1 of up to 51mm per decade in some areas of Abim and Napak districts as compared to minimum 5mm in some areas of Kaabong district in Season-3.The difference in the two seasons is observed to be as large as 46mm per decade and this is bound to have significant impact on the suitability of irrigation within the individual seasons.

Seasonal Effective Rainfall Maps

The seasonal effective maps were calculated to model the wet year scenario (20% probability of exceedance), a normal year scenario (50% probability of exceedance) and dry year scenario (80% probability of exceedance) as shown in Figures 4.10 – 4.12.



a) Effective Rainfall Estimates for Season 1 at 20% Probability of exceedance
b) Effective Rainfall Estimates for Season 1 at 50% Probability of exceedance
c) Effective Rainfall Estimates for Season 1 at 80% Probability of exceedance

Figure 4.10: Effective Rainfall Maps for Season-1 for Karamoja, Uganda

It is observed from Figure 4.10 that the region has relatively low variation in effective rainfall among the three scenarios, a situation which may cause similar indices of irrigation suitability. This small difference of rainfall amounts across these scenarios was attributed to the fact that it is this time of the year that Karamoja receives the most amount of rainfall hence a small variation across the scenarios.

In Figure 4.11, a larger variation across the scenarios is now evident with about 25 mm per decade rainfall margins observed between the wet and dry year scenarios.

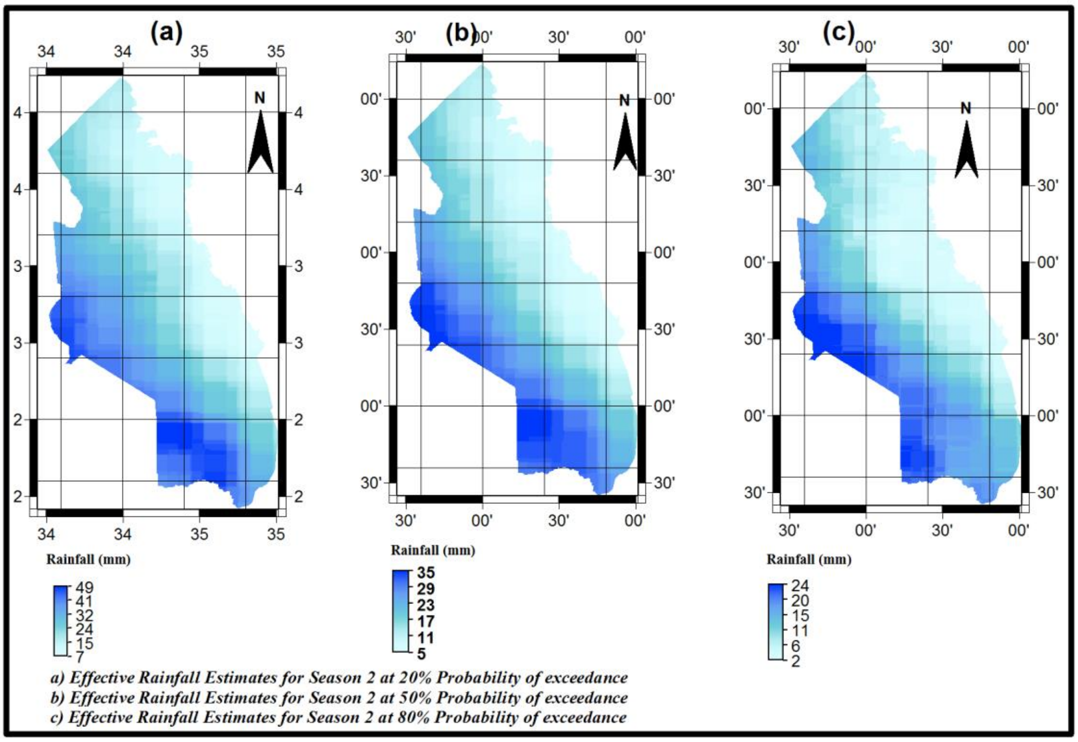


Figure 4.11: Effective Rainfall Maps for Season-2 for Karamoja, Uganda

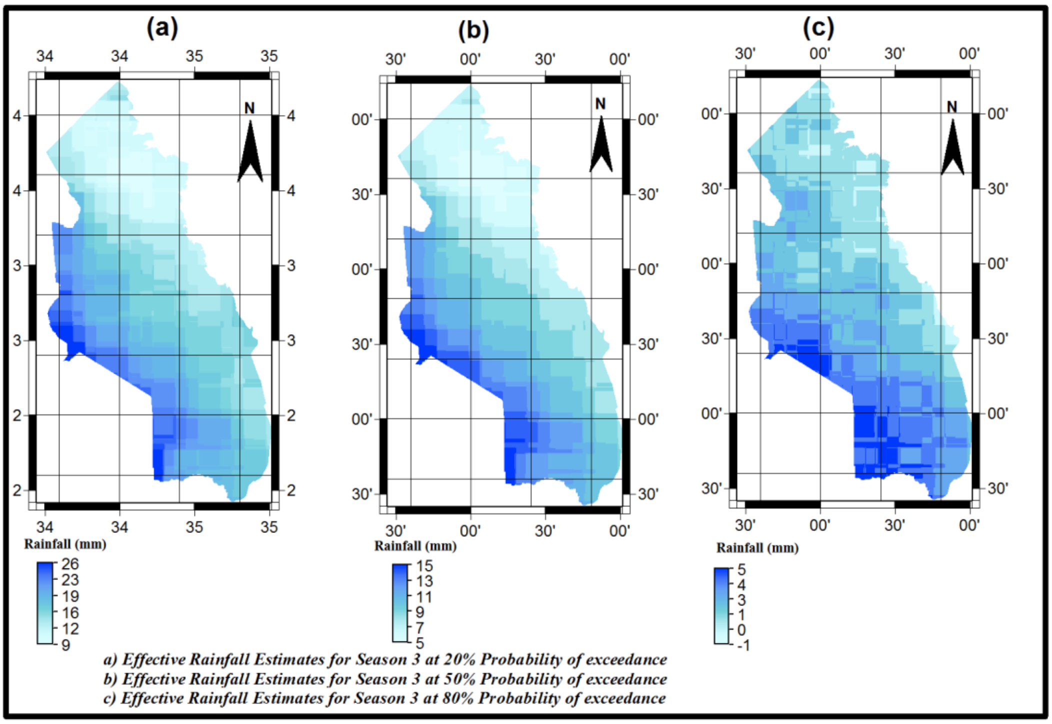


Figure 4.12: Effective rainfall maps for Season-3 for Karamoja, Uganda

It was observed in figure 4.12 that Karamoja region receives the least amount of rainfall in Season-3 and this was expected owing to the fact that it is this time in the year that Karamoja is driest. This season will therefore require more water for irrigation if sustainable crop production is to be sustained.

Seasonal Net Irrigation water requirement Maps

The Seasonal NIR was finally obtained as the deficit between the respective average decadal crop water requirement (Et_c) per season as shown in Table 3.3 and the seasonal effective rainfall estimates presented above. These maps, shown in Figures 4.13 - 4.18, summarise the varying NIR for both Maize and Sorghum across all seasons across all scenarios.

It was generally observed that NIR of Maize for all seasons across all scenarios is greater than the respective NIR for Sorghum. This is attributed to higher crop water requirement for Maize as compared to that of Sorghum. It is also important to note that the higher the NIR within a particular season / scenario, the more the amount of irrigation water required in that particular season/scenario and the less suitable it is for supplemental irrigation.

Figures 4.13 – 4.18 were very pivotal in the subsequent analysis in which they were "*crossed*" with the respective classified land suitability maps (Figures 4.7 – 4.8) inorder to generate irrigation suitability maps as shown in Figures 4.19 – 4.24.

Table 4.4: Decadal Crop Water Requirement per season for Maize and Sorghum

	MAIZE			**SORGHUM**		
	Decadal Crop Water Requirement (Et_c) in mm					
	Season-1	**Season-2**	**Season-3**	**Season-1**	**Season-2**	**Season-3**
Decade 1	15.5	13.3	14	15.5	13.3	14
Decade 2	18.1	16.8	16.6	17.1	15.9	15.7
Decade 3	37.8	35.5	34.4	31.1	29.3	28.3
Decade 4	56.5	53.1	51.4	46.8	44	42.5
Decade 5	50	57	54	52	52	50
Decade 6	56	58	55	51	53	51
Decade 7	56	58	55	51	53	51
Decade 8	47	49	49	43	45	45
Decade 9	33	35	37	30	32	34
Average Decadal Et_c	**41.1**	**41.7**	**40.9**	**37.5**	**37.5**	**36.8**

These decadal values were obtained as totals of 10-day daily crop water requirement as calculated in APPENDIX III and IV.

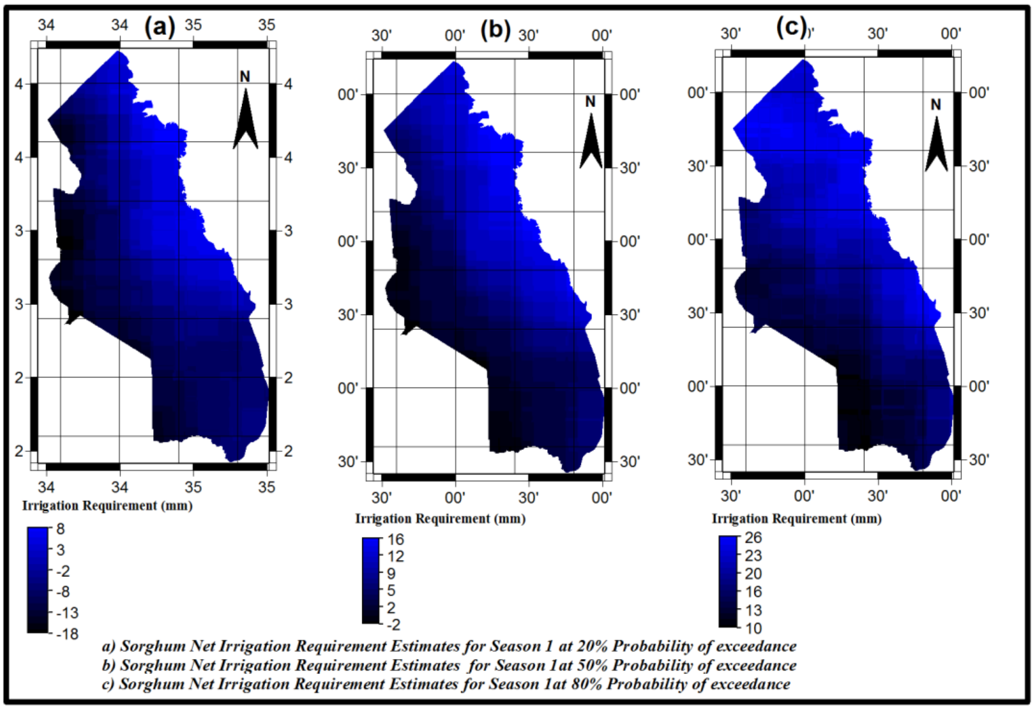


Figure 4.13: Net Irrigation Requirement for Sorghum in Season-1 for Karamoja, Uganda

