ASSESSMENT OF RUNOFF FOR DESIGN OF FARM PONDS FOR IRRIGATION IN MARAGUA WATERSHED, MURANG'A COUNTY, KENYA

SUSAN MBITHE MAINGI

MASTER OF SCIENCE

(Soil and Water Engineering)

JOMO KENYATTA UNIVERSITY

OF

AGRICULTURE AND TECHNOLOGY

2023

Assessment of Runoff for Design of Farm Ponds for Irrigation in Maragua Watershed, Murang'a County, Kenya

Susan Mbithe Maingi

A Thesis Submitted in Partial Fulfilment of the Requirements for the Degree of Master of Science in Soil and Water Engineering of the Jomo Kenyatta University of Agriculture and Technology

2023

DECLARATION

This thesis is my original work and has not been presented for a degree in any other University

Signature …………………………………….. Date……………..……………………

Susan Mbithe Maingi

This thesis has been submitted for examination with our approval as University Supervisors

Signature …………………………………….. Date……………..……………………

Dr. Jackline Ndiiri, PhD

JKUAT, Kenya

Signature …………………………………….. Date……………..……………………

Prof. Eng. Bancy Mati, PhD

JKUAT, Kenya

DEDICATION

This thesis is dedicated to my loving husband, Dr. Stephen N. Mailu and my dear parents Mr and Mrs. Timothy Maingi.

ACKNOWLEDGEMENT

First and foremost, Glory to God for the far I have come.

Secondly, I offer my sincerest gratitude to my supervisors, Dr. Jackline Ndiiri and Prof. Eng. Bancy Mati, for their support throughout my research work. Your efforts are highly appreciated. I attribute the level of my Master's degree to their encouragement and effort without which this research would not have been completed.

Besides, I would like to express my gratitude to staff, Department of Soil, Water and Environmental Engineering at Jomo Kenyatta University of Agriculture and Technology (JKUAT) for the guidance throughout the research work. Further, thanks to my classmates and friends who were a close encouragement during my studies.

I wish to extend my deepest gratitude to my beloved husband Dr. Stephen N. Mailu, for financial, moral and research support, my sons, Raymond, Gideon and Caleb for their patience, understanding, un-ending love, inspiration and blessings to achieve this height of my career.

Finally, a big thank you to the Upper Tana Nairobi Water Fund (UTNWF) and The Nature Conservancy (TNC) for providing the financial support for the research work, as well as the Water Research and Resource Centre (WARREC) for logistical support. In addition, many thanks go to the KALRO-NARL Kabete lab technologists for providing research support during laboratory analysis which was extremely helpful for completion of this research work.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF APPENDICES

ABBREVIATIONS AND ACRONYMS

A.M.S.L	Above Mean Sea Level
AMC	Antecedent Moisture Condition
AutoCAD	Automated Computer-Aided Design
CropWAT	Crop Water requirement software
CWR	Crop Water Requirement
DEM	Digital Elevation Model
FAO	Food and Agriculture Organization
GIS	Geographical Information Systems
HDPE	High-Density Poly Ethylene
HSG	Hydrologic Soil Groups
IHP	International Hydrological Programme
ITCZ	Inter-Tropical Convergence Zone
IWMI	International Water Management Institute
JKUAT	Jomo Kenyatta University of Agriculture and Technology
LULC	Land Use Land Cover
MWI, GOK	Ministry of Water and Irrigation, Government of Kenya
NGO	Non- Governmental Organization

SCS-CN	Soil Conservation Service – Curve Number
TNC	The Nature Conservancy
UDFCD	Urban Drainage and Flood Control District
UN	United Nations
USDA	United States Department of Agriculture
USGS	United States Geological Survey
WARREC	Water Research and Resource Centre
WRMA	Water Resource Management Authority

ABSTRACT

This study involved the assessment of runoff and design of three different farm ponds for harvesting runoff to supplement irrigation. The study was carried out in Maragua watershed in Murang'a County where farmers face the challenge of water shortage during the dry season and therefore require water for supplemental irrigation of their horticultural crops. This was achieved by; assessing the water requirement for crops within the watershed, assessment of the runoff from the agricultural fields and design for the storage volume of a farm pond for the generated runoff from the agricultural fields. In this research, CropWAT model was used to determine the crop water requirement, while the Soil Conservation Service – Curve Number Model using ArcGIS 10.1 software was used in the estimation of the runoff depth in mm. The value of runoff depth was converted to runoff volume which was then used to design for the water storage facility. AutoCAD 2019 was used to make technical drawings for the farm pond. The design of the farm pond was done based on different slopes; gentle slopes and steep slopes in accordance to Design manual 2015. The study results showed that ET_0 varied from 3.01 to 5.10 mm/day and the effective rainfall varied from 8.0 to 154.4 mm. The ETc values for the garden pea, sweet pepper and tomato were 395.6, 460.1 and 432.7 mm per the growing season respectively. The irrigation requirements were 181.4, 216.6 and 187 mm per season for garden pea, tomato, and sweet pepper respectively. The results indicate increasing ETc throughout the growth stages which is high at the mid-season stage and starts to decrease slightly at the later stages. The results for runoff estimation demonstrated that the SCS-CN method by using satellite imagery data to estimate runoff is convenient and effective. The runoff volume calculated from the area and depth of runoff indicates that the crop land had the highest volume of runoff since it occupied the largest area among the three land use classes which was at 9,368,519.10 m^3, 2,858,923.47 m^3, 2,511,768.72 m^3, for Kambirwa, Gituamba and Maragua ridge micro-watersheds respectively. This runoff come from the entire sub watersheds which will supply water to the farm ponds in the area. The values indicate that there is enough runoff to be harvested to the farm ponds. The design of farm ponds was done for each of the ponds surveyed in the different micro watersheds using the practice manual for small dams. The different capacities for the three farm ponds were; the design criteria was obtained for the three different farm ponds in slopes of 1%, 2% and 3%. the design criteria was able to achieve the water demand, evaporation and seepage losses , dead storage, average storage capacity, spillway channel size and slopes. The study recommends CropWAT model as a suitable decision support tool for policy makers and investors on irrigation and water resources in the region with regard to irrigation water management.

CHAPTER ONE

INTRODUCTION

1.1 Background to the Study

Water is one of the most precious and common resources naturally occurring on earth. It covers more than 70% of the earth's surface and all living things including human, animals and plants rely on water (Chellaney, 2013). Its uses are quite massive and its importance can never be assumed since it plays a great role both in human and animal life (FAO, 2016).

Globally, close to 771 million people in the world - 1 in 10 - lack access to water. According to a report by the World Economic Forum, the water crisis is the number five global risk in terms of impact to society. Lack of water of adequate quality and quantity is a major constraint to development in many areas of the world. It affects every aspect of human life including health, agricultural yields, food security, technical development and the economy of every state. Water scarcity and water quality problems are of particular concern in the tropical regions of the world where many countries are less developed (Fauraes *et al*., 2012).

Kenya is an agricultural country that relies on its land and water resources to meet the needs of its rapidly increasing population. In the arid and semi-arid areas of Kenya, insufficient water for household use, crop and livestock production has been the major constraint to rural development (Fauraes *et al.*, 2012). Due to great variations in rainfall, several rainwater harvesting systems have been tested in previous years, both in Kenya and in other water-stressed nations, with the aim to reduce drought and water shortages. Kenya is classified as a water scarce country with annual water supplies below $1000m^3$ /person (UNEP, 2002). Out of Kenya's population, approximately 75 % lives in rural areas where rain-fed farming and livestock keeping are the main livelihoods (Wani *et al*., 2009). Moreover, the population is increasing at a rate of 2.6 % every year. There is a high level of dependability on the seasonal rains (World Bank, 2010).

The situation is predicted to worsen drastically within the near future. In semiarid regions temperatures are projected to increase and precipitation decline by 2030 due to climate change. Some figures estimate annually available freshwater at around 250 m^3 per capita in 2025 (Leal, 2011). Most precipitation that falls on human settlements is lost to the atmosphere through evapotranspiration or runs into rivers away from settlements before it can be used. However, if the rain is collected using appropriate structure, it can contribute greatly to the volume of water available for agricultural use. This is particularly relevant in arid and semi-arid regions, where the little rainfall received is usually very intense and often seasonal (Bush, 2017).

As water remains a critical input in agricultural production, its demand is still too high hence making it insufficient to meet the crop water needs especially during the dry season. This is due to high water usage in the agricultural sector accounting for over 70% of water usage in farming. One of the solutions to address water shortage is by rainwater harvesting during the rainy season and store for use in the dry season. While irrigation may be the most obvious response to water stress in crops, it has proved costly and can only benefit the fortunate few. Currently, the interest for water harvesting has increased due to the low cost associated with it (Oweis *et al.,* 1999) hence can be implemented as a feasible alternative to conventional water supply or on-farm irrigation projects considering that any land in any part of the world can be used to harvest rainwater (Pielke, 2013). Irrespective of the type of water harvesting technology, rainwater harvesting is just to harvest and store water in days when it is in abundance and use it in thin days. This water can be harvested using simple and eco-friendly low-cost technologies such as tanks, dams, ponds and plastic-lined water ponds. Such technologies are sustainable, cost-effective and affordable to farmers. Despite this, most farmers have serious challenges in getting the right structure for their farms due to lack of construction knowledge contributed by lack of proper design guidelines for the structures (DeBusk & Hunt, 2014). This results to the farmers ending up with insufficient water harvesting structures to store enough water for their crops hence the water doesn’t meet the crop water demand.

Rainwater harvesting refers to the collection, conveyance, conservation and storage of rainwater for various purposes like drinking water, livestock watering or agriculture. It also involves harnessing and improving the productive use of excess rainfall by turning surface runoff from a destructive element into an asset. The rainwater is normally collected where it falls, through in-situ conservation and/or channeling excess runoff water in a guided manner from catchment areas to storage reservoirs for various uses, especially for agriculture or stored in the soil profile for soil moisture replenishment (Mati, 2012). It is one of the practices that can be adopted by many nations as a viable decentralized water source to meet the growing water demand (Jacobsen *et al.*, 2012). Rainwater harvesting is either rooftop or runoff. Surface runoff water harvesting is the collection, accumulation and storage of rainwater for its eventual reuse. Sources of runoff water include catchment areas from manmade surfaces, such as roads, or other urban environments, parks, gardens and agricultural fields. If surface runoff catchment systems are properly designed, they can collect large quantities of rainwater (Gould & Nissen-Petersen, 1999). Precipitation in arid and semi-arid regions is scarce, unreliable, and unevenly distributed throughout the year. A large proportion of the precipitation is therefore converted into runoff due to various factors such as a lack of vegetation and high intensity. Runoff harvesting has the potential to alleviate the water shortage in Kenya (Bates *et al.*, 2008). If rainwater was effectively utilized through runoff harvesting, the rainfall contribution is more than adequate to meet the needs of the current population several times (Novak *et al.*, 2014).

The inhabitants of Maragua watershed in Murang'a County majorly rely on the water although restricted from the Maragua River for domestic and agricultural purposes (MUWASCO Project Report, 2017). This has led to over-exploitation leading to declining water levels even in the downstream water bodies that rely on this river. Due to the increased water demand, there was the need for alternative water supply since the major sources which are surface water and subsurface are either constant or declined over time (Murang'a County Integrated Development Plan, 2018). The Nature Conservancy (TNC) with the help of the Nairobi Water Fund began to construct farm ponds for water storage during the rainy season. One of their interventions, is reducing dry season water demand from rivers and streams by irrigators by engaging smallholder farmers who harvest rainwater, storing it in water ponds, and applying it to their crops during the dry season, the quality and quantity of the river improves which is good for downstream water users, hydropower generation, and other water needs. In Maragua watershed, more than 1,000 small-scale farmers are adopting water harvesting structures like ponds that capture and store runoff for use in the dry season and making use of the drip irrigation method to support their horticultural crops. This has helped them even further reduce the amount of water that goes into the entire farm (TNC, 2015). The report from TNC indicates that the already constructed water ponds are insufficient to sustain crop production due to poor design guidelines. This study, therefore, seeks to assess the runoff and formulate a design criterion for farm ponds which is a viable solution that can address water shortage for crops during the dry season.

1.2 Statement of the Problem

Like most developing countries, the water status in Kenya cannot satisfy water shortage which is driven mainly by population growth. This happens in most arid and semi-arid areas of the country like some parts of Murang'a County especially Maragua sub county which lies in the Eastern part of the county. Since the 1970s, large areas of forests in the Upper Tana where the Maragua watershed lies have been replaced by agricultural fields (Geertsma *et al.,* 2009). During the 2019 census, the Murang'a population was recorded as 1,056,640 with an average increment rate of 1.2 % which recorded a density of 413 persons per sq. km (KNBS, 2019). Due to this rate of population increase, the amount of food required to meet the population demand was set to increase in the area to meet the population needs. This would be increased by irrigation in the sense that farmers are able to grow high value crops all year round. This motivates farmers to invest more on farming activities hence increasing the overall agricultural productivity. Encroachment on natural wetlands that once stored runoff water and recharged aquifers reduced dry-season flows hence less water reaches the agricultural land (TNC, 2015). In order to meet the increasing water demand for agriculture, farmers in Maragua in Murang'a County are currently constructing farm ponds for runoff harvesting to meet the crop water requirements during the dry season (Murang'a County Integrated Development Plan, 2018). This is to supply water for supplemental irrigation to support horticulture crop production that is done over the dry season. However, the farmers still face challenges of water shortage because the ponds are not able to hold enough water to last a crop season. This has been attributed by the limited technical know-how and inappropriate design approaches. Most farm ponds especially with small scale farmers have been constructed not considering farmers' water demand and the available catchment area hence the farmers do not harvest enough water in them. Some of them are either oversize reducing the crop land or undersize hence cannot hold enough water to satisfy the crop water demand. Therefore benefits can only be realized through technical improvements of the existing water harvesting initiatives and technologies. To minimize on crop loss, land wastage, reduced land productivity, there is the need to provide design guidelines and essential technical data to properly design a farm pond that can hold enough water to meet the crop water demand. This will be a viable solution to increase water availability to crops during the dry season which will go a long way in increasing agricultural productivity amongst the smallholder farmers in Maragua watershed.

1.3 Justification of the Study

This research study falls within the lower area in Maragua Watershed where there is limited availability of water and farmers have to look for extra source of water for their crops to avoid constrained crop production. The amount of rainfall received is not only insufficient to sustain a crop through to maturity but it is also unevenly distributed hence creates below optimal cumulative soil water availability during the growing season. Currently, farmers in the Maragua Region have benefited from funding to enable construction of water harvesting facilities like farm ponds which enable harvest water during the rainy season to use it when rains decline. The farmers have also benefited from increased agricultural yields from their farms since there is sufficient moisture to keep the crops to maturity. Simple and sustainable rainwater harvesting technologies could be the long awaited solution for improving rain fed agriculture and overall food security. In areas of Upper Tana and especially, Maragua watershed where the study has been carried out, a number of water harvesting systems have been set up including water pans and farm ponds to curb the problem of water shortage in crop production. Out of this, few have succeeded in combining technical efficiency with low cost and local farmer acceptance but quite a number of them have not.

1.4 Objectives

1.4.1 General Objective

The general objective is to assess runoff for the design of farm ponds for irrigation in Maragua watershed, Murang' a County in Kenya.

1.4.2 Specific Objectives

i. To determine the crop water requirements of garden pea, tomato and sweet pepper in the Kambirwa, Maragua ridge and Gituamba sub catchments of Maragua watershed.

ii. To determine the runoff from the Kambirwa, Maragua ridge and Gituamba sub catchments in Maragua watershed.

iii. To formulate design criteria for farm ponds for harvesting the generated runoff in the Kambirwa, Maragua ridge and Gituamba zones for farmers to meet Crop water requirements.

1.5 Research Questions

i. What are the crop water requirements for garden pea, tomato and sweet pepper in the Kambirwa, Maragua ridge and Gituamba sub catchments of Maragua?
ii. How much runoff can be harvested for a farmer in Kambirwa, Maragua ridge and Gituamba sub catchments in Maragua watershed?
iii. What are the design guidelines for farm ponds for harvesting the generated runoff for Kambirwa, Maragua ridge and Gituamba sub catchments in Maragua watershed?

1.6 Scope and Limitation

The study was limited to Kambirwa, Maragua ridge and Gituamba sub catchments of Maragua watershed zones with different gradients in Maragua watershed in Murang'a County which is within the Upper Tana Catchment. Water Regulation Authority activities in the catchment area were considered since it was one of the key sources of the information for this research during data collection. However assessment of crop water requirement was done on garden pea, tomato and sweet pepper which are the three major crops grown under irrigation in the areas delineated for the study. Estimation of runoff was achieved by the use of SCS-CN approach which was modified to fit the conditions of the area. The design criteria of the farm pond was done based on three different gradients; steep, middle and gentle slopes and the technical drawings were done using AutoCAD 2019.

CHAPTER TWO

LITERATURE REVIEW

2.1 Introduction

This chapter covers the various aspects incorporated for design of farm ponds which includes, water requirement by the crops in the particular area under consideration and the methods of determination, the available runoff that can be harvested and the various approaches used in determination of the runoff. Most of the work is normally in the Arid and semi-arid areas (ASALs) which suffer seasonal water scarcity, although they receive some little rainfall, which may be low or erratic. Most ASALs receive between 250 and 850 mm of annual rainfall which is insufficient for crop production (Mati, 2018). But much of this rainfall is lost through surface runoff that end up in unrecoverable water bodies and the rest is lost through seepage and evaporation losses. Harvesting this water and storing in farm ponds enhances utilization of a free and less costly water resource after the rains have elapsed (Ahmed & Gemeda, 2021).

2.2 Crop Water Requirement

Crop Water Requirement (CWR) is defined as the depth of water needed to meet the water loss through crop evapotranspiration (ET_c) of a disease-free crop, growing in fields under non-restricting soil conditions including soil water and fertility and achieving full production potential under the given growing environment (Seethapathi *et al.*, 2008). Both CWR and ET_c concepts apply to either irrigated or rainfed crops. Their determination is highly significant in the calculation of the equilibrium of water and soil resources, design, operation, and management of the irrigation projects (Johl, 2014). There are various methods of measuring and estimating crop water requirement that have been proposed all over the world. Four methods namely, the Blaney-Criddle, Radiation, FAO Penman Monteith method and Pan Evaporation method, are reviewed herein for predicting water requirement of crops (Abtew & Melesse, 2013). Each of the four methods predicts reference crop evapotranspiration (ET_o) and only one set of crop coefficients is required since they relate ET_o to (ET_c). Procedures for selection of appropriate kc values take into account the crop characteristics, time of planting or sowing, and stages of crop development and general climatic conditions.

2.2.1 Blaney-Criddle

This method applies in areas where available climate data cover air and temperature data. This involves calculation of the consumptive use factor (f) from mean temperature (T) and percentage (p) of total annual daylight hours that normally occur during the period of consideration in the particular area of study. The consumptive use crop coefficient (K) which is empirically determined is then applied to obtain the consumptive water requirements (CU) (Zhan & Lin, 2009).

$$CU = K * f = {}^{p.T}/_{100} \tag{2.1}$$

Where T is in °F.

Consumptive use being referred to as 'the amount of water required to meet the evapo-transpiration needs of vegetative areas so that plant production is not affected by water shortage

2.2.2 Radiation Method

This method applies for areas where available climate data include measured air temperature and sunshine, cloudiness or radiation, but not wind and humidity. The Knowledge of humidity and wind levels is significant and can be estimated by use of published weather descriptions or extrapolations obtained from nearby areas. Relationships are given between the presented radiation formula and reference crop evapotranspiration (ET_o). This method is more reliable in equatorial zones or high altitudes areas. In cases where measured sunshine or cloudiness data are not available; solar radiation maps can be used to provide the necessary solar radiation data.

Calculation of Solar Radiation (R_s)

To calculate solar radiation (R_s) from sunshine duration or cloudiness data, the weighting factor (W) from temperature and altitude data and the appropriate adjustment given by the relationship between W.Rs and ET_o for different mean humidity and daytime wind conditions, the following procedure is suggested;

The amount of radiation received at the top of the atmosphere (Ra) is dependent on latitude and the time of year. Part of it is usually absorbed and scattered when passing through the atmosphere. The remaining bit, is identified as solar radiation (Rs). Therefore, R_s is dependent on R_a and the transmission through the atmosphere, which is largely dependent on cloud cover. Radiation is expressed in several units then converted to heat and further related to the energy required to evaporate water from an open water surface.

R_s can be measured directly but is frequently not available for the area of investigation. In this case, it is obtained from measured sunshine duration records as follows:

$$R_s = (0.25 + 0.50\,n/N)R_a \qquad (2.2)$$

Where n/N is the ratio between measured sunshine hours and maximum possible sunshine hours.

Data for n, can be obtained locally using the Campbell Stokes sunshine recorder. Both n and N are expressed as mean daily values, in hours. R_s is obtained in mean equivalent evaporation for the period under consideration (Masoumeh *et al.*, 2019).

2.2.3 FAO Penman-Monteith Method

This applies in areas where measured data on temperature, humidity, wind and sunshine duration or radiation are available. It determines the evapotranspiration from the hypothetical grass reference surface and provides a standard to which evapotranspiration in different periods of the year or in other regions can be compared and to which the evapotranspiration from other crops can be related. It uses mean daily climatic data; since day and night time weather conditions considerably affect the level of evapo-transpiration (Pereira *et al.*, 2015).

This method to estimate ET_0 is expressed as:

$$ET_0 = \frac{0.408\,\Delta(R_n - G) + \gamma\frac{900}{T+273}U_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (2.3)$$

Where;

ET_o reference evapotranspiration [mm day^{-1}], R_n net radiation at the crop surface [MJ m^{-2} day^{-1}], G soil heat flux density [MJ m^{-2} day^{-1}], T air temperature at 2 m height [°C], u_2 wind speed at 2 m height [m s^{-1}], e_s saturation vapour pressure [kPa], e_a actual vapour pressure [kPa], e_s - e_a saturation vapour pressure deficit [kPa], D slope vapour pressure curve [kPa °C^{-1}], g psychometric constant [kPa °C^{-1}].

Crop Evapotranspiration (ETc): This is the amount of water required by the crop during the growing season. It is usually determined by the crop coefficient approach whereby the effect of the various weather conditions are incorporated into ET_o and the crop characteristics into the Crop coefficient. It is expressed as;

$$ET_c = K_c * ET_0 \qquad (2.4)$$

2.2.4 Pan Evaporation Method

Evaporation pans provide a measurement of the integrated effect of radiation, wind, temperature, and humidity on evaporation from a specific open water surface. In the absence of rain, the amount of water evaporated during a period (mm/day) corresponds with the decrease in water depth in that period. Reflection of solar radiation from water in the shallow pan might be different from the assumed 23% for the grass reference surface. Storage of heat within the pan can be appreciable and may cause significant evaporation during the night while most crops transpire only during the daytime. There are also differences in turbulence, temperature and humidity of the air immediately above the respective surfaces. Heat transfer through the sides of the pan occurs and affects the energy balance. Notwithstanding the difference between pan-evaporation and the evapotranspiration of cropped surfaces, the use of pans to predict ET_o for periods of 10 days or longer may be warranted. The pan evaporation is related to the reference evapotranspiration by an empirically derived pan coefficient (Grismer, et al., 2002).

$$ET_0 = K_p \, E_{pan} \tag{2.5}$$

Where

ET_0 reference evapotranspiration [mm/day], K_p pan coefficient [-], E_{pan} pan evaporation [mm/day].