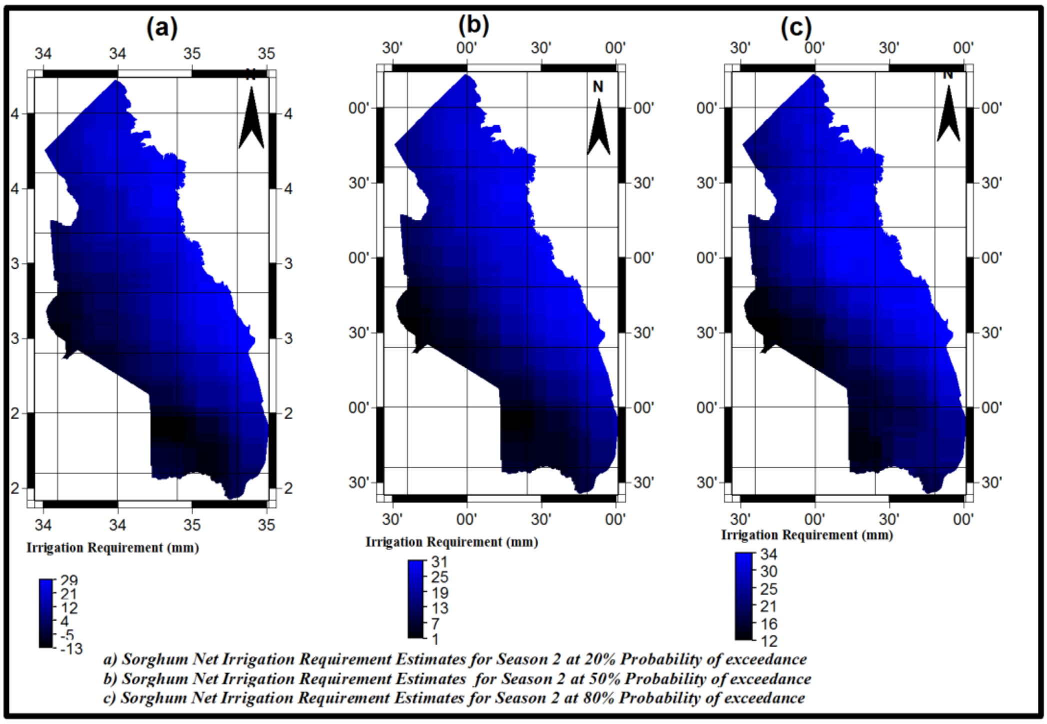


Figure 4.14: Net Irrigation Requirement for Sorghum in Season-2 for Karamoja, Uganda

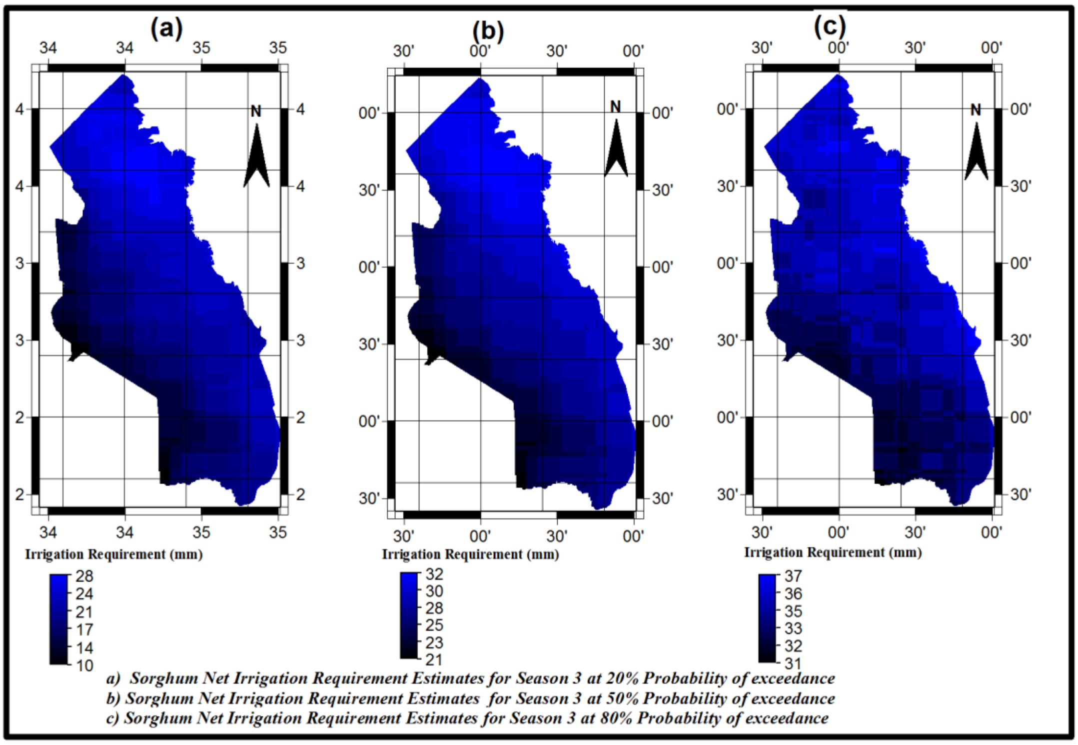


Figure 4.15: Net Irrigation Requirement for Sorghum in Season-3 for Karamoja, Uganda

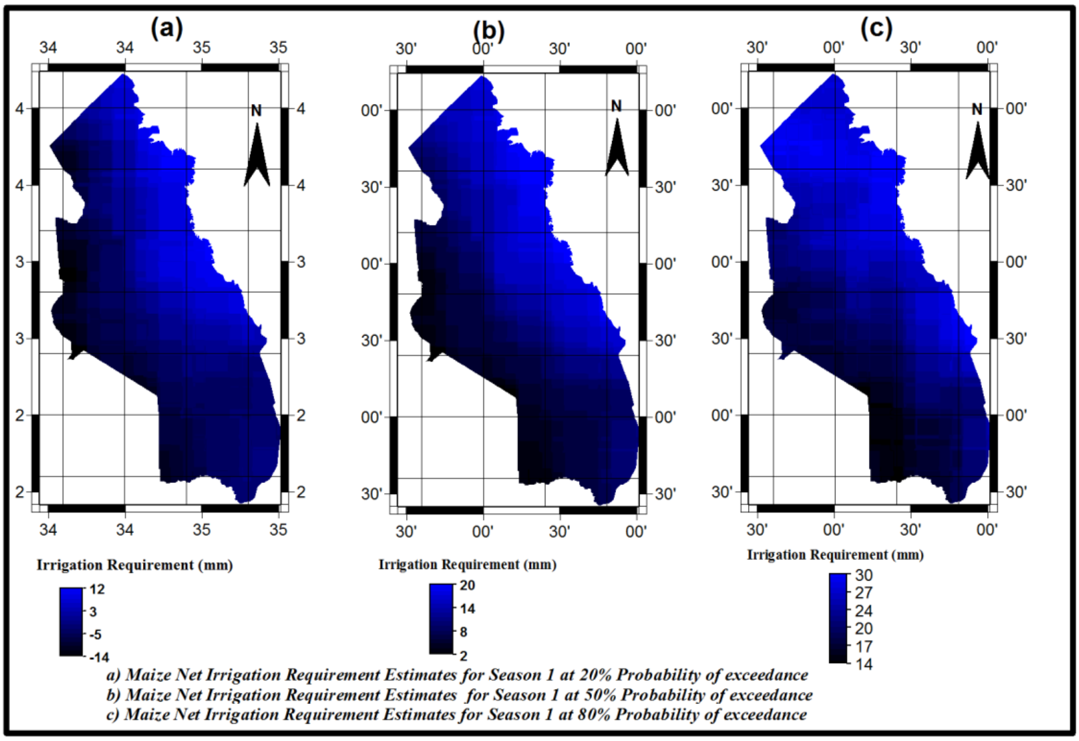


Figure 4.16: Net Irrigation Requirement for Maize in Season-1 for Karamoja, Uganda

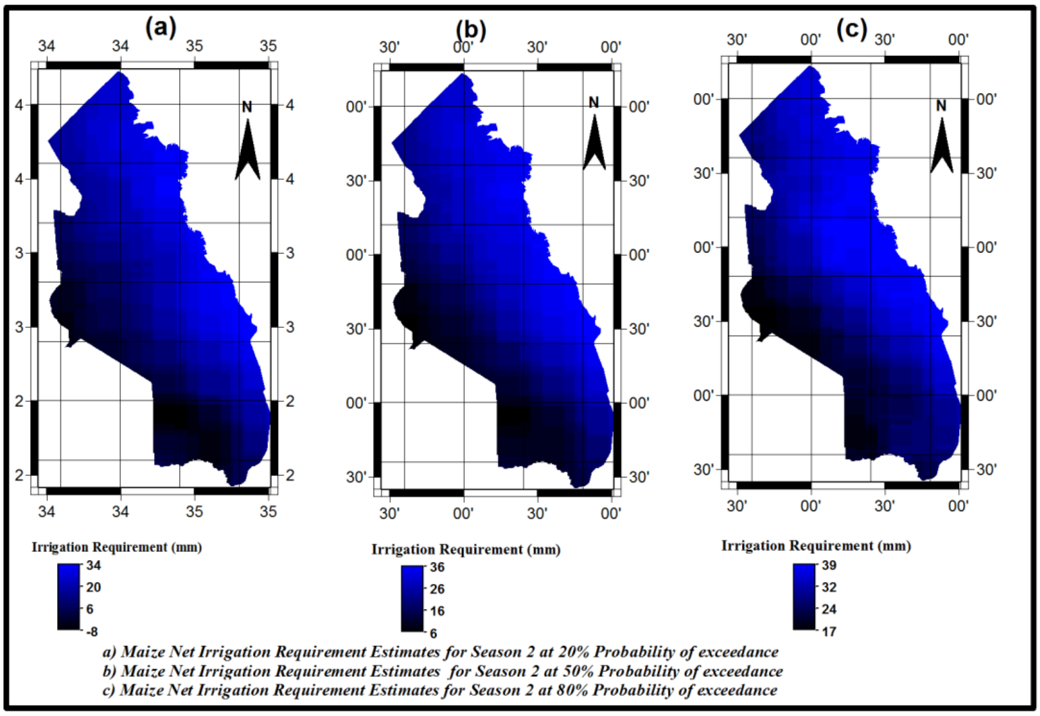


Figure 4.17: Net Irrigation Requirement for Maize in season 2 for Karamoja, Uganda

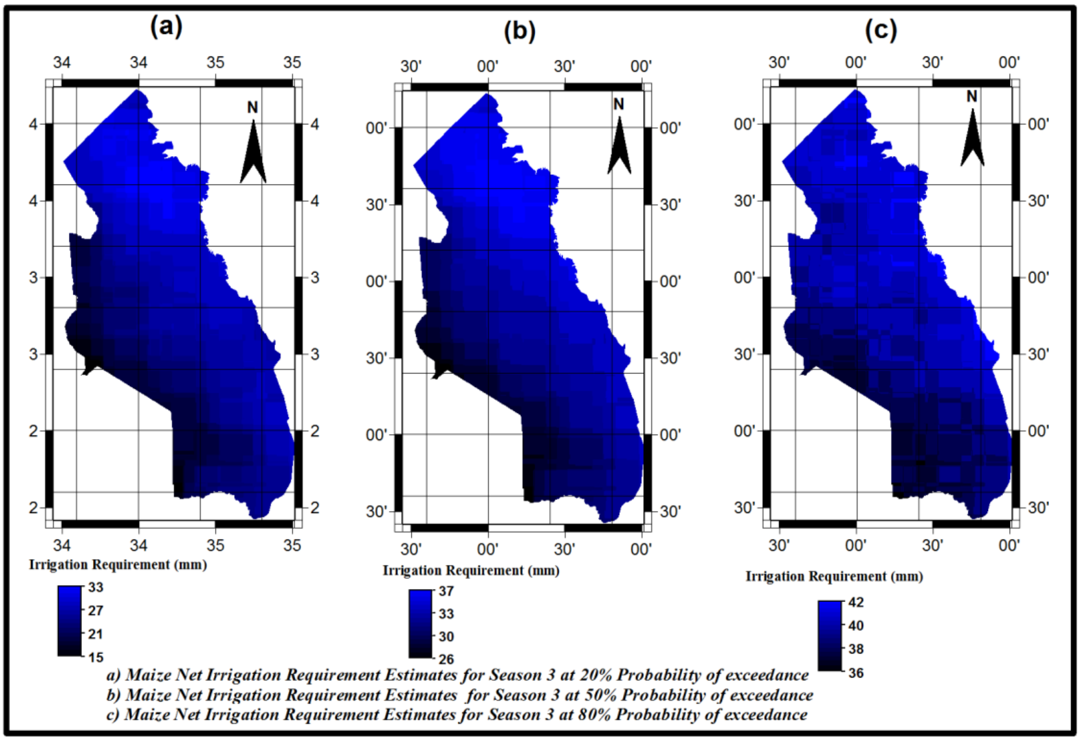


Figure 4.18: Net Irrigation Requirement for Maize in Season-3 for Karamoja, Uganda

Table 4.5: NIR Statistics across all scenarios for the three seasons

Season-1 *(All values in mm)*						
Scenarios of varying probability of exceedance	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Minimum NIR	-16	-20	1	-3	13	9
Maximum NIR	14	10	22	18	32	28
Average NIR	-1	-5	12	8	23	19
Season-2 *(All values in mm)*						
Scenarios of varying probability of exceedance	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Minimum NIR	-10	-15	6	1	16	11
Maximum NIR	36	31	38	33	40	35
Average NIR	13	8	22	17	28	23
Season-3 *(All values in mm)*						
Scenarios of varying probability of exceedance	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Minimum NIR	13	8	25	20	35	30
Maximum NIR	33	28	37	32	43	38
Average NIR	23	18	31	26	39	34

It was observed in Table 4.5 that NIR values vary in each of the seasons and scenarios. These varying statistics had a significant contribution and impact in the subsequent generation of irrigation suitability maps. Another important observation is the presence of negative NIR in some of the scenarios. This is as a result of excess rainfall as compared to the amount of water required by the crops in that particular period of time.

The recommendation could be devise means of harvesting this excess rainfall, or increase the plant populations in these particular seasons, or plant a relay crop to utilize this excess, or adopt a means of conservation tillage among other options.

4.3.2 Irrigation suitability Maps

Following the procedure as discussed in section 3.2.2, irrigation suitability maps as shown in Figures 4.19 – 4.24 were derived for each crop across all seasons and scenarios using *logical-IFF condition* statements coded according to the NIR ranges as shown in Section 3.4.2. The results from these analysis were then extracted and tabulated to guide cropping and irrigation alternatives (Section 4.4) as a means of enhancing effective land utilization within the region.

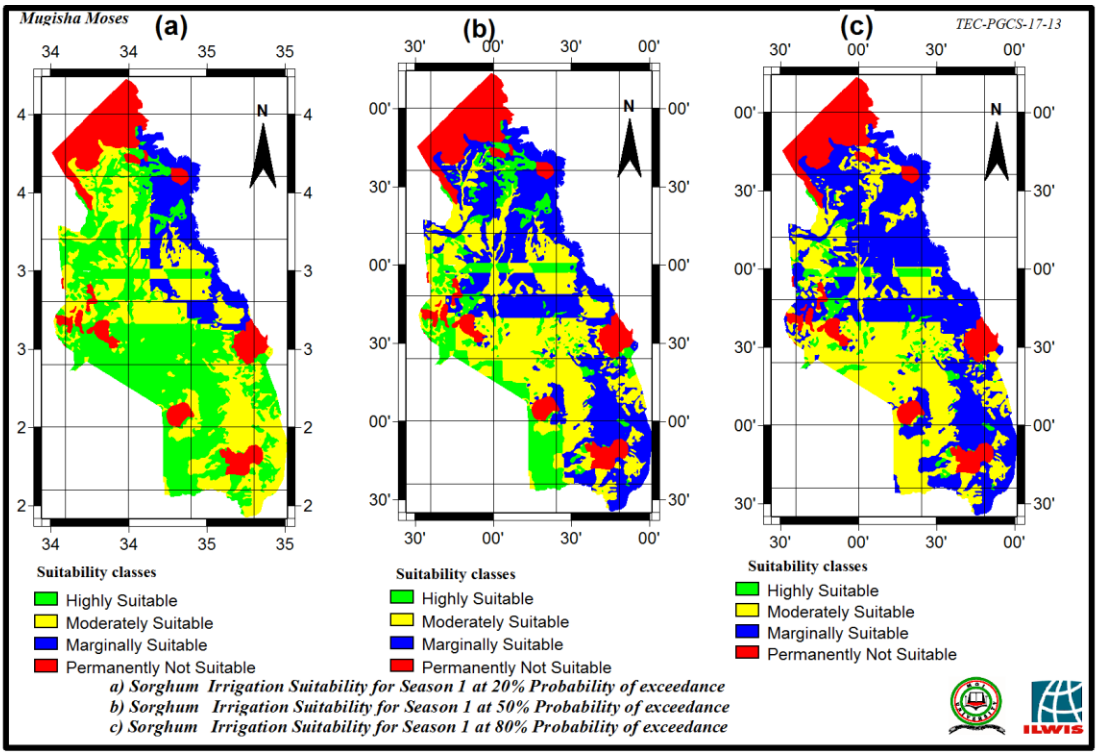


Figure 4.19: Irrigation suitability maps for Sorghum in Season-1 for Karamoja, Uganda

It was observed in figure 4.19 that in this particular season for Sorghum crop those significant areas are highly suitable for supplemental irrigation especially considering a wet year scenario. This is greatly attributed to the effect of 30 mm per decade average effective rainfall on for Sorghum Production in this season.

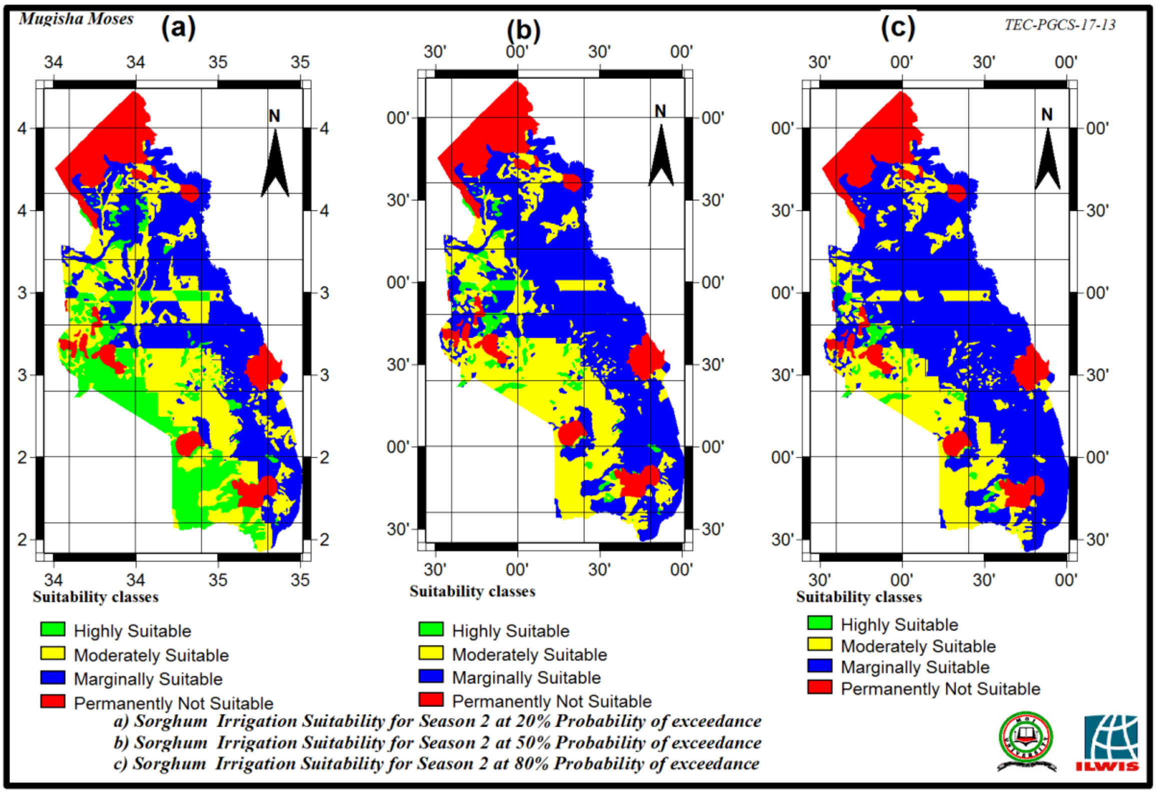


Figure 4.20: Irrigation Suitability Maps for Sorghum in Season-2 for Karamoja, Uganda

In Figure 4.20, it was observed that in this particular season that there lies a slight difference in the suitability indices of the normal and dry year scenario. This is due to the slight difference in the estimated rainfall amounts in each of these scenarios.