2.3 CWR Determination using CropWAT Model

This is a decision support system developed by the Land and Water Development Division of the FAO for calculation of reference evapotranspiration, crop water requirements and irrigation requirements. The calculations are based on soil, climate and crop data. This enhances development of irrigation schedules under various water management conditions and scheme water supply in order to evaluate rain fed production, drought effects and efficiency of irrigation practices. It uses the FAO

Penman-Monteith method for calculating reference crop evapotranspiration whose estimate is used in crop water requirements and irrigation scheduling calculations. CROPWAT calculates the irrigation water requirements per a certain period either daily or weekly or as required by cropping pattern in an irrigated area, for various stages of crop development throughout the crops growing season. The model can also be used to evaluate farmers' irrigation practices and to estimate crop performance under both rainfed and irrigated conditions. The development of irrigations schedules in the model is based on a daily soil-water balance using various user-defined options for water supply and irrigation management conditions (FAO, 2017).

Hashem et al. (2016) made an attempt to compare the ET_0 computed using a mathematical model with ET_0 estimated using CROPWAT software program. It is found to be good correlation between the two methods of computing ET_0. In this case, the ET_0 is calculated using the CROPWAT 8.0 model and its value is multiplied with crop coefficient to get the actual evapotranspiration.

Crop Coefficient (Kc): this is the ratio of the crop ET_c to the reference ET_o, and represents an integration of the effects of four primary characteristics that distinguish the crop from reference grass i: e Crop height. Albedo of the crop-soil surface, Canopy resistance, Evaporation from soil, especially exposed soil (Allen, *et al*., 1998). In developing the crop coefficients for the growing season, different stages of crop development were considered; initial stage, development stage, mid-season and late season stage. Below is a description of the behavioural changes of the crops at each stage. The figure 2.1 shows the different growth stages. Below is a description of every stage;

Initial Stage: This starts from germination and early growth when the soil surface is not or is hardly covered by the crop (groundcover less than10%).

Development Stage: This begins from the end of initial stage to attainment of effective full groundcover (groundcover approx. 70-80%).

Mid-season: This begins from attainment of effective full groundcover to time of start of maturing.

Late Season Stage: This begins from end of mid-season stage until full Maturity where harvesting is done.

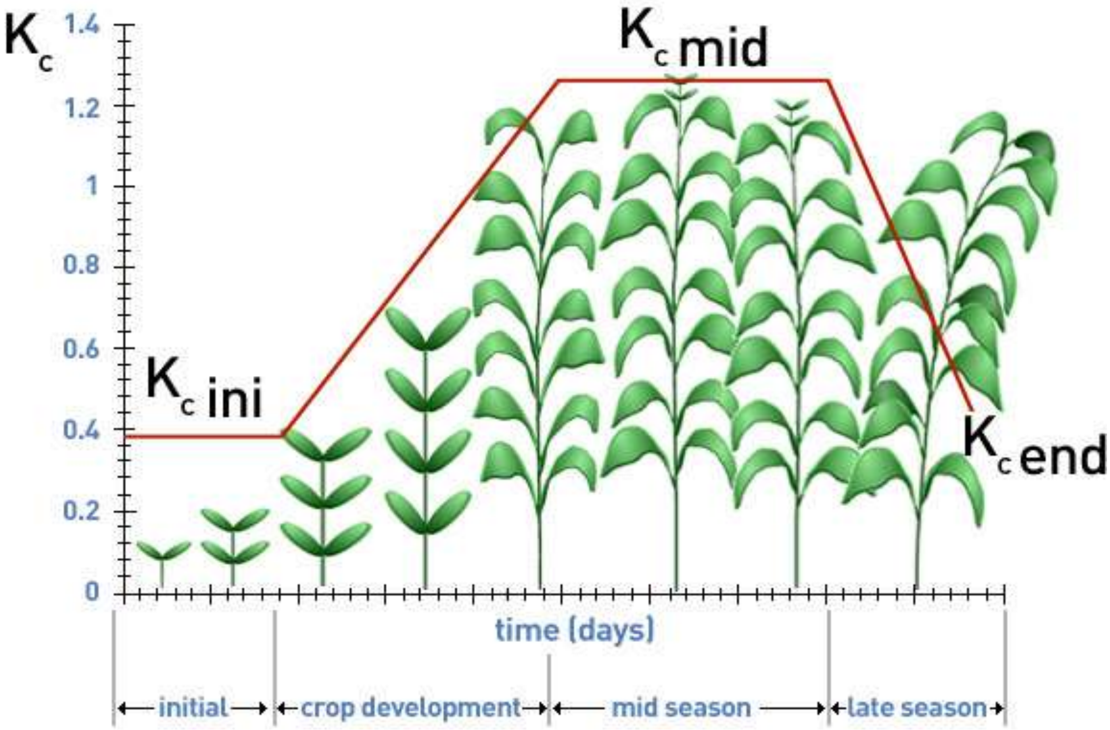


Figure 2.1: Crop Coefficient (Kc) for a General Crop

2.4 Description of Runoff Occurrence

Surface runoff is the water flow that occurs when excess rainwater or other sources flow over the Earth's surface and find their way into downstream water bodies. This occurs because the soil is saturated to full capacity, since precipitation may arrive more quickly than the soil can absorb it, or because impervious areas send their runoff to surrounding soil that cannot absorb all of it. This is common in arid areas where rainfall intensities are high but the soil infiltration capacity is reduced due to surface sealing or paved areas. This is referred to as infiltration excess overland flow. There are different processes involved in runoff occurrence as in figure 2.2. These processes are in most cases affected by climatic and physiographical factors (Bengtsson & Sept, 2004).

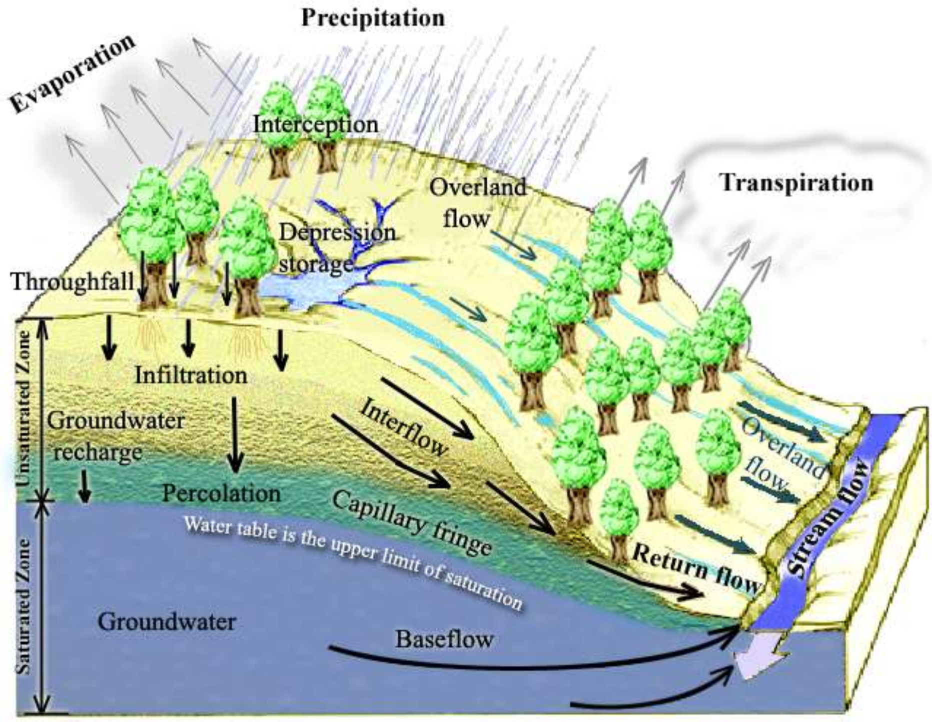


Figure 2.2. Physical Processes Involved in Runoff Generation

The occurrence and quantity of runoff are dependent on the characteristics of a rainfall event, i.e. the intensity, duration and distribution pattern of any rainfall event in a particular area. Apart from these rainfall characteristics, there are several catchment specific factors, which have a direct effect on the occurrence and volume of runoff (Rodda & Robinson, 2015). Runoff has been a growing issue for lakes and rivers all over the world. This is because as it moves, it picks up and carries away natural and human-made pollutants, finally depositing them into watersheds through lakes, rivers, wetlands. It has caused considerable land degradation in areas which are prone to erosion. This is contributed by the detachment and transport of soil by either rainwater or irrigation water through different forms of erosion and deposition downstream in water bodies (Calhoun & Seideman, 2005). Increased runoff also causes nutrient loss from agricultural fields which have become major problems environmentally and economically in Kenya and globally (Evans, 2002). This has left most agricultural fields less productive hence threatening agricultural output and the economy as well. This, in turn, contributes to low income and low livelihoods among the farmers (Mandel, 2014).

Most of the river basins in Kenya have been affected by such runoff issues since they get much of their water upstream hence leading to increased sedimentation in the river basins from their water contributing catchment. Within these water catchments areas, water resources are properly managed in terms of its quantity and quality. The water quality is affected by runoff which deposits its load into rivers (Shaver *et al.*, 2007). A good example is the Upper Tana River catchment which serves the Ndakaini Dam which is an important water resource to the Kenyan people. Decrease in water quality and quantity is contributed by the people living upstream leading to increased sedimentation in the water bodies downstream. This happens after heavy rains, which causes runoff from agricultural fields containing fertilizer and pesticides like nitrogen and phosphorus to be washed downstream, into streams, lakes, and groundwater supplies hence down to rivers. As these pollutants runoff from these fields, as a result of precipitation or uncontrolled irrigation, they find their way into rivers and streams that eventually end up in drinking water. These excess nutrients have the potential to degrade water quality. Water treatment plants have spent millions of funds in the purchase of chemicals to remove these pollutants from farms, to make it safe for human consumption (Morgan, 2004). All this has been contributed by growing rural populations in the upper catchments along with an associated rise in demand for agricultural land which has encouraged he conversion of forested areas into small-scale agricultural plots (Baker *et al.*, 2015.)

Instead of this runoff being left to cause erosion and degradation of land, it can be harvested and utilized. In the semi-arid drought-prone areas where it is already practiced, water harvesting is a direct productive form of soil and water conservation.

Both yields and reliability of production can be significantly improved with this method (Foley, 2019).

2.5.1 Factors Affecting Runoff

2.5.1.1 Rainfall

The intensity, duration and distribution of rainfall are the most common rainfall characteristics affecting the rate of runoff in a catchment. As the rain continues to fall on the ground, water reaching the ground surface infiltrates into the soil until the rate of rainfall intensity exceeds the infiltration capacity of the soil. Thereafter, surface depression storage is filled, after which runoff is generated (Singh & Sharma, 2002).

5.1.1.2 Soil Type

The integration of the soil matrix in a particular catchment area may facilitate or hinder infiltration and promote soil losses (Bot *et al.,* 2005). The infiltration capacity of a certain soil is highly dependent on the porosity of a soil which also determines the water storage capacity and affects the resistance of water to flow into deeper layers. Different types of soils with different soil profiles have different infiltration rates. The highest infiltration capacities are observed in loose, sandy soils while heavy clay or loamy soils have low infiltration capacities. The infiltration capacity also depends on the initial moisture content prevailing in the soil at the onset of a rainstorm. The initial high capacity decreases with time until it reaches a constant value when soil profile becomes saturated such that it cannot hold any more water but this is for cases of undisturbed soils. There is usually a close relationship between the intensity of a rainstorm and the breakdown of soil aggregates. High-intensity storms have considerable kinetic energy when hitting the soil surface which causes soil aggregate to break hence soil dispersion which drives fine soil particles into the upper soil pores. This results in clogging of the pores hence formation of a thin but dense and compacted layer at the surface which highly reduces the infiltration capacity. This effect, often known as capping, crusting or sealing, explains why in arid and semi-arid areas where rainstorms with high intensities are frequent, considerable quantities of surface runoff are observed even when the rainfall duration is short and the rainfall depth is comparatively small. Soils which contain a high amount of clay or loam (e.g., Loess soils with about 20% clay) are the most prone to creating a cap with therefore lower capacities of infiltration. On coarse, sandy soils the capping effect is comparatively small (Vaezi *et al.*, 2010).