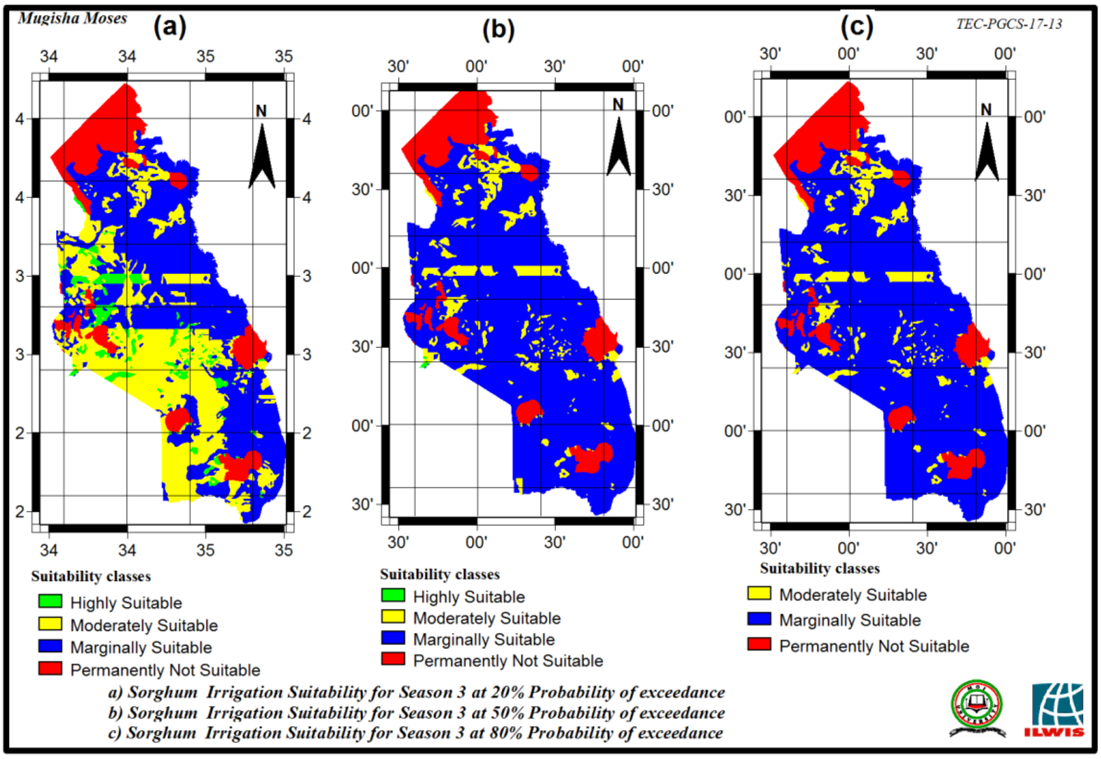


Figure 4.21: Irrigation suitability maps for Sorghum in Season-3 for Karamoja, Uganda

As seen in Figure 4.21 in the dry year scenario, none of areas is highly suitable for supplemental irrigation with up to 74% of the areas only marginally suitable. This is strongly attributed to the relatively low rainfall received within this time of the year (November to February).

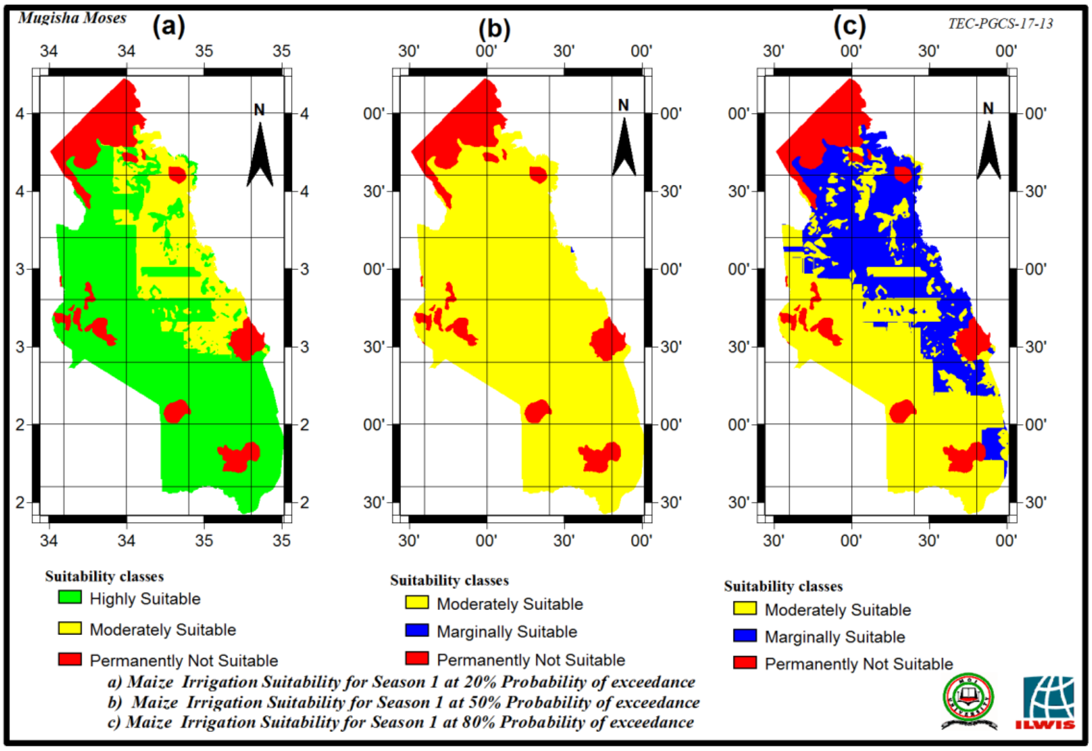


Figure 4.22: Irrigation suitability maps in Maize Season-1 for Karamoja, Uganda

It was observed in Figure 4.22 that in this particular season for Maize that only the wet year scenario has highly suitable areas for supplemental Irrigation. This is due to the relatively higher rainfall estimates modeled within this scenario.

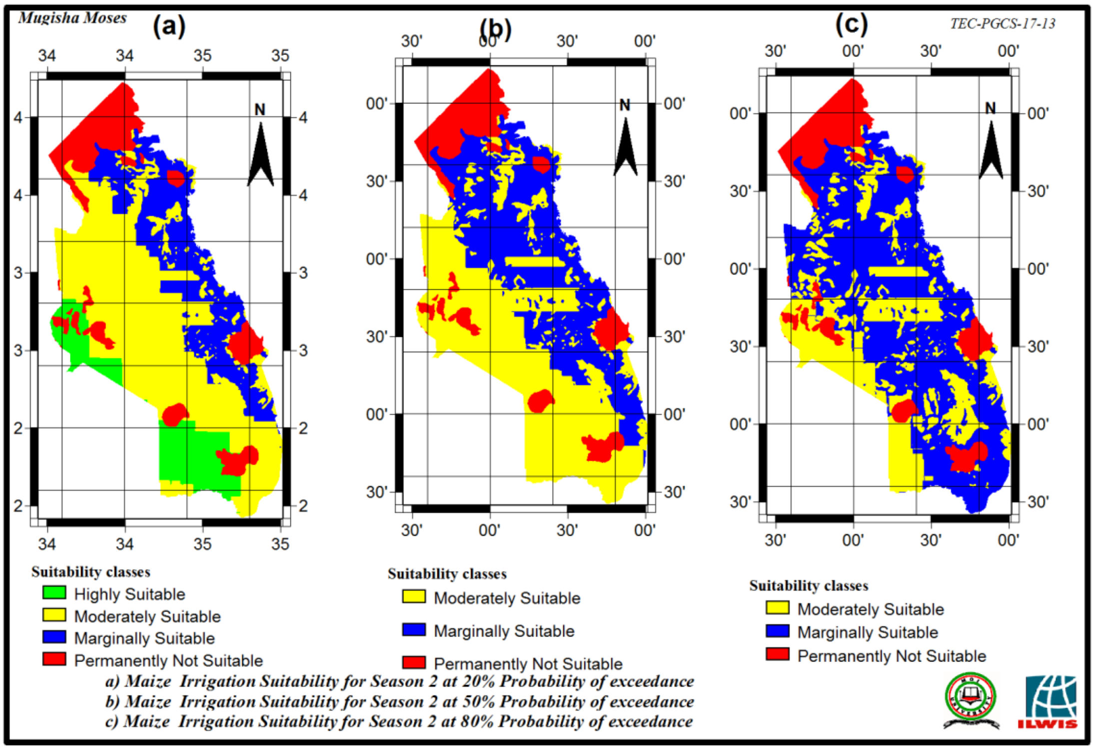


Figure 4.23: Irrigation suitability maps for Maize in Season-2 for Karamoja, Uganda

In Figure 4.23, it is still observed that the region has only highly suitable areas in the 20% probability of exceedance scenario. However there is a significant drop as compared to those in the same scenario in Season-1. This is majorly attributed to relatively higher NIR in this particular season in comparison with that of Season-1.

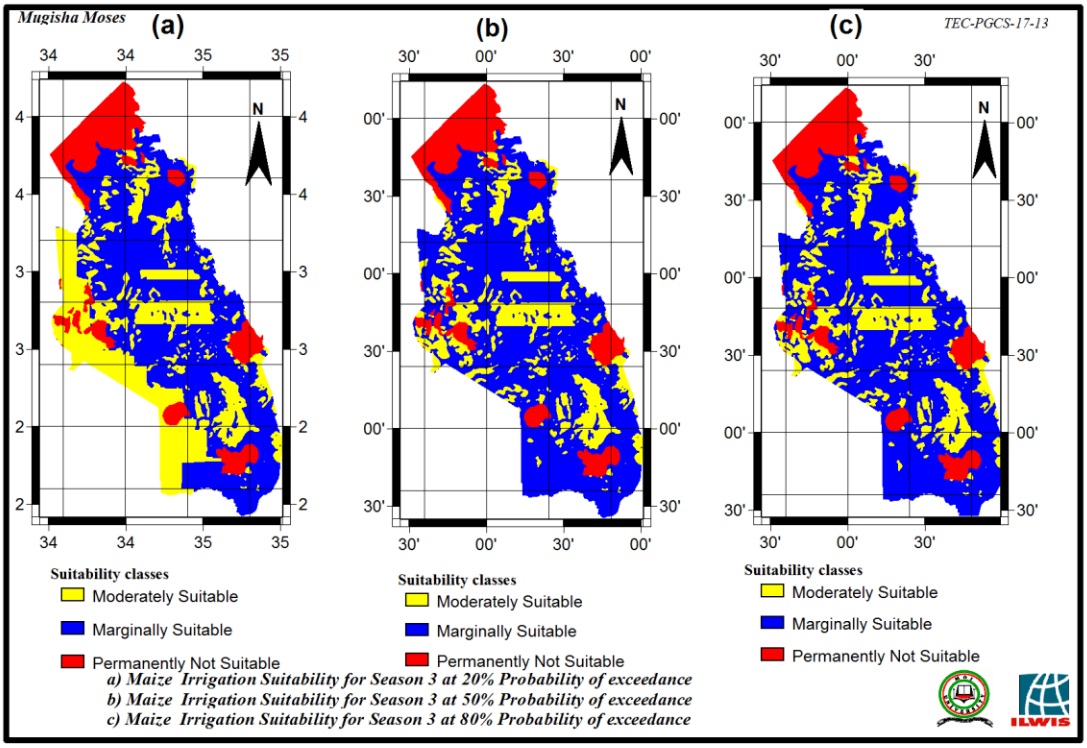


Figure 4.24: Irrigation Suitability Maps for Maize in Season-3 for Karamoja, Uganda

It was observed in Figure 4.24 that in this particular season for Maize, none of the areas is highly suitable for supplemental irrigation with most areas in all scenarios marginally suitable. This is attributed to the fact that Karamoja region receives the least amount of rainfall in this time of the year Season-3 thereby calling for more water for irrigation if sustainable crop production is to be sustained.

4.4 Cropping and Irrigation Alternatives for Effective Land Utilization

The approach adopted used was to summarise information regarding the most appropriate times each crop (Maize and Sorghum) would be grown under the specific suitability class for each of the individual seasons. This was started by manually extracting data showing areas measured in pixels for each class from the eighteen maps computed as shown in Tables 15-17. This pixel information was then converted to the equivalent areas in hectares (Tables 18-20) and then finally respective percentages of total area per suitability class for each crop in each season and scenarios were inferred as shown in Tables 21-23.

4.4.1 Respective pixels per class across all scenarios for the three seasons

Tables 4.6 – 4.8 summarise information regarding the number of pixels that were contained in each of the classes of the eighteen maps computed in section 4.3.2. This was achieved by manually extracting this information from the individual histograms generated for each suitability map in ILWIS.

Table 4.6: Respective pixels per class across all scenarios for Season-1

Seasons	**Season-1 *(All values in pixel units)***					
Scenarios	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Highly Suitable	2,170,567	1,419,415	0	583,972	0	240,260
Moderately Suitable	741,158	1,060,722	2,911,725	1,135,139	1,771,260	1,209,001
Marginally Suitable	0	431,588	0	1,192,614	1,140,465	1,462,464
Permanently NOT Suitable	471,992	471,992	471,992	471,992	471,992	471,992
TOTAL	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717

Table 4.7: Respective pixels per class across all scenarios for Season-2

Seasons	**Season-2 *(All values in pixel units)***					
Scenarios	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Highly Suitable	439,192	655,584	0	201,035	0	131,520
Moderately Suitable	1,700,286	1,012,308	1,669,488	1,087,466	1,064,689	862,851
Marginally Suitable	772,247	1,243,833	1,242,237	1,623,224	1,847,036	1,917,354
Permanently NOT Suitable	471,992	471,992	471,992	471,992	471,992	471,992
TOTAL	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717

Table 4.8: Respective pixels per class across all scenarios for Season-3

Seasons	Season-3 *(All values in pixel units)*					
Scenarios	20%		50%		80%	
Crop Choice	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
Highly Suitable	0	215,315	0	60,496	0	0
Moderately Suitable	1,151,206	1,148,831	792,539	375,803	792,539	395,273
Marginally Suitable	1,760,519	1,547,579	2,119,186	2,475,426	2,119,186	2,516,452
Permanently NOT Suitable	471,992	471,992	471,992	471,992	471,992	471,992
TOTAL	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717	3,383,717

4.4.2 Respective hectares per class across all scenarios for the different seasons

The respective numbers of pixels tabulated above were converted to the equivalent areas in hectares by multiplying them by the square of the individual pixel size with the results presented in Tables 4.9 – 4.11. For this set of datasets, the individual pixel size was 90m equivalent to a total pixel area of 8100m^2.

Table 4.9: Respective hectares per class across all scenarios for Season-1

Seasons	Season-1 *(All values in hectares)*					
Scenarios	20%		50%		80%	
Crop Choice	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
Highly Suitable	1,758,159	1,149,726	0	473,017	0	194,611
Moderately Suitable	600,338	859,185	2,358,497	919,463	1,434,721	979,291
Marginally Suitable	0	349,586	0	966,017	923,777	1,184,596
Permanently NOT Suitable	382,314	382,314	382,314	382,314	382,314	382,314
TOTAL	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811

From Table 4.9, it was observed that for Season-1 significant areas were moderately suitable for irrigation for both crops (Maize and Sorghum) under all scenarios. This is majorly attributed to the relatively higher effective rainfalls in the region around this time of the year.

Table 4.10: Respective hectares per class across all scenarios for Season-2

Seasons	Season-2 *(All values in hectares)*					
Scenarios	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Highly Suitable	355,745	531,023	0	162,838	0	106,531
Moderately Suitable	1,377,232	819,969	1,352,285	880,847	862,398	698,909
Marginally Suitable	625,520	1,007,505	1,006,212	1,314,811	1,496,099	1,553,057
Permanently NOT Suitable	382,314	382,314	382,314	382,314	382,314	382,314
TOTAL	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811

Unlike the case in Season-1 where majority of the area was highly suitable for Maize production under supplemental irrigation in the wet year scenario, the areas in the same scenario in this season show a 51% decrease something that could be attributed to the relatively high NIR during this season.

Table 4.11: Respective hectares per class across all scenarios for Season-3

Seasons	Season-3 *(All values in hectares)*					
Scenarios	**20%**		**50%**		**80%**	
Crop Choice	**Maize**	**Sorghum**	**Maize**	**Sorghum**	**Maize**	**Sorghum**
Highly Suitable	0	174,405	0	49,002	0	0
Moderately Suitable	932,477	930,553	641,957	304,400	641,957	320,171
Marginally Suitable	1,426,020	1,253,539	1,716,541	2,005,095	1,716,541	2,038,326
Permanently NOT Suitable	382,314	382,314	382,314	382,314	382,314	382,314
TOTAL	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811	2,740,811

The highest NIR was calculated within Season-3 majorly because it is within this season that the region receives the least amounts of rainfall. Owing to this fact, the area requires significantly more irrigation water in order to guarantee effective crop production.

4.4.3 Respective percentages per class across all scenarios

To further view the suitability variations in a more clear way, the converted areas per crop per class across each scenario were now computed as percentages of the total area within the study area as tabulated in Table 4.12 – 4.14. This step gives a clear conclusion on the percentage per cropping/irrigation alternative within the study area.

Table 4.12: Respective percentages for Maize and Sorghum production per class across all scenarios for Season-1

Seasons	Season-1 *(All values represented as Percentages)*					
Scenarios	20%		50%		80%	
Crop Choice	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
Highly Suitable	64	42	0	17	0	7
Moderately Suitable	22	31	86	34	52	36
Marginally Suitable	0	13	0	35	34	43
TOTAL	86	86	86	86	86	86

Table 4.13: Respective percentages for Maize and Sorghum production per class across all scenarios for Season-2

Seasons	Season-2 *(All values represented as Percentages)*					
Scenarios	20%		50%		80%	
Crop Choice	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
Highly Suitable	13	19	0	6	0	4
Moderately Suitable	50	30	49	32	31	26
Marginally Suitable	23	37	37	48	55	57
TOTAL	86	86	86	86	86	86

Table 4.14: Respective percentages for Maize and Sorghum production per class across all scenarios for Season-3

Seasons	Season-3 *(All values represented as Percentages)*					
Scenarios	20%		50%		80%	
Crop Choice	Maize	Sorghum	Maize	Sorghum	Maize	Sorghum
Highly Suitable	0	6	0	2	0	0
Moderately Suitable	34	34	23	11	23	12
Marginally Suitable	52	46	63	73	63	74
TOTAL	86	86	86	86	86	86

The above results in Tables 4.12 – 4.14 present a broad picture of the estimated percentages of area out of the entire region that can support Maize and Sorghum production respectively in varying scales of suitability considering a dry, normal or wet year. The arable area is 86% of the total area with the remaining 14% of the area gazetted for National Parks, and Central forest reserves.

The information contained in chapter four precisely equips stakeholders with knowledge on the respective locations, specific areas, and varying suitability classes for effective growth of Maize and Sorghum across Karamoja region respectively. Stake holders could refer to this information while planning for sustainable food production and also in designing appropriate cropping and irrigation alternatives to guide effective land utilization.

CHAPTER FIVE: CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The main objective of the study was to apply geospatial techniques such as GIS, GPS and remotely sensed data in assessing supplemental irrigation for Sorghum and Maize productivity within Karamoja region. Achieving the main goal of this study was accompolished by satisfying on the following objectives:

a. Conducting a land suitability analysis using SMCE: This involved generation of geospatial datasets for the study area to include the current boundary map of the study area, the slope map, soil attribute maps, and the protected areas map. These maps were then structured, standardized, weighted to guide generation of two (2) maps in which areas suited for Maize and Sorghum production were each calculated having varying suitability index as guided by FAO (1985) guidelines.