2.5.1.3 Land Cover /Land Use

Before any rainfall becomes runoff, it goes through a series of phases in a given catchment. The rate of runoff in a catchment is influenced by catchment management practices. Interference with the vegetation cover due to land-use changes exposes the soil to erosion risks since when the rain falls on the soil it causes detachment and transport of soil particles. Vegetation, especially in the case of forested and vegetated areas, plays a significant role in regulating the rate of runoff since it reduces intensely the impact of raindrops on the soil by interception, the surface water volume, runoff velocity and peak discharge. The amount of rain lost to interception storage on the foliage usually depends on the kind of vegetation and its growth stage. More substantial is the effect the vegetation has on the infiltration capacity of the soil. A dense vegetation cover shields the soil from the raindrop impact and reduces the crusting effect hence reduced surface runoff. Besides, the root system as well as organic matter that drops from vegetated areas on the soil increase the soil porosity thus allowing more water to infiltrate. Again the roots of plants increase porosity hence the water infiltrates instead of being carried away. Vegetation also retards the surface flow particularly on gentle slopes, giving the water more time to infiltrate and to evaporate hence reducing a catchments contribution to runoff. In conclusion, an area densely covered with vegetation yields less runoff than bare ground (Gonzalez Barrios *et al.*, 2001).

2.5.1.4 Slope and Catchment Size in Relation to Runoff

The size, shape and location of the catchment determine the rate and quantity of runoff in a particular catchment. Generally, more rainfall on smaller area results to greater runoff but there is less runoff in larger catchments due to uniform rainfall distribution over the entire area, thus only a few tributaries of the stream feed water to the mainstream during a particular storm. Again on the same catchment, the quantity of runoff decreases with increasing slope length. This is majorly due to lower flow velocities and subsequently a longer time needed for a drop of water to reach the outlet of a catchment from the most remote location in the catchment. This means that the water is exposed for long hours to infiltration and evaporation before it reaches the measuring point. Therefore runoff efficiency defined as the volume of runoff per unit area usually increases with the decreasing size of the catchment i.e. the larger the size of the catchment the larger the time of concentration and the smaller the runoff efficiency (Al- Jabari *et al.,* 2009).

2.6 Runoff Coefficients

The runoff coefficient (C) has no dimensions and relates the amount of runoff to the amount of precipitation received in a given catchment. It is important for flood control channel construction and for possible flood zone hazard delineation. A high runoff coefficient (C) value may indicate flash flooding areas during storms as water moves fast overland on its way to a river channel or a valley floor. It is usually a larger value for areas with low infiltration and high runoff (pavement, steep gradient), and lower for permeable, well-vegetated areas (Jolley *et al.,* 2017). Apart from the factors that influence the rate of runoff from rainfall, the physical conditions of the specific catchment should be considered. This is because different catchments have different characteristics. Each catchment will, therefore, respond differently in terms of runoff to different rainstorm events. The design of any water harvesting facility requires knowledge of the runoff estimation and quantification to be produced by rainstorms in a given catchment area. It is always assumed that the quantity or volume of runoff is a percentage of the rainfall depth (Shaver *et al.,* 2007). The coefficient of runoff is measured by determining the soil type, gradient, permeability and land use of the particular catchment under consideration. The table 2.1 shows the different ranges of runoff Coefficients for each type of ground cover.

Table 2.1: Rational Method Runoff Coefficients

Ground Cover	**Runoff Coefficient, c**
Lawns	0.05 - 0.35
Forest	0.05 - 0.25
Cultivated land	0.08-0.41
Meadow	0.1 - 0.5
Parks, cemeteries	0.1 - 0.25
Unimproved areas	0.1 - 0.3
Pasture	0.12 - 0.62
Residential areas	0.3 - 0.75
Business areas	0.5 - 0.95
Industrial areas	0.5 - 0.9
Asphalt streets	0.7 - 0.95
Brick streets	0.7 - 0.85

2.7 Runoff Assessment and Modelling

Assessment of surface runoff is of great significance in areas dealing with hydrological issues. Surface runoff is a significant factor affecting the development and progress of floods, soil erosion, and other hydrological hazards (Magar & Jothiprakash, 2012). Catchment conditions will impact the proportion of rain or snow that becomes runoff. Generally, estimates of peak rate of runoff, runoff volume, and the time distribution of flow provide a basis for all planning, design, and construction of drainage facilities (UDFCD, 2007).

Research on the estimation of runoff from watersheds, catchments and other water contributing features has been intensively carried out all over the world. Several studies that have research on runoff estimation using different models include; A study by Pandey *et al.,* in 2003 estimated runoff for agricultural watershed using Soil Conservation Service – Curve Number (SCS - CN) and Geographic Information System (GIS) in Hazaribagh district of Jharkhand State where it involved various types of information related to Hydrologic soil Group, vegetation and antecedent moisture condition of the watershed. The SCS model output in this study was validated by comparing estimated runoff with measured runoff for four selected events. Another study by Asmita *et.al,* in 2014 on analysis of rainfall-runoff for an agricultural watershed area in Hinganghat District. This was meant to do a comparison of observed runoff with SCS Model, Modified SCS Model and Mockus Model. From the study, it was found out that the runoff calculated using SCS-CN model is very low as compared to the other models hence use of several catchments was recommended to increase model efficiency. From the analysis, the SCS-CN model emerged the best for this catchment area. Khopade & Oak, 2014 did research on estimation of runoff yield for Nira Deoghar Catchment using different empirical equations. In this study, rainfall-runoff studies were carried out by using various rainfall-runoff empirical formulae. During the study, an investigation of the appropriateness of 9 runoff estimation methods that are widely used in Indian hydrology was done for Nira Deoghar catchment and the models were evaluated using available rainfall-runoff relationships of the adjacent Dhom dam and downstream Veer dam. It was found out that there were significant deviations between the measured and calculated yields for the catchment. Ahmad, Verma, & Verma (2015) researched on the application of the Curve Number Method for estimation of Runoff Potential in GIS Environment. These findings show that GIS-based Curve Number method with remote sensing can be used to estimate runoff in river basins having the same hydrological characteristics. The study also revealed that the SCS-CN method with GIS can be used planning of land use issues and watershed management.

Silva and Oliveira carried out research on runoff measurement and prediction for a watershed under natural vegetation in central Brazil (Silva & Oliveira, 1999). The study involved measurement and analysis of total rainfall (P), rainfall intensity and five-day antecedent rainfall effects on runoff (R); comparison of measured and simulated runoff values using the Soil Conservation Service Curve Number method (CN) for each rainfall event: establishing average runoff/precipitation ratios for observed runoff values. The findings were that watershed physical characteristics favoured water infiltration into the soil and that CN method should be carefully used in areas where natural vegetation has grown. (Arvind, 2017) did a research study on geospatial technique for runoff estimation based on SCS-CN Method in Upper South Koel River Basin of Jharkhand in India. This study was carried out using the SCS-CN technique for run-off computation using geo-informatics. The study recommends that runoff harvesting to be done and structure construction such as farm ponds for proper water management.

In Kenya, research on runoff estimation has been carried out by different researchers. A recent study by Kimeli (2017) was carried out on the application of GIS for estimation of water runoff volume in water collection sites. In this study, estimation of floodwaters by SCS-CN method using GIS was carried out using land use map, hydrologic soil groups, daily rainfall data and digital elevation model (DEM). This study was carried out at the Northern Collector water tunnel to investigate the impact of land-use changes on the rate of runoff as well as the determination of the relationship between the amount of rainfall and the resultant runoff and applicability of SCS-CN model in Kenya. The study revealed that insignificant changes in land use results to very slow rate of runoff.

Most studies on runoff estimation are limited to runoff estimation from the entire catchment which gives the values of runoff against the available rainfall. Most of don’t consider the use of the available runoff through runoff harvesting from the specific land use in the catchment area.

2.8 Runoff Estimation Models

There are a series of methods and models that have been developed and used by most of the researchers of scientific organizations throughout the world to determine the amount of water that runs off a surface. In addition to some of the observations that are made while in the field, the use of computer models and simulations are alternatives to estimate runoff. These are useful for extrapolating the observed runoff data records by applying it on the history of rainfall data. Mathematical models are also used for modelling the real process of runoff under normal circumstances. Runoff estimation is done depending on the purpose, data availability and type of runoff result desired. Some of the methods are linear and multiple linear regression models, unit hydrograph method, rational method and hydrological models (Wagener *et al.*, 2004).

2.8.1 Rational Method

The Rational equation is a method to determine peak discharge from drainage basin runoff. It is a simple method for determination of a discharge from a small watershed. It is acceptable for drainage areas less than 100 acres when only peak flow rates are needed. This equation was developed by Kuichling in 1889 for small drainages in urban centers.

It is given by the following equation;

$$Q = CiA/360 \tag{2.6}$$

Where,

Q =Peak rate of runoff, m^3/sec;

i =Intensity of rainfall, mm/s.

C = runoff coefficient

A =Area of the catchment, m^2

Runoff coefficient (C) is usually a function of the soil type and drainage basin slope. The rainfall intensity (I) is generated from Intensity/Duration/Frequency curves for rainfall events in the geographical region of interest. The duration is equivalent to concentration time of the area of drainage. The frequency of the storm is stated by local authorities depending on the impact of the storm development. A storm frequency of 10-yr, 30-yr, 50-yr, or even 100-yr may be specified.

The assumptions made in this method include; the computed maximum rate of runoff to the design point is a function of the average rainfall rate during the time of concentration to that point, the depth of rainfall used is one that occurs from the start of the storm to the time of concentration, and the design rainfall depth during that time period is converted to the average rainfall intensity for that period and the maximum runoff rate occurs when the entire area is contributing flow. On the other hand, the limitations of the rational method are;

Despite its adequacy in the approximation of the peak flow rate and total volume of runoff from a design rainstorm in a given catchment, this method provides only one point on the runoff hydrograph. It overestimates the actual flow in complex catchment areas which results in oversizing of drainage facilities. It also provides no direct information needed to route hydrographs through the drainage facilities. The reason why the Rational Method is limited to small catchment is that good design practice requires the routing of hydrographs for larger catchments to achieve an economic design. Another limitation is that in cases of under-designed systems the rational method must be modified for it to fit for use, unlike other models which can still be used without any big errors. For example in systems designed minor storm and one wishes to analyze the effects of a major storm (UDFCD, 2007). Due to the above limitations, this method is unsuitable for this research study.

2.8.2 SCS - Curve Number Model

The SCS - CN method relates a calculated runoff curve number (CN) to runoff, accounting for initial abstraction losses and infiltration rates of soils. It is a simple empirical method for estimating the quantity of rainwater available in a given catchment for runoff (USDA, 1986). It entails the use of an empirical equation to make estimates of runoff depth that occurs after a rainfall event. The SCS -CN method, is naturally well-known for small agricultural watersheds. Analysis of storm rainfall events and runoff records indicates that there is a threshold that must be exceeded before runoff occurs. The rainstorm must satisfy interception, depression storage, and infiltration volume before the onset of runoff. The part of precipitation which is required to satisfy the above volumes is referred to as initial abstraction. Additional losses will occur as infiltration after runoff begins, whereas accumulated infiltration increases with rainfall up to some maximum retention amount. Runoff also increases with rainfall (Shadeed & Almasri, 2010).

2.9 Rainwater Harvesting

Rain water harvesting can be defined as a method for collecting, storing and conserving either local surface runoff from a catchment or water from rooftops in suitable water storage facility for agriculture. According to Athavale (2003) rainwater harvesting is the collection and storage of natural precipitation and also other activities aimed at harvesting surface and groundwater, prevention of losses through evaporation and seepage and all other hydrological studies and engineering interventions which is aimed at conservation and efficient utilization of the limited water endowment of a physiographic unit, such as watershed. All over the world, rainwater harvesting systems have been used for many years especially for the areas where the water supply has been limited by climate or infrastructure. Hygienic and dependable water supplies are significant for the industry, agriculture, and energy production. Yet the world's water systems face formidable threats. More than a billion people currently live in water-scarce regions, and as many as 3.5 billion could experience water scarcity by 2025 (Molden *et al.*, 2007). Harvesting rainwater where and when it falls presents opportunities to address water scarcity through water storage in small dams, ponds and other water conservation structures. The potential of water harvesting for improved crop production received great attention close to 40 years ago due to the impact of widespread droughts in Africa which left a track record of crop failures and hence a serious threat to human and livestock life. Consequently, several water harvesting projects were set up in Sub-Sahara Africa to address this issue (Hatibu & Mahoo, 1999).

2.10 Design of Water Storage Ponds

The basic standards of any design is to produce an acceptable functional structure at the minimum cost possible. The importance of proper designs, construction and the need for involvement of experts during the process of construction of farm ponds cannot be assumed (Pandey, *et al*., 2021).The design and construction of farm ponds require a systematic knowledge of the site conditions and requirements which includes determination of capacity, its location, utilization plan and shape and size (Stephens, 2010). Some of the features for the design area shown in figure 2.3.

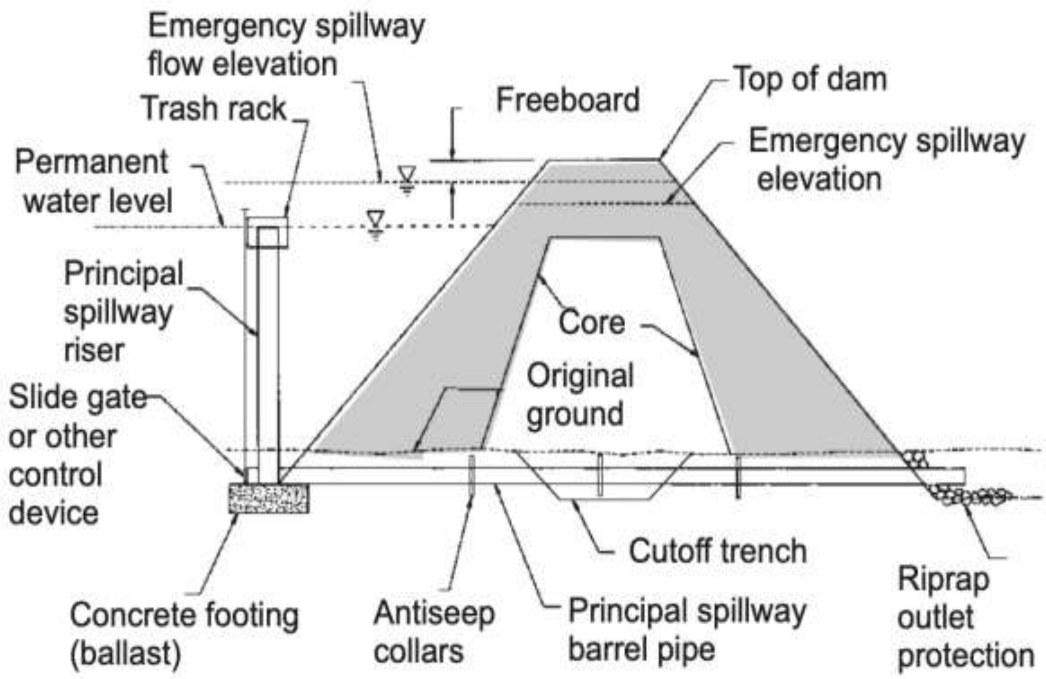


Figure 2.3: Design Features of a Farm Pond

2.10.1 Site Selection

Appropriate site selection is important, and preliminary studies are needed before finalizing the design and construction since this determines the success of any farm pond. Before any farm pond is constructed, the retention capacity of the soil on site and its fertility has to be considered since they are influential to the response of organic and inorganic fertilization round the farm pond. There should be adequate supply of water to ensure that the pond fills up. The pond construction has to be based on the topographic area where a suitable site for a farm pond should consider landscape structure and a site relationship to associated ecological functions and values. If any site is found to be feasible then one should consider numerous locations, make a keen study of each of the sites in order to decide which is the most appropriate in terms of ecological location for a long-lasting farm pond. All onsite and offsite benefits and consequences of the pond's location should also be considered (Panigrahi, 2011).

Farm pond sites should be also be free from pollution, industrial waste, domestic waste and any other harmful activities to avoid contamination since the water is to be used for crop and animal life. In selection of site for a farm pond, ecological factors should be a major consideration. (Van *et al*., 2021)

2.10.2 Determination of the Capacity of the Pond

Several methods have been adopted for determination of the capacity of farm ponds which depends on the shape either rectangular, square or round shaped. This renders most of the results obtained to be approximations since the pond side measurements are not vertical. The capacity is always calculated in cubic meters.The capacity of the pond can be determined from a contour survey of the site at which the pond is to be located. From the contour plan of the site the capacity is calculated for different stages using the trapezoidal or Simpson's rule. For this purpose, the area enclosed by each contour is measured using a planimeter (Reddy *et al*., 2012).

According to the trapezoidal rule, as discussed by Waller and Yitayew in (2016) the volume V between two contours at an interval H and having areas A_1 and A_2 is given by;

$$V = \frac{H}{2}(A_1 + A_2) \tag{2.7}$$

Using Simpson's rule the volume between any odd numbers of contours is given;

$$V = \frac{H}{3}[\text{Twice the area of odd contours} + 4(\text{area of even contours} + \text{Area of the first and last contours} \tag{2.8}$$

Where V is the volume in cubic metres representing the farm pond capacity.

2.10.3 Design of the Embankment

According to Pandey *et al.* (2021), the design of the embankment for the farm pond follows different aspects which should be put into consideration. These include; foundation conditions and cross section. The foundation of the embankment should be stable enough and resistant to any amount of water passing on its base. In addition, the subsoil conditions at the proposed site should be properly studied. The materials for the foundation should be good enough to provide both stability and imperviousness. A mixture of coarse and fine textured soils like gravel-sand-clay mixtures, gravel- sand-silt mixtures, sand-clay mixtures and sand-silt mixtures will be good foundation materials. The cross-section design usually depends on the nature of material used in the foundation as well as the fill material on site. If the material is porous, a cutoff trench should be in place to provide seepage control and should be joined up by an impervious soil stratum.

2.10.4 Provision for Seepage Control from the Bottom

Seepage control is a means of controlling the amount of water leaching through the soil. Seepage losses occur through the floor of the reservoir area, and beneath or through the embankment walls. The seepage is a function of the hydraulic head, soil properties, and the embankment design and construction techniques. To control seepage losses there are various techniques in place by different water structure designers (Panigrahi, 2011). These can be broadly categorized into; (i) reducing wetted surface area of the pond and (ii) using a cost effective sealant. Seepage-control method is usually selected depending on the combination of hydrogeological conditions, canal extension, soil filtration characteristics, size of required enhancement of losses and presence of locally available material. Accepted seepage-control measures are to be substantiated by feasibility study (Chen *et al*., 2012).

CHAPTER THREE

MATERIALS AND METHODS

3.1 Study Area

Figure 3.1 shows the study area where the research was carried out. The study focused on Maragua watershed of Murang'a County in Kenya. The watershed has an area of 420 km^2 and lies within the Upper Tana catchment and situated between 0° 37' 12" to 0° 50' 0" S latitude and 36° 42' 0" to 37° 9' 0"E longitude. Maragua watershed originates from the Aberdare ranges and flows from the west towards the East with an altitude ranging from 1191 m to 3769 m. The watershed traverses Kigumo, Kiharu, Maragua, and Kahuro sub-counties in Murang'a County (Muema *et al.*, 2018).

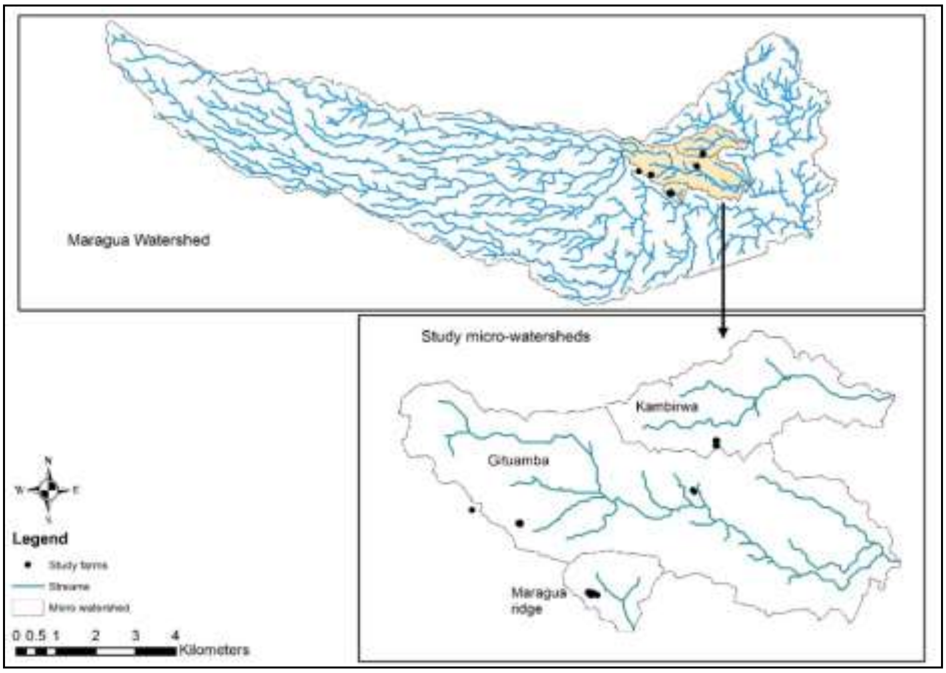


Figure 3.1: Study area: Maragua Watershed showing the Study Micro-Watersheds

Maragua watershed receives a bimodal type of rainfall. The long rains occur between March and June while the short rains occur between October and December with an average annual rainfall of 700mm-1300mm. Temperatures range from less than 10 °C in the uplands to 27 °C in the semi-humid zone. Maragua is found on the eastern part of Murang'a County and receive less rain and crop production requires irrigation. The higher part of the watershed such as the slopes of the Aberdare ranges is dominated by volcanic ash soils (Andosols). Nitosols are mainly found in the middle and lower parts of the catchment with few patches of fluvisols, cambisols and vertisols (Wilschut, 2010).

3.2 Data Collection Tools and Software

Tables 3.1 & 3.2 shows the tools and equipment, data and their sources respectively required for the study which includes; ArcGIS 10.1 software, AutoCAD 2019 and a laptop for collecting and analysis of data. DEM data of 15m x 15m resolution obtained from the United States Geological Survey (USGS) website was utilized for delineation of rivers within the watershed. The Sentinel-2A satellite imagery downloaded from the USGS website was used to prepare the land use/cover (LULC) maps of the catchment area. Soil data was obtained from analysis of samples obtained from field as well as from ISRIC website.

Table 3.1: Data Collection Equipment and their Uses

Equipment/software	**Purpose**
ArcGIS 10.1 software	Develop and create different layers and maps
Sentinel - 2A Imagery	Creating LU map of the Catchment area
AutoCAD 2019	Creating technical drawings of the farm pond
Laptop	Collecting, analysis of data and thesis writing
CropWAT	For calculation of crop water requirement

Table 3.2: Data and their Uses

Data type	Source
Precipitation data	Kenya Meteorological Department – Kangema station
Sentinel 2A Images	https://www.earthexplorer.usgs.gov/
Soil sample data	Field measurements and laboratory analysis
Aster DEM data	https://www.earthexplorer.usgs.gov

3.3 Delineation of the Study Site

Delineation was achieved using the application of ArcGIS 10.1. At first, the DEM and clip to the study area was downloaded from the USGS Earth Explorer website as a raster data (.tiff file) and at a resolution of 30m. It was then loaded in ArcGIS 10.1 and taken through the process of delineation to create watersheds as follows; using the hydrology tools in the spatial analyst tools of the Arc toolbox, the DEM was filled using the fill tool. This was followed by the flow direction tool and the filled DEM as input in order to obtain a flow direction raster. The flow accumulation tool was then used with the flow direction raster as input to obtain a flow accumulation raster. The basin tool was used to create watersheds using flow direction as input. The obtained output was converted to polygons using raster to polygon tool. The watershed was selected and clipped out. Finally, flow accumulation was used to create streams using the raster calculator.