   SMCE results indicated that the study area has relatively more areas suitable for Maize Production with 85.3% at least moderately suitable as compared to 45.4% areas at least moderately suitable for Sorghum production. This is attributed to Maize's tolerance to minimal clay content in Karamoja region, a factor that affects effective Sorghum production (*refer to section 2.3*).

b. Conducting an irrigation suitability analysis based on Net Irrigation Requirement: This was conducted by initially developing seasonal effective rainfall maps for each of the designed three (3) seasons across the set scenarios i.e. wet, normal and dry Year scenarios. This was done using several commands such as *cross* operation, *attribute* map operation, *resampling* operation and many others in ILWIS. Respective seasonal NIR maps were calculated and finally eighteen (18) respective irrigation suitability maps were classified using set NIR ranges in

ILWIS. Tables 4.12 – 4.14 summarise respective areas in percentages which support supplemental irrigation. This information is very pivotal in guiding stakeholders on the magnitude if they are to sustain respective crop production in each of the seasons across the different scenarios.

c. Determination of cropping and irrigation alternatives to guide effective land utilization. This was achieved following an inferential approach in which statistic information was collated from the eighteen (18) irrigation suitability maps as summarized below:

It was observed for Season-1 that significant areas are highly suitable for both crops particularly in the wet year scenario. This is majorly attributed to the relatively higher effective rainfalls in the region around this time of the year negating the Irrigation requirement. It was also observed in this season that the region has 64% of its area highly suitable for Maize production during the wet year scenario. This is majorly attributed to relatively high suitability of Maize production as compared to that of Sorghum.

Critical observation of Season-2 statistics showed significant areas falling in the marginally suitable class unlike the case in season one. The region was particularly observed to have up to 57% of the area marginally suitable for Sorghum production in the dry year scenario. This increased marginal suitability is majorly attributed to the relatively high NIR during this season.

Season-3 which runs from November to February coincides with the driest spell with this region with average decadal rainfall ranging from 0-26 mm as compared to the 10-54 mm in Season-1. This statistic calls for relatively more irrigation water supply across all three scenarios of Season-3 as compared in order to guarantee effective crop production.

5.2 Recommendations

Based on this study that contributed to the assessment of supplemental irrigation for Sorghum and Maize production in Karamoja region, the study recommends the following:

a) A thorough soil water balance analysis at a relatively higher spatial resolution should be done to ascertain the specific contribution of factors such as Antecedent Moisture Content (AMC), Leaching requirement and Capillary rise to supplemental irrigation estimation within the study area. Furthermore detailed mapping of water resources should be done so that the results can guide more in decision making.

b) In order to achieve even more accurate subsequent geospatial analyses, relevant datasets such as a relatively higher resolution soil map with more relevant pixel attribute characteristics such as pixel fertility/productivity index; more site specific climatic data such as Temperature, Radiation, and Humidity should be digitized and made available. This will greatly simplify the computations and also greatly reduce the margin of error between the actual and computed results.

c) Further study on supplemental irrigation assessment should be carried out on an intensive/farmer level to compare/validate results of this extensive approach.

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APPENDICES

Appendix I: Relevant Agronomic Information For Sorghum And Maize

The following tables are extracts from FAO (1998) and form basis for computation of Et_o, Et_c and NIR as discussed in section 2.4.2

Table 2: Average ETo for different Agro climatic regions in mm/day pp. 8 (FAO, 1998)

Regions		
	Moderate (20°C)	**Warm (>30°C)**
Humid & Sub-Humid	3-5	5-7
Arid & Semi-Arid	4-6	6-8

Table 11: Length of Crop Development Stages for Various planting periods and Climatic regions pp.104-108 (FAO, 1998)

Crop	**Initial**	**Development**	**Mid**	**Late**	**Total**	**Planting date**	**Region**
Sorghum	20	35	45	30	140	March/ April	Arid Region
Maize	20	35	40	25	120	March/ April	Arid Region

Table 12: Single (Time-averaged) crop coefficients, Kc, and mean maximum plant heights for non-stressed well managed crops in Sub-humid climates pp.110-114 (FAO, 1998)

Crop	**Kc_i**	**Kc_{mid}**	**Kc_{end}**	**Maximum crop Height**
Sorghum (Grain)	0.3	1.0-1.10	0.55	1-2
Sorghum (Sweet)	0.3	1.2	1.05	2-4
Maize	0.3	1.2	0.35	2

Table 13: Classifications of Rainfall Depths pp.115 (FAO, 1998)

Rainfall Event	**Depth**
Very light (drizzle)	<= 3mm
Light (light showers)	5mm
Medium (Showers)	>= 10mm
Heavy (Rain storms)	>= 40mm

Table 22: Ranges of maximum effective rooting depth (Zr), and Soil water depletion fraction for no stress (p) for common crops pp.163-165 (FAO, 1998)

Crop	**Maximum Root Depth (m)**	**Depletion fraction for ET=5mm/day**

Sorghum (Grain)	1.0-2.0	0.55
Sorghum (Sweet)	1.0	0.55
Maize	0.9	0.55

NOTE

1. The larger values for Zr are for soils having no significant layering or other characteristics that can restrict rooting depth. The smaller values for Zr may be used for Irrigation scheduling
2. The values of p apply for ET=5mm/day. The value for p can be adjusted for different ETc according to; **$p = P_{table22} + 0.04(5 - Etc)$**; where p is expressed as a fraction and Etc as mm/day

Table 24: Seasonal Yield Response factor (Ky) pp.181 (FAO, 1998)

Crop	**Ky**
Sorghum	0.9
Maize	1.25

Appendix II: Cropwat Table Showing Estimated ET_o For Karamoja Region

Appendix II is a tabular extract from CROPWAT software showing reference evapotranspiration (ET_o) per month for Karamoja region. It is from these ET_o that the crop evapotranspiration (Et_c) were calculated as shown in Appendix III and IV.

Monthly ETo Penman-Monteith - E:\MOI PROJECT\CROPWAT\KaramojaETo.PEM

Country: Uganda | Station: Karamoja (Averaged)

Altitude: 1400 m. | Latitude: 2.52 °N | Longitude: 34.31 °E

Month	Min Temp	Max Temp	Humidity	Wind	Sun	Rad	ETo
	°C	°C	kPa	m/s	hours	MJ/m²/day	mm/day
January	18.6	28.4	1.67	2.0	6.7	18.7	4.62
February	19.6	29.8	1.76	2.0	7.0	19.9	5.03
March	19.4	29.6	1.74	2.0	7.0	20.4	5.16
April	18.0	28.0	1.60	2.0	6.9	19.9	4.89
May	17.5	27.5	1.54	2.0	7.0	19.1	4.66
June	16.8	26.8	1.48	2.0	7.0	18.5	4.47
July	16.5	26.4	1.45	2.0	6.9	18.6	4.44
August	16.6	26.6	1.46	2.0	7.0	19.5	4.60
September	17.6	27.5	1.56	2.0	6.9	19.9	4.79
October	17.4	27.4	1.53	2.0	6.9	19.8	4.76
November	17.7	27.7	1.56	2.0	6.8	19.1	4.65
December	17.6	27.3	1.56	2.0	6.6	18.3	4.45
Average	**17.8**	**27.8**	**1.58**	**2.0**	**6.9**	**19.3**	**4.71**

Appendix III: Sorghum Crop Water Requirement (ETc)

Appendix III is a calculation of Sorghum crop water requirement for each of the three designed seasons as discussed in section 3.2.1.

Season-1 …..March 21st -June 18th					Season-2 …..July 20th -October 17th					Season-3 …..November 17th -February 14th				
MARCH	**Day**	**Eto**	Kci	Etc (mm/day)	**JULY**	**Day**	**Eto**	Kci	Etc (mm/day)	**NOV**	**Day**	**Eto**	Kci	Etc (mm/day)
21	1	5.16	0.3	1.55	20	1	4.44	0.3	1.33	17	1	4.65	0.3	1.40
22	2	5.16	0.3	1.55	20	1	4.44	0.3	1.33	18	2	4.65	0.3	1.40
23	3	5.16	0.3	1.55	20	1	4.44	0.3	1.33	19	3	4.65	0.3	1.40
24	4	5.16	0.3	1.55	20	1	4.44	0.3	1.33	20	4	4.65	0.3	1.40
25	5	5.16	0.3	1.55	20	1	4.44	0.3	1.33	21	5	4.65	0.3	1.40
26	6	5.16	0.3	1.55	20	1	4.44	0.3	1.33	22	6	4.65	0.3	1.40
27	7	5.16	0.3	1.55	20	1	4.44	0.3	1.33	23	7	4.65	0.3	1.40
28	8	5.16	0.3	1.55	20	1	4.44	0.3	1.33	24	8	4.65	0.3	1.40
29	9	5.16	0.3	1.55	20	1	4.44	0.3	1.33	25	9	4.65	0.3	1.40
30	10	5.16	0.3	1.55	20	1	4.44	0.3	1.33	26	10	4.65	0.3	1.40
31	11	5.16	0.3	1.55	20	1	4.44	0.3	1.33	27	11	4.65	0.3	1.40
APRIL	**Day**	**Eto**	Kci	Etc (mm/day)	20	1	4.44	0.3	1.33	28	12	4.65	0.3	1.40
1	13	4.89	0.3	1.47	**AUG**	**Day**	**Eto**	Kci	Etc (mm/day)	29	13	4.65	0.3	1.40
2	14	4.89	0.3	1.47	1	13	4.6	0.3	1.38	30	14	4.65	0.3	1.40
3	14	4.89	0.3	1.47	2	14	4.6	0.3	1.38	**DEC**	**Day**	**Eto**	Kci	Etc (mm/day)
4	15	4.89	0.3	1.47	3	15	4.6	0.3	1.38	1	15	4.45	0.3	1.34
5	16	4.89	0.332	1.62	4	16	4.6	0.332	1.53	2	16	4.45	0.332	1.48
6	17	4.89	0.364	1.78	5	17	4.6	0.364	1.67	3	17	4.45	0.364	1.62
7	18	4.89	0.396	1.94	6	18	4.6	0.396	1.82	4	18	4.45	0.396	1.76
8	19	4.89	0.428	2.09	7	19	4.6	0.428	1.97	5	19	4.45	0.428	1.90