3.4 Creating of Micro-watersheds for the Study Farms

The coordinates for the study farms were taken using a GPS Garmin and loaded into ArcGIS 10.1. A 30m x 30m resolution DEM was clipped to cover an area around the study sites and watershed delineation process repeated on a smaller scale. The output of the micro watersheds are presented in the next chapter of results and discussion. The three micro watersheds under study are Gituamba, Kambirwa and Maragua ridge.

3.5 Determination of Crop Water Requirement

The CWR was determined by use of FAO-CROPWAT model applying the appropriate procedures described by FAO (2008). Data requirements for the model included: crop data which included the respective planting and harvesting dates, Kc, growth stages, critical depletion and yield response factor. Soil data including Total Available Water (TAW), maximum infiltration rate, maximum rooting depth and initial soil moisture depletion and finally climate data which required total monthly precipitation (P) and monthly average maximum and minimum temperature, Wind speed, radiation and sunshine hours. The soil and crop data were collected from the field where the particular crops under observation were grown. Crop coefficient values (Kc) were taken from the already published data from the FAO drainage paper 56. Kc values for initial, mid and late growth stages of the specific crops under study were utilized.

In this research study, the Penman-Monteith method was used for determination of crop water requirement with CropWAT since it offers the best results with a minimum possible error of plus or minus 10 % in summer, and up to 20 % under low evaporative conditions. The Pan method can be graded next with a possible error of 15 %, depending on the location of the pan. The Radiation method, in extreme conditions, involves a possible error of up to 20 % in summer. The Blaney-Criddle method is only useful where for periods of one month; in humid, windy, mid-latitude winter condition have been considered (Allen & FAO-UN, 1998).

3.5.1 Meteorological Data

The respective meteorological data was collected from the Kenya meteorological station at Upper Tana station at Kangema in Murang'a County. The data used for ET_0 computation was minimum and maximum temperatures (^{0}C), wind speed in km per day, the relative humidity in %, sunshine hours and the physical data such as altitude, latitude and longitude. The climatic data was then adjusted into the format accepted by CROPWAT 8.0. The rainfall data collection was obtained from rainfall records of 10 years (2008 - 2018) were used to allow for a calculation of effective rainfall in the model.

3.5.2 Crop Data

The data for growth stages for the crops studied and their cropping patterns was obtained by means of a local survey conducted on the farms. The crops which were observed in the field mainly grown were tomatoes (*Solanum lycopersicum*), Sweet pepper (*Capsicum annuum)* and garden peas (*Pisum sativum*). Field observations, interviews with farmers were used to aid in the assessment of the existing cropping patterns of the crops. This was achieved by recording planting dates and carefully monitoring the different stages of development up to the harvesting date for the three selected crops. The stages monitored were initial stage, development stage, mid-season stage and late season stage. This was done by observing the changes at every stage and recorded together with the number of days taken to reach a certain growth stage. The different stages of growth are as given in figures 3.2, 3.3, 3.4, 3.5, 3.6 and 3.7 for Garden pea, tomato and sweet paper respectively.

Figure 3.2: Garden Pea in the Field at 45 Days

Figure 3.3: Garden Pea in the Field at Maturity

Figure 3.4: Tomato in the Field at 35 days

Figure 3.5: Tomato in the Field at Maturity

Figure 3.6: Sweet Pepper in the Field at 45 days

Figure 3.7: Sweet Pepper in the Field at Maturity

3.5.3 Soil Data

The data utilized on the soil characteristics was acquired through laboratory soil analysis done on the soil samples collected from the three study sites. The soil samples were collected using a soil auger. The samples were analysed at National Agricultural Research Laboratories (**NARL**) in Kabete. The analysed outputs were soil texture, bulk density, and total available water were then used as inputs into the CROPWAT 8.0 program, and saved.

a. Dry Soil Bulk Density

The dry bulk density has been estimated as follows; the soil was dried in the oven and left to cool down. The sample was then poured in to a plastic cylinder. The cylinder was then allowed to drop from a height of 5-30 cm. The volume was then read and weighed to determine the weight of the soil. The weight of the soil divided by the volume gave the bulk density.

b. Soil Texture Bouyoucos Hydrometer Method

The soil texture was determined as follows; 50g of oven-dry at 40^0 C soil sample (< 2 mm) was weighed and transferred into a 500-ml plastic shaking bottle. The 300 ml of distilled water and 50 ml of dispersion agent (calgon) were added and shaken overnight. After shaking the soil suspension was transferred into a sedimentation cylinder and toped up to the 1 L mark. It was then mixed thoroughly with a plunger to bring the soil particles into suspension. The temperature of the suspension was observed and recorded. A hydrometer was then lowered into the solution and a reading taken and recorded 40 seconds after stirring ceased. After a duration of 2 hours a second reading was taken. The first hydrometer reading gave the percentage for silt and clay. The second reading gave the density of clay particles, silt and sand calculated as in equation 3.1.

$$\%Sand = 100 - \%\ (silt\ and\ clay) \tag{3.1}$$

After getting the percentage sand, silt and clay a textural classification chart was used to classify the soil as in figure 3.8.

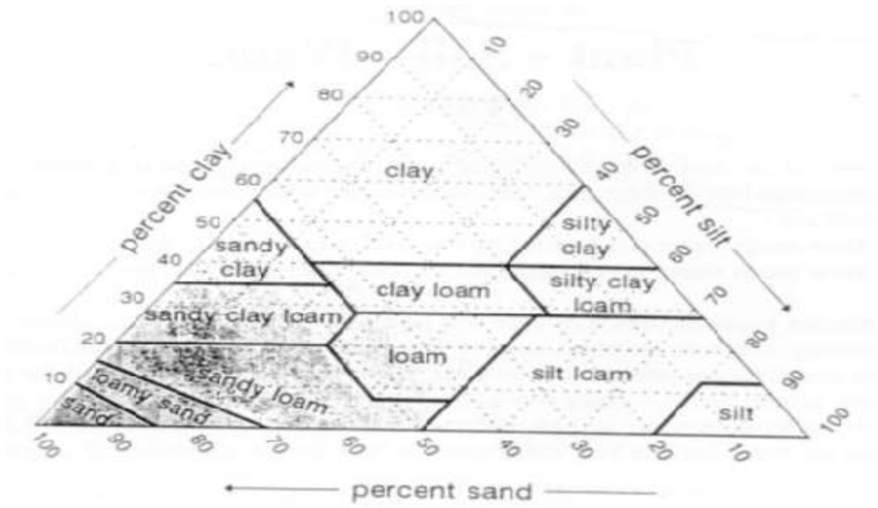


Figure 3.8: Soil Textural Classification Chart

3.6 Estimation of Runoff Depth

Runoff was estimated from selected agricultural fields using the Soil Conservation Service – curve number (SCS-CN) model which is the Curve Number Method. This method was preferred to other methods because it can be applied to catchments of different sizes up to over 100 acres. Again, it was preferred due to its simplicity and fewer demands in data requirements (Kimeli, 2017). The requirements for this method are the rainfall amount and curve number. This method was developed by the Soil Conservation Service to estimate quantities of runoff generated from rainfall based on easily obtainable catchment characteristics. The flow chart in figure 3.9 shows the step by step methodology that was used to obtain the runoff depth from raw data.

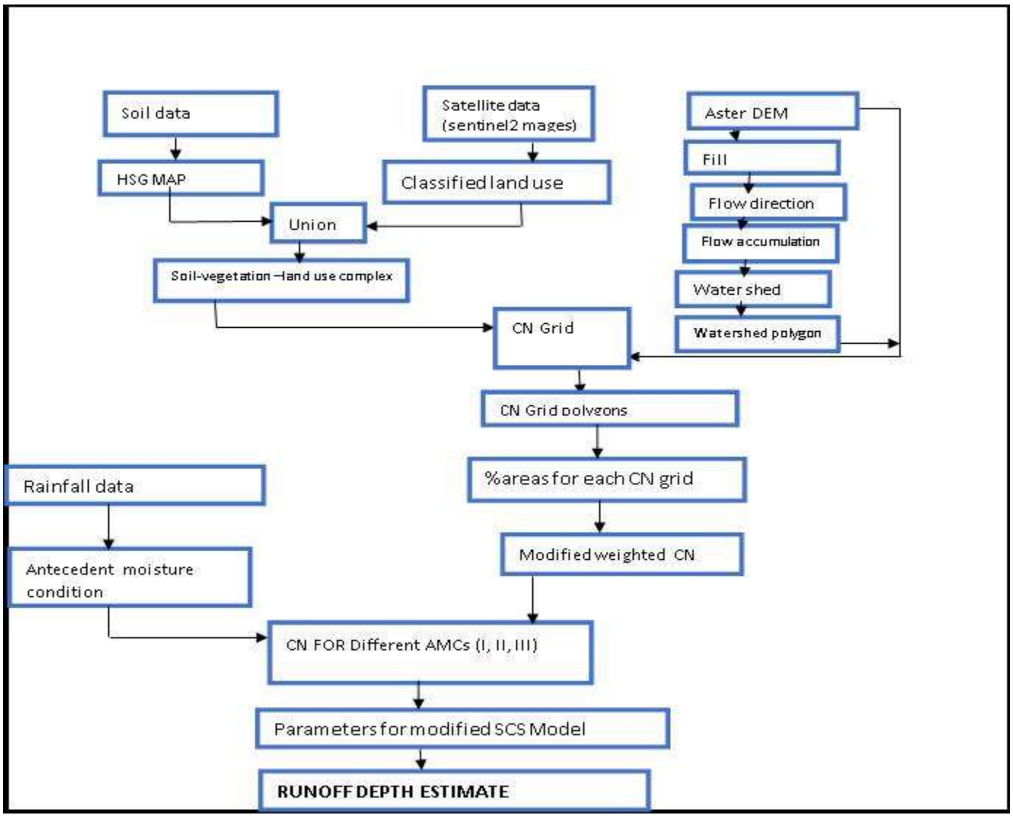


Figure 3.9: Runoff Depth using SCS-CN Method

3.6.1 Soil Conservation Service -Curve Number Method

SCS- CN model is one of the most current methods used in computation of runoff depth from a rainfall occurrence. It is a popular method since it is simple, easy to understand and apply, and stable, and accounts for most of the runoff producing watershed characteristics, such as soil type, land use, hydrologic condition, and antecedent moisture condition. The SCS-CN method was originally developed for its use on small agricultural watersheds and has since been extended and applied to rural, forest and urban watersheds. Since the inception of the method, it has been applied to a wide range of environments (Mishra & Singh, 2003; Singh, 2002). The CN model was used in obtaining the runoff depth the three study farms. The fundamental concept in this method is that the ratio of actual infiltration (F) to the potential maximum retention (S) is equal to the ratio of direct runoff (Q) to rainfall (P) minus initial abstraction (I_a). Potential runoff is equal to rainfall minus initial abstraction (Mishra and Singh, 2004). The interpretation is as below;

$$\frac{Q}{P-I_a} = \frac{F}{S} \tag{3.2}$$

$$I_{a} = \lambda S \tag{3.3}$$

In the CN method, the runoff depth (Q) is dependent on several parameters, including the amount of rainfall (P), the potential maximum soil retention (S), F the actual infiltration and the initial abstraction (I_a), λ is initial abstraction parameter.The maximum soil retention (S) is related to the physical characteristics of the soil. The curve number was determined, based on analysis of natural rainfall and runoff records, and that runoff does not begin immediately after rainfall starts, but only begins to occur after some amount of rainfall has penetrated the ground over a certain period. This delayed onset of runoff is a result of interception, infiltration, and surface storage of rainfall, and is termed the initial abstraction by the SCS. The equation used for calculating the runoff depth, Q is:

$$Q = \frac{(P - I_a)^2}{(P + I_a + S)} \tag{3.4}$$

Since I, the initial abstraction, through studies of many agricultural catchments, is approximated by empirical equations such as I_a = 0.2S (for a Kenya condition) then Eq. 3.5 becomes;

$$Q = \frac{(P - 0.2\,S)^2}{(P + 0.8S)} \tag{3.5}$$

Where,

Q = Runoff depth, mm,

P = Rainfall, mm

S = the potential maximum retention after runoff begins (millimetres)