9	20	4.89	0.46	2.25	8	20	4.6	0.46	2.12	6	20	4.45	0.46	2.05
10	21	4.89	0.492	2.41	9	21	4.6	0.492	2.26	7	21	4.45	0.492	2.19
11	22	4.89	0.524	2.56	10	22	4.6	0.524	2.41	8	22	4.45	0.524	2.33
12	23	4.89	0.556	2.72	11	23	4.6	0.556	2.56	9	23	4.45	0.556	2.47
13	24	4.89	0.588	2.88	12	24	4.6	0.588	2.70	10	24	4.45	0.588	2.62
14	25	4.89	0.62	3.03	13	25	4.6	0.62	2.85	11	25	4.45	0.62	2.76
15	26	4.89	0.652	3.19	14	26	4.6	0.652	3.00	12	26	4.45	0.652	2.90
16	27	4.89	0.684	3.34	15	27	4.6	0.684	3.15	13	27	4.45	0.684	3.04
17	28	4.89	0.716	3.50	16	28	4.6	0.716	3.29	14	28	4.45	0.716	3.19
18	29	4.89	0.748	3.66	17	29	4.6	0.748	3.44	15	29	4.45	0.748	3.33
19	30	4.89	0.78	3.81	18	30	4.6	0.78	3.59	16	30	4.45	0.78	3.47
20	31	4.89	0.812	3.97	19	31	4.6	0.812	3.74	17	31	4.45	0.812	3.61
21	32	4.89	0.844	4.13	20	32	4.6	0.844	3.88	18	32	4.45	0.844	3.76
22	33	4.89	0.876	4.28	21	33	4.6	0.876	4.03	19	33	4.45	0.876	3.90
23	34	4.89	0.908	4.44	22	34	4.6	0.908	4.18	20	34	4.45	0.908	4.04
24	35	4.89	0.94	4.60	23	35	4.6	0.94	4.32	21	35	4.45	0.94	4.18
25	36	4.89	0.972	4.75	24	36	4.6	0.972	4.47	22	36	4.45	0.972	4.33
26	37	4.89	1.004	4.91	25	37	4.6	1.004	4.62	23	37	4.45	1.004	4.47
27	38	4.89	1.036	5.07	26	38	4.6	1.036	4.77	24	38	4.45	1.036	4.61
28	39	4.89	1.068	5.22	27	39	4.6	1.068	4.91	25	39	4.45	1.068	4.75
29	40	4.89	1.1	5.38	28	40	4.6	1.1	5.06	26	40	4.45	1.1	4.90
30	41	4.89	1.1	5.38	29	41	4.6	1.1	5.06	27	41	4.45	1.1	4.90
MAY	**Day**	**Eto**	Kci	Etc (mm/day)	30	42	4.6	1.1	5.06	28	42	4.45	1.1	4.90
1	42	4.66	1.1	5.13	31	43	4.6	1.1	5.06	29	43	4.45	1.1	4.90
2	43	4.66	1.1	5.13	SEPT	**Day**	**Eto**	Kci	Etc (mm/day)	30	44	4.45	1.1	4.90
3	44	4.66	1.1	5.13	1	44	4.79	1.1	5.27	31	45	4.45	1.1	4.90

4	45	4.66	1.1	5.13	2	45	4.79	1.1	5.27	**JAN**	**Day**	**Eto**	Kci	Etc (mm/day)
5	46	4.66	1.1	5.13	3	46	4.79	1.1	5.27	1	46	4.62	1.1	5.08
6	47	4.66	1.1	5.13	4	47	4.79	1.1	5.27	2	47	4.62	1.1	5.08
7	48	4.66	1.1	5.13	5	48	4.79	1.1	5.27	3	48	4.62	1.1	5.08
8	49	4.66	1.1	5.13	6	49	4.79	1.1	5.27	4	49	4.62	1.1	5.08
9	50	4.66	1.1	5.13	7	50	4.79	1.1	5.27	5	50	4.62	1.1	5.08
10	51	4.66	1.1	5.13	8	51	4.79	1.1	5.27	6	51	4.62	1.1	5.08
11	52	4.66	1.1	5.13	9	52	4.79	1.1	5.27	7	52	4.62	1.1	5.08
12	53	4.66	1.1	5.13	10	53	4.79	1.1	5.27	8	53	4.62	1.1	5.08
13	54	4.66	1.1	5.13	11	54	4.79	1.1	5.27	9	54	4.62	1.1	5.08
14	55	4.66	1.1	5.13	12	55	4.79	1.1	5.27	10	55	4.62	1.1	5.08
15	56	4.66	1.1	5.13	13	56	4.79	1.1	5.27	11	56	4.62	1.1	5.08
16	57	4.66	1.1	5.13	14	57	4.79	1.1	5.27	12	57	4.62	1.1	5.08
17	58	4.66	1.1	5.13	15	58	4.79	1.1	5.27	13	58	4.62	1.1	5.08
18	59	4.66	1.1	5.13	16	59	4.79	1.1	5.27	14	59	4.62	1.1	5.08
19	60	4.66	1.1	5.13	17	60	4.79	1.1	5.27	15	60	4.62	1.1	5.08
20	61	4.66	1.1	5.13	18	61	4.79	1.1	5.27	16	61	4.62	1.1	5.08
21	62	4.66	1.1	5.13	19	62	4.79	1.1	5.27	17	62	4.62	1.1	5.08
22	63	4.66	1.1	5.13	20	63	4.79	1.1	5.27	18	63	4.62	1.1	5.08
23	64	4.66	1.1	5.13	21	64	4.79	1.1	5.27	19	64	4.62	1.1	5.08
24	65	4.66	1.1	5.13	22	65	4.79	1.1	5.27	20	65	4.62	1.1	5.08
25	66	4.66	1.1	5.13	23	66	4.79	1.1	5.27	21	66	4.62	1.1	5.08
26	67	4.66	1.1	5.13	24	67	4.79	1.1	5.27	22	67	4.62	1.1	5.08
27	68	4.66	1.1	5.13	25	68	4.79	1.1	5.27	23	68	4.62	1.1	5.08
28	69	4.66	1.1	5.13	26	69	4.79	1.1	5.27	24	69	4.62	1.1	5.08
29	70	4.66	1.1	5.13	27	70	4.79	1.1	5.27	25	70	4.62	1.1	5.08
30	71	4.66	1.0725	5.00	28	71	4.79	1.0725	5.14	26	71	4.62	1.0725	4.95
31	72	4.66	1.045	4.87	29	72	4.79	1.045	5.01	27	72	4.62	1.045	4.83
JUNE	**Day**	**Eto**	Kci	Etc	30	73	4.79	1.0175	4.87	28	73	4.62	1.0175	4.70

				(mm/day)										
1	73	4.47	1.0175	4.55	OCT	**Day**	**Eto**	Kci	Etc (mm/day)	29	74	4.62	0.99	4.57
2	74	4.47	0.99	4.43	1	74	4.76	0.99	4.71	30	75	4.62	0.9625	4.45
3	75	4.47	0.9625	4.30	2	75	4.76	0.9625	4.58	31	76	4.62	0.935	4.32
4	76	4.47	0.935	4.18	3	76	4.76	0.935	4.45	FEB	**Day**	**Eto**	Kci	Etc (mm/day)
5	77	4.47	0.9075	4.06	4	77	4.76	0.9075	4.32	1	77	5.03	0.9075	4.56
6	78	4.47	0.88	3.93	5	78	4.76	0.88	4.19	2	78	5.03	0.88	4.43
7	79	4.47	0.8525	3.81	6	79	4.76	0.8525	4.06	3	79	5.03	0.8525	4.29
8	80	4.47	0.825	3.69	7	80	4.76	0.825	3.93	4	80	5.03	0.825	4.15
9	81	4.47	0.7975	3.56	8	81	4.76	0.7975	3.80	5	81	5.03	0.7975	4.01
10	82	4.47	0.77	3.44	9	82	4.76	0.77	3.67	6	82	5.03	0.77	3.87
11	83	4.47	0.7425	3.32	10	83	4.76	0.7425	3.53	7	83	5.03	0.7425	3.73
12	84	4.47	0.715	3.20	11	84	4.76	0.715	3.40	8	84	5.03	0.715	3.60
13	85	4.47	0.6875	3.07	12	85	4.76	0.6875	3.27	9	85	5.03	0.6875	3.46
14	86	4.47	0.66	2.95	13	86	4.76	0.66	3.14	10	86	5.03	0.66	3.32
15	87	4.47	0.6325	2.83	14	87	4.76	0.6325	3.01	11	87	5.03	0.6325	3.18
16	88	4.47	0.605	2.70	15	88	4.76	0.605	2.88	12	88	5.03	0.605	3.04
17	89	4.47	0.5775	2.58	16	89	4.76	0.5775	2.75	13	89	5.03	0.5775	2.90
18	90	4.47	0.55	2.46	17	90	4.76	0.55	2.62	14	90	5.03	0.55	2.77
			Seasonal ETc	**337**				**Seasonal ETc**	**337**				**Seasonal ETc**	**331**

Appendix IV: Maize Crop Water Requirement (ET_c)

Appendix IV is a calculation of Maize crop water requirement for each of the three designed seasons as discussed in section 4.3.2.

Season-1 …..March 21st -June 18th					**Season-2 …..July 20th -October 17th**					**Season-3 …..November 17th -February 14th**				
MARCH	**Day**	**Eto**	Kci	Etc (mm/day)	**JULY**	**Day**	**Eto**	Kci	Etc (mm/day)	**NOV**	**Day**	**Eto**	Kci	Etc (mm/day)
21	1	5.16	0.3	1.55	20	1	4.44	0.3	1.33	17	1	4.65	0.3	1.40
22	2	5.16	0.3	1.55	21	2	4.44	0.3	1.33	18	2	4.65	0.3	1.40
23	3	5.16	0.3	1.55	22	3	4.44	0.3	1.33	19	3	4.65	0.3	1.40
24	4	5.16	0.3	1.55	23	4	4.44	0.3	1.33	20	4	4.65	0.3	1.40
25	5	5.16	0.3	1.55	24	5	4.44	0.3	1.33	21	5	4.65	0.3	1.40
26	6	5.16	0.3	1.55	25	6	4.44	0.3	1.33	22	6	4.65	0.3	1.40
27	7	5.16	0.3	1.55	26	7	4.44	0.3	1.33	23	7	4.65	0.3	1.40
28	8	5.16	0.3	1.55	27	8	4.44	0.3	1.33	24	8	4.65	0.3	1.40
29	9	5.16	0.3	1.55	28	9	4.44	0.3	1.33	25	9	4.65	0.3	1.40
30	10	5.16	0.3	1.55	29	10	4.44	0.3	1.33	26	10	4.65	0.3	1.40
31	11	5.16	0.3	1.55	30	11	4.44	0.3	1.33	27	11	4.65	0.3	1.40
APRIL	**Day**	**Eto**	Kci	Etc (mm/day)	31	12	4.44	0.3	1.33	28	12	4.65	0.3	1.40
1	12	4.89	0.3	1.47	**AUG**		**Eto**	**Kc**		29	13	4.65	0.3	1.40
2	13	4.89	0.3	1.47	1	13	4.6	0.3	1.38	30	14	4.65	0.3	1.40
3	14	4.89	0.3	1.47	2	14	4.6	0.3	1.38	DEC	**Day**	**Eto**	Kci	Etc (mm/day)
4	15	4.89	0.3	1.47	3	15	4.6	0.3	1.38	1	15	4.45	0.3	1.34
5	16	4.89	0.345	1.69	4	16	4.6	0.345	1.59	2	16	4.45	0.345	1.54
6	17	4.89	0.39	1.91	5	17	4.6	0.39	1.79	3	17	4.45	0.39	1.74
7	18	4.89	0.435	2.13	6	18	4.6	0.435	2.00	4	18	4.45	0.435	1.94
8	19	4.89	0.48	2.35	7	19	4.6	0.48	2.21	5	19	4.45	0.48	2.14
9	20	4.89	0.525	2.57	8	20	4.6	0.525	2.42	6	20	4.45	0.525	2.34

10	21	4.89	0.57	2.79	9	21	4.6	0.57	2.62	7	21	4.45	0.57	2.54
11	22	4.89	0.615	3.01	10	22	4.6	0.615	2.83	8	22	4.45	0.615	2.74
12	23	4.89	0.66	3.23	11	23	4.6	0.66	3.04	9	23	4.45	0.66	2.94
13	24	4.89	0.705	3.45	12	24	4.6	0.705	3.24	10	24	4.45	0.705	3.14
14	25	4.89	0.75	3.67	13	25	4.6	0.75	3.45	11	25	4.45	0.75	3.34
15	26	4.89	0.795	3.89	14	26	4.6	0.795	3.66	12	26	4.45	0.795	3.54
16	27	4.89	0.84	4.11	15	27	4.6	0.84	3.86	13	27	4.45	0.84	3.74
17	28	4.89	0.885	4.33	16	28	4.6	0.885	4.07	14	28	4.45	0.885	3.94
18	29	4.89	0.93	4.55	17	29	4.6	0.93	4.28	15	29	4.45	0.93	4.14
19	30	4.89	0.975	4.77	18	30	4.6	0.975	4.49	16	30	4.45	0.975	4.34
20	31	4.89	1.02	4.99	19	31	4.6	1.02	4.69	17	31	4.45	1.02	4.54
21	32	4.89	1.065	5.21	20	32	4.6	1.065	4.90	18	32	4.45	1.065	4.74
22	33	4.89	1.11	5.43	21	33	4.6	1.11	5.11	19	33	4.45	1.11	4.94
23	34	4.89	1.155	5.65	22	34	4.6	1.155	5.31	20	34	4.45	1.155	5.14
24	35	4.89	1.2	5.87	23	35	4.6	1.2	5.52	21	35	4.45	1.2	5.34
25	36	4.89	1.2	5.87	24	36	4.6	1.2	5.52	22	36	4.45	1.2	5.34
26	37	4.89	1.2	5.87	25	37	4.6	1.2	5.52	23	37	4.45	1.2	5.34
27	38	4.89	1.2	5.87	26	38	4.6	1.2	5.52	24	38	4.45	1.2	5.34
28	39	4.89	1.2	5.87	27	39	4.6	1.2	5.52	25	39	4.45	1.2	5.34
29	40	4.89	1.2	5.87	28	40	4.6	1.2	5.52	26	40	4.45	1.2	5.34
30	41	4.89	1.2	5.87	29	41	4.6	1.2	5.52	27	41	4.45	1.2	5.34
MAY	**Day**	**Eto**	Kci	Etc (mm/day)	30	42	4.6	1.2	5.52	28	42	4.45	1.2	5.34
1	42	4.66	1.2	5.59	31	43	4.6	1.2	5.52	29	43	4.45	1.2	5.34
2	43	4.66	1.2	5.59	SEPT	**Day**	**Eto**	Kci	Etc (mm/day)	30	44	4.45	1.2	5.34
3	44	4.66	1.2	5.59	1	44	4.79	1.2	5.75	31	45	4.45	1.2	5.34
4	45	4.66	1.2	5.59	2	45	4.79	1.2	5.75	JAN	**Day**	**Eto**	Kci	Etc (mm/day)

5	46	4.66	1.2	5.59	3	46	4.79	1.2	5.75	1	46	4.62	1.2	5.54
6	47	4.66	1.2	5.59	4	47	4.79	1.2	5.75	2	47	4.62	1.2	5.54
7	48	4.66	1.2	5.59	5	48	4.79	1.2	5.75	3	48	4.62	1.2	5.54
8	49	4.66	1.2	5.59	6	49	4.79	1.2	5.75	4	49	4.62	1.2	5.54
9	50	4.66	1.2	5.59	7	50	4.79	1.2	5.75	5	50	4.62	1.2	5.54
10	51	4.66	1.2	5.59	8	51	4.79	1.2	5.75	6	51	4.62	1.2	5.54
11	52	4.66	1.2	5.59	9	52	4.79	1.2	5.75	7	52	4.62	1.2	5.54
12	53	4.66	1.2	5.59	10	53	4.79	1.2	5.75	8	53	4.62	1.2	5.54
13	54	4.66	1.2	5.59	11	54	4.79	1.2	5.75	9	54	4.62	1.2	5.54
14	55	4.66	1.2	5.59	12	55	4.79	1.2	5.75	10	55	4.62	1.2	5.54
15	56	4.66	1.2	5.59	13	56	4.79	1.2	5.75	11	56	4.62	1.2	5.54
16	57	4.66	1.2	5.59	14	57	4.79	1.2	5.75	12	57	4.62	1.2	5.54
17	58	4.66	1.2	5.59	15	58	4.79	1.2	5.75	13	58	4.62	1.2	5.54
18	59	4.66	1.2	5.59	16	59	4.79	1.2	5.75	14	59	4.62	1.2	5.54
19	60	4.66	1.2	5.59	17	60	4.79	1.2	5.75	15	60	4.62	1.2	5.54
20	61	4.66	1.2	5.59	18	61	4.79	1.2	5.75	16	61	4.62	1.2	5.54
21	62	4.66	1.2	5.59	19	62	4.79	1.2	5.75	17	62	4.62	1.2	5.54
22	63	4.66	1.2	5.59	20	63	4.79	1.2	5.75	18	63	4.62	1.2	5.54
23	64	4.66	1.2	5.59	21	64	4.79	1.2	5.75	19	64	4.62	1.2	5.54
24	65	4.66	1.2	5.59	22	65	4.79	1.2	5.75	20	65	4.62	1.2	5.54
25	66	4.66	1.2	5.59	23	66	4.79	1.2	5.75	21	66	4.62	1.2	5.54
26	67	4.66	1.2	5.59	24	67	4.79	1.2	5.75	22	67	4.62	1.2	5.54
27	68	4.66	1.2	5.59	25	68	4.79	1.2	5.75	23	68	4.62	1.2	5.54
28	69	4.66	1.2	5.59	26	69	4.79	1.2	5.75	24	69	4.62	1.2	5.54
29	70	4.66	1.2	5.59	27	70	4.79	1.2	5.75	25	70	4.62	1.2	5.54
30	71	4.66	1.17	5.45	28	71	4.79	1.17	5.60	26	71	4.62	1.17	5.41
31	72	4.66	1.14	5.31	29	72	4.79	1.14	5.46	27	72	4.62	1.14	5.27
JUNE	**Day**	**Eto**	Kci	Etc (mm/day)	30	73	4.79	1.11	5.32	28	73	4.62	1.11	5.13

1	73	4.47	1.11	4.96	OCT	**Day**	**Eto**	Kci	Etc (mm/day)	29	74	4.62	1.08	4.99
2	74	4.47	1.08	4.83	1	74	4.76	1.08	5.14	30	75	4.62	1.05	4.85
3	75	4.47	1.05	4.69	2	75	4.76	1.05	5.00	31	76	4.62	1.02	4.71
4	76	4.47	1.02	4.56	3	76	4.76	1.02	4.86	FEB	**Day**	**Eto**	Kci	Etc (mm/day)
5	77	4.47	0.99	4.43	4	77	4.76	0.99	4.71	1	77	5.03	0.99	4.98
6	78	4.47	0.96	4.29	5	78	4.76	0.96	4.57	2	78	5.03	0.96	4.83
7	79	4.47	0.93	4.16	6	79	4.76	0.93	4.43	3	79	5.03	0.93	4.68
8	80	4.47	0.9	4.02	7	80	4.76	0.9	4.28	4	80	5.03	0.9	4.53
9	81	4.47	0.87	3.89	8	81	4.76	0.87	4.14	5	81	5.03	0.87	4.38
10	82	4.47	0.84	3.75	9	82	4.76	0.84	4.00	6	82	5.03	0.84	4.23
11	83	4.47	0.81	3.62	10	83	4.76	0.81	3.86	7	83	5.03	0.81	4.07
12	84	4.47	0.78	3.49	11	84	4.76	0.78	3.71	8	84	5.03	0.78	3.92
13	85	4.47	0.75	3.35	12	85	4.76	0.75	3.57	9	85	5.03	0.75	3.77
14	86	4.47	0.72	3.22	13	86	4.76	0.72	3.43	10	86	5.03	0.72	3.62
15	87	4.47	0.69	3.08	14	87	4.76	0.69	3.28	11	87	5.03	0.69	3.47
16	88	4.47	0.66	2.95	15	88	4.76	0.66	3.14	12	88	5.03	0.66	3.32
17	89	4.47	0.63	2.82	16	89	4.76	0.63	3.00	13	89	5.03	0.63	3.17
18	90	4.47	0.6	2.68	17	90	4.76	0.6	2.86	14	90	5.03	0.6	3.02
Seasonal ETc				**375**	**Seasonal ETc**				**375**	**Seasonal ETc**				**368**