P is a measurable quantity and can, therefore, be obtained but S is a variable that is hard to determine. Therefore variable *S*, which varies with antecedent soil moisture and other variables and can be estimated as;

$$S = \frac{25400}{CN} - 254 \tag{3.6}$$

Where CN = Curve Number

CN is a dimensionless catchment parameter ranging from 0 to 100. A CN of 100 represents a limiting condition of a perfectly impermeable catchment with zero retention, in which all rainfall becomes runoff. A CN of zero conceptually represents the other extreme, with the catchment abstracting all rainfall and with no runoff regardless of the rainfall amount (Shadeed & Almasri, 2010). The runoff curve number was calculated based on the area's hydrologic soil group, land use/land cover, and hydrological condition. The Curve number is calculated in ArcGIS through the union processing attributes combined to one of the lands and Hydrological soil groups. (Using the *Union tool* in *Arc Toolbox* available under *Analysis Tools →Overlay*. Browse the *soil clip and landuse_poly* as input features, name the output feature class as “soil_lu” in the same geodatabase, leave the default options, and click *OK).*

3.6.2 Soil Data

The soil data required included; Soil texture and soil depth to bedrock. Soil files were downloaded from the soil grids site by International Soil Reference and Information Centre (ISRIC) at a resolution of 250m. Soil texture global layers were downloaded up to a 1-meter depth. The layers were; Layer 1 at the soil surface, Layer 2 at 5cm depth, Layer 3 at 15 cm depth, Layer 4 at 30 cm depth, Later 5 at 60 cm depth, Layer 6 at 100cm depth. The layers were averaged using numerical integration methodology provided by Hengl *et al.,* (2017) to create one GIS raster layer of texture of up to a depth of 1m. The different types of soil textures were defined and classified under the different hydrologic soil groups where; **Group A** was a group of the soils of high infiltration rate and having low runoff potential when they are completely wet, **Group B** are soils with moderate infiltration rate and low runoff potential when completely wet, **Group C** are soils with low infiltration rate and moderately high runoff when completely wet and finally **Group D** have low infiltration rate and high runoff where they have low water conveyance. The output is then represented under results and discussions.

3.6.3 Land Use/ Land Cover

Satellite imagery was downloaded from earth explorer from sentinel-2. The images were merged in ArcGIS to create composite bands by merging band 2, 3, 4 and 8.

These were taken through supervised image classification using the image classification tool in ArcGIS spatial analyst extension to create a land use map with the following classes; cropland, water, built-up areas, tree cover/forests and bare areas.

3.6.4 Merging the Soil and Land Use Data

The Union tool in Arc toolbox under Analysis tools Overlay was used. The soil and land use data sets were used as inputs and the output feature was named as soil_lu. This was done for the three micro-watersheds to obtain the soil_lu unions for the three micro-watersheds which was now used to generate the curve numbers.

3.6.5 Creating CN Look-up Table

The table named "CN Look Up" was created by going through the ArcCatalog, then selecting Data Management Tools→Table→Create Table. The following fields were then created on the table;

- LU Value (type: short integer)
- Description (type: text)
- A (type: short integer)
- B (type: short integer)
- C (type: short integer)
- D (type: short integer)

The newly created table for the three sub watersheds was then edited and populated as presented in table 3.3, 3.4 and 3.5. The three tables show the soil type classification and curve number as a function of land use and hydrologic soil group.

The curve numbers for corresponding soil groups for each land use category (LU_Value) is clearly shown on the same tables which were obtained from SCS TR55 (1986).

Table 3.3: Runoff Curve Numbers for Hydrologic Cover Complex (AMC II, Ia = 0.2s), SCS TR55, 1986_Maragua Ridge Micro Watershed

Class	Treatment	Hydrologic condition	A	B	C	D
Crop land	Row crops: Contoured and crop residue cover	Poor	69	78	83	87
Built-up areas	Newly graded areas - (pervious areas only, no vegetation)		77	86	91	94

Table 3.4: Runoff Curve Numbers for Hydrologic Cover Complex (AMC II, Ia = 0.2s) SCS TR55, 1986_ Kambirwa micro watershed

Class	Treatment	Hydrologic condition	A	B	C	D
Water			100	100	100	100
Crop land	Straight row	Good	63	75	83	87
Built-up areas	Newly graded areas - (pervious areas only, no vegetation)		77	86	91	94

Table 3.5: Runoff Curve Numbers for Hydrologic Cover Complex (AMC II, Ia = 0.2s) SCS TR55, 1986_ Gituamba micro-watershed

Class	Treatment	Hydrologic condition	A	B	C	D
Crop land	Contoured and crop residue	Poor	67	78	85	89
Built-up areas	Newly graded areas - (pervious areas only, no vegetation)		77	86	91	94

3.6.6 Creating CN Grid

The HEC-GeoHMS Project View toolbar was first activated on the software. Since HEC-GeoHMS uses the merged feature class (soil_lu) and the lookup table (CNLookUp) to create the curve number grid, then format and the field names that were used in creating the CNLookUp table were made consistent with HEC-GeoHMS. A field in the merged feature class 10 (soil_lu) named "LandUse" that had land use category information to link it to CNLookUp table was created. This was done by clicking on Utility on the HEC-GeoHMS Project View toolbar then generate CNGrid.

3.7 Estimation of Runoff Depth using Parameters for SCS Model

3.7.1 Rainfall Data

The estimation of runoff requires precipitation data that is normally obtained from the Kenya Meteorological Department within the watershed. In this study, daily precipitation data that was collected within the watershed was utilized since the antecedent moisture condition of the soil can only be computed using precipitation of 5 days successively preceding a storm.

3.7.2 Runoff Depth and Antecedent Moisture Condition (AMC)

The runoff depth was estimated using the SCS_CN model where the equations 3.3 - 3.7 were utilized. This model utilize runoff producing capability which is normally expressed as a numeric value known as the Curve Number varying between 0-100. The CN values were assigned based on the AMC which represents a five – day precipitation. The potential maximum retention (S) was then computed using equation 3.7 and the initial abstraction which represents surface storage, interception by canopy and infiltration was computed using equation 3.4.

3.7.3 Runoff Volume Calculation

The runoff depth obtained above was converted to runoff volume. The area of the particular land classes under the three study farms were then multiplied by the obtained values of runoff depth to obtain the resultant volume of excess water that passes through the pour point of each of the study farms after any precipitation.

3.8 Design Guidelines for Farm Ponds

The design of the pond had the following considerations;

The water demand for crops, evaporation losses and seepage losses; silting allowance which was taken as 10 % of the storage, the size of the catchment area draining into the pond and the expected volume of runoff water from the catchment, the area available for constructing the pond and the soil type. Evaporation and seepage losses were calculated using formulas given from the practice manual from the ministry of water and irrigation (Lindqvist, 2005).

3.8.1 Design of the Water Storage Facility

The proposed farm ponds were designed to be dug out in the study area after the provision of design parameters. Figure 3.10 shows one of the farm ponds that was observed during data collection within the watershed. Among the large water storage facilities, farm ponds were chosen as opposed to dams and water pans due to the size of land for the small scale farmers. The practice manual provided by ministry of water in (2015) describes design procedures and provides minimum requirements for planning, design and construction of small dams, pans and other water conservation structures. The technical drawings were created using AutoCAD 2019 software. The key data collected include the project location, pour points of the catchment area, crops grown in the area, water sources, climatic data and soils type in each of the sites.

Figure 3.10: Types of Farm Ponds in Maragua

3.8.2 Storage Capacity

The storage capacity of the farm ponds was depended on the runoff volume with runoff from the immediate area. This was calculated from the all water demand within the area and the total losses.

For technical drawings of the storage facility, Auto CAD 2019 software was used. It included the following; shape of the pond, inlet channel cross-section, outlet channel cross-section and cross-section (pond and silt trap). The figure 3.11 gives the details of the design for the farm pond.

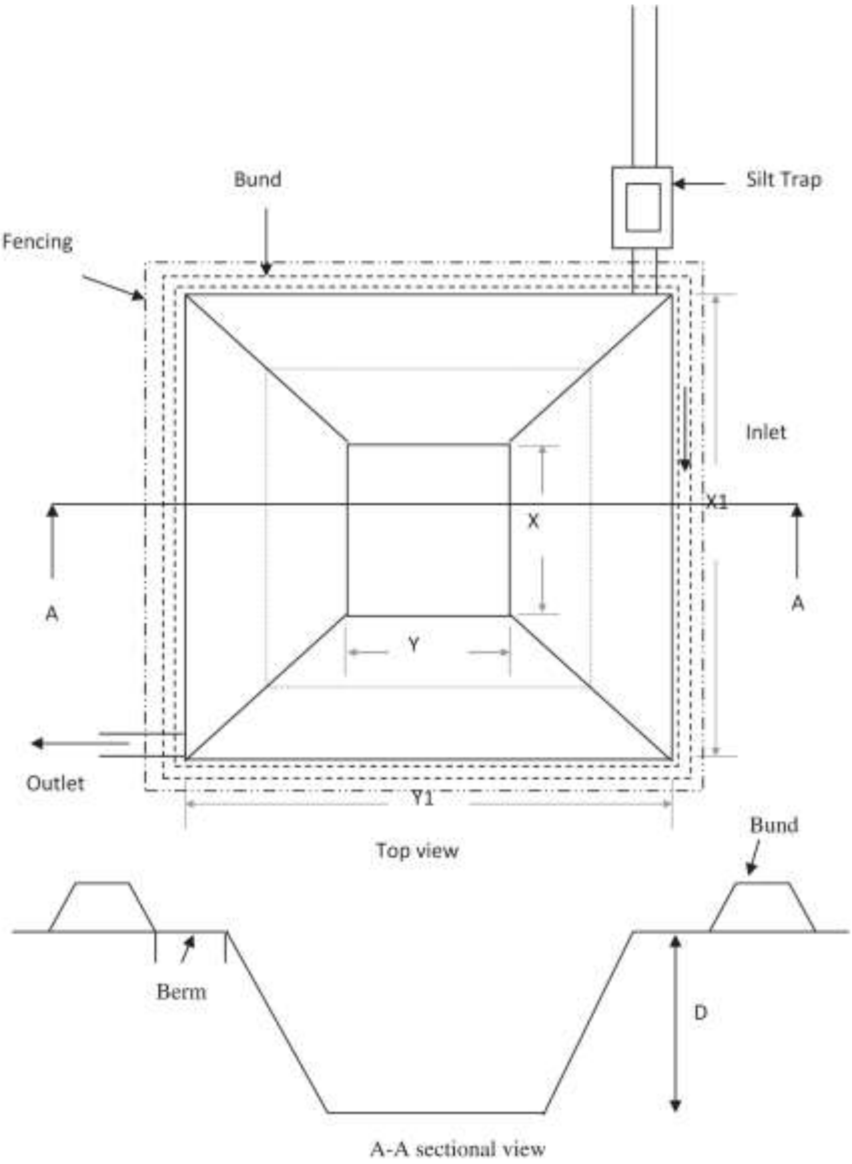


Figure 3.11: Layout of a Farm Pond (MWI, 2015)

3.8.3 Total Water Storage Requirement

The total water storage required for each farm pond was calculated on the basis of runoff obtained from catchment area. This was also based on the capacity to meet the crop water demand for the dry period even after the rains elapsed. Some of the factors taken into consideration were evaporation and seepage loss. Evaporation loss that can remove up to 2.5 m depth of water per year from an open reservoir in a hot climate, although for a good estimate of this loss, the evaporation rate in the specific location and the surface area of water must be known and seepage loss which should be estimated because reservoirs are built on different types of soil which have different degrees of seepage.

3.8.4 Shape of Pond

Excavated farm ponds are normally of three shapes, including; square, rectangular and inverted cone shapes. However, any curve shape brings a lot of difficulties in construction as well as lining, either square or rectangular ponds are normally adopted. Inverted cone ponds with circular cross section are theoretically cheaper, but difficult to construct and manage.

For the case of the study sites considered in Maragua watershed, Rectangular shaped ponds were proposed and designed to be adopted by farmers. This is because they are more economical especially if they are to be lined to reduce seepage and percolation losses (Lindqvist, 2005). Based on the pond shape, the total amount of required water was calculated, then the farm pond storage capacity that will cater for an evaporation loss and seepage loss was therefore, determined.

3.8.5 Evaporation Losses

Evaporation losses are estimated from the prospective area of the farm pond based on this equation from the practice manual for small dams (MWI (2015) which gives mmaximum daily evaporation loss estimated using Equation 3.7 as;

$$E_{vol} = Amax * E_0 * 10 \quad (3.7)$$

Where: Evol = Maximum evaporative losses [m^3/day]

Amax = Maximum pond surface area [ha]

E_O = Open water evaporation [mm/day] as defined by the average over the dry season months

3.8.6 Seepage Losses

Seepage losses are likely to occur through the floor of the area of the pond, and beneath or through the embankment. They are calculated using hydraulic head, soil properties, and embankment design and construction techniques. Table 3.6 provides hydraulic conductivity values for different soil conditions. Maximum daily seepage losses were approximated using Equation 3.8 which assumes a unit hydraulic gradient and uses the surface area rather than the wetted surface area.

Table 3.6: Hydraulic Conductivity

Soil conditions	**Hydraulic Conductivity (m/s)**	
	Lower limit	Upper limit
Permeable	$2 * 10^{-7}$	$2 * 10^{-1}$
Semi-Permeable	$1 * 10^{-11}$	$1 * 10^{-5}$
Impermeable	$1 * 10^{-11}$	$5 * 10^{-7}$

Source: Practice manual for small dams, pans and other storage structures, 2nd ed., 2015

$$S_{vol} = K * Amax * 86400 \qquad (3.8)$$

Where;

S_{vol} = Maximum seepage losses [m^3/day]

K = Hydraulic Conductivity [m/s]

A_{max} = Maximum pond surface area [ha]

3.8.7 Total Water Demand

Total water demand is the total water required to meet the water needs of the crops in the planted area. In Maragua and specifically the three study areas, the water demand was calculated as the summation of irrigation, evaporation and seepage losses in the three respective sites as shown in equation 3.9

$$TWD = IR + ET + S \tag{3.9}$$

Where,

TWD is the total amount of water required to meets the water demand

IR is the irrigation requirement

E is the demand due to evaporation

S is the water demand due to seepage loss

3.8.8 Estimation of Dead Storage

The dead storage requirement is a function of the expected volume of sediments and the need for permanent water within the reservoir, for fish keeping or other ecological factors. The dead storage forms part of the storage volumes of the reservoir. It is usually estimated as 5 % of total water demand while the storage capacity is the sum of total water demand plus the dead storage.

Dead storage = 5 % of Total water demand

This value of dead storage was added to the total water demand to get the storage capacity.

3.8.9 Spill Way Design Considerations for the Spillway

The spillway should be designed in such a way that it can safely dispose the excess water during the worst design flood without damaging the embankment structure. The determination of the spillway discharge capacity was calculated using the equation 3.10 of continuity of flow as flows;

$$Q = VA \qquad (3.10)$$

Where, Q = Flow (discharge) m^3/s

A= cross sectional area of the spillway (m^2)

V= average velocity of flow (m/s)

The above equation is used together with the Manning's formula given below.

Manning's formula;

$$V = \frac{R^{2/3} S^{1/2}}{n} \qquad (3.11)$$

Where;

V=flow

Velocity (m/s)

R=hydraulic radius (m)

S=slope (m/m)

n=Manning's roughness factor

For earth channel, flows of not over 1.5 m/sec are recommended.

i. Determination of Discharge, Q

The process of designing a spillway was done by first determining the discharge Q which was the used to inform the design of the inflow section of the spillway and outflow spillway channel dimensions and the depths of approach. This value symbolizes the peak discharge of the pond. The value is important in spillway design since a spillway of insufficient capacity will lead to overtopping of the embankment and downstream erosion, eventually causing embankment failure. Richard's method for estimating flood flows was used to provide a suitable criterion for estimating the peak discharge.

Estimation of the time of concentration was done using equation 3.12;

$$\frac{T_C^3}{T_C+1} = \frac{CL^2}{K_r * R * S * f(a)} \tag{3.12}$$

Where:

T_c = Time of concentration in hours

L = the longest path of the catchment in km obtained from google earth from the delineated micro watersheds for each of the study sites.

C = a coefficient function of (Kr. R) which can be obtained from Richards graph (obtained from figure 3.6)

K_r = Run-off factor as in table 3.12

R= Rainfall coefficient = [(t+1)] / t]. F

F = Total rainfall in mm given by Intensity [mm/hr] x storm duration (t) [hours], for the selected storm duration and frequency. Intensity is obtained from the rainfall intensity maps in figure 4.23

t = Selected storm duration

S = the average slope of the catchment

f (a) = ratio of the average (i) to the maximum rainfall intensity (I) over the catchment area, obtained from figure 3.13

a = the area of the catchment in Km^2

Table 3.7: Runoff-Factor (Kr) Values Versus the Catchment Soil Type

Catchment soil type	**K_r**
Rocky and impermeable	0.80 to 1.00
Slightly permeable, bare	0.60 to 0.80
Slightly permeable, partly cultivated or covered with vegetation	0.40 to 0.60
Cultivated, absorbent soil	0.30 to 0.40
Sandy bare soil	0.20 to 0.30
Heavy forest	0.10 to 0.20

Source: MWI, 2015

The study area for the three sites is cultivated, absorbent soil. Thus, it falls into the fourth raw of the table with a K_r value of between 0.30 to 0.40. A median value of 0.35 was used.

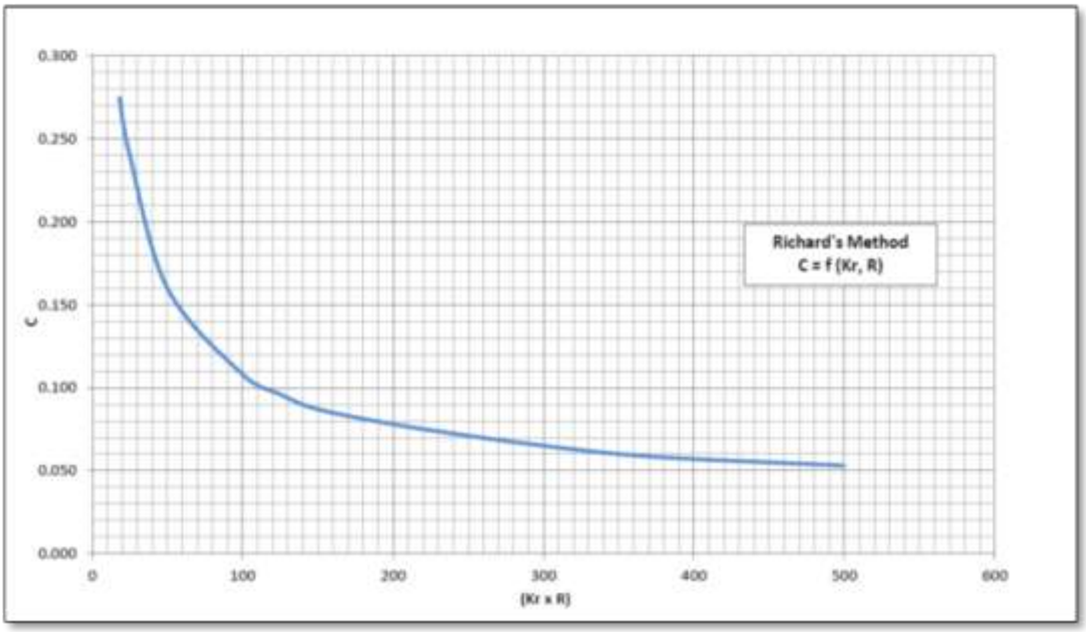


Figure 3.12: Coefficient C, Richard's Method

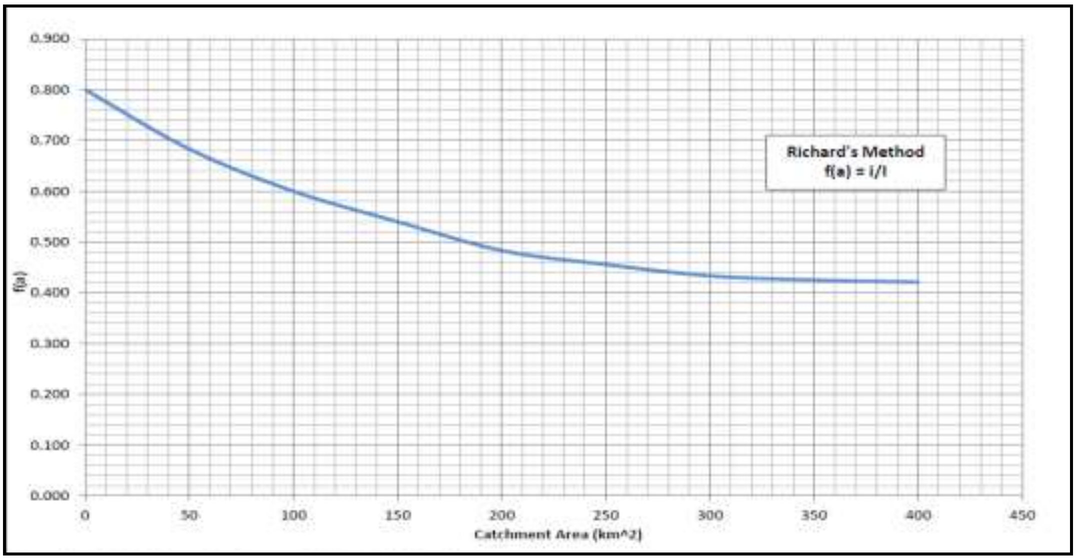


Figure 3.13: Rainfall Intensity Factor, Richard's Method

ii Inflow spillway channel

This channel leads water to the crest during flood flow, thereby ensuring that waters remain far enough from the embankment. Recommended slopes for inflow spill way channels range from 0.3 % to 1 % with a widening inflow inlet or mouth.

iii Outflow spillway channel

This is the channel that discharges waters back to the river from the farm pond overflows at acceptable velocities to prevent soil from being eroded from the sides of the pond. A velocity of 2.5 m/s is usually suitable for Kenyan conditions in instances when the outflow channel consists of excavated earth (MWI, 2015). The values of manning's coefficient was obtained from appendix 3 which was extracted from the guidelines for selecting manning's coefficient by Arcement *et al*., in 1989 for the case of the three ponds in this study area, the size of this channel was determined using manning's equation as;

$$Manning's Equation \quad V = \frac{(R)^{\frac{2}{3}} S^{\frac{1}{2}}}{n} \tag{3.12}$$

Where,

V= velocity

S= slope

R= Hydraulic radius

n= manning's coefficient depends on the material of floor

Manning's coefficients were obtained from the appendix 3.

After all manning's coefficient and velocity of flow was known, iteration exercises were then performed to determine the adequate velocity of flow and the corresponding dimensions of the channel.

3.8.10 Slopes

The table 3.8 shows the values of slopes which were taken as the ratio of horizontal versus vertical height of the farm pond. The values of slope correspond to a particular soil type. For each of the soil types in the three sites a value of slope was recommended. These were used for design of slopes for the farm pond.

Table 3.8: Suitable Slope for Different Soil Types

Soil type	Slope (Horizontal : vertical)
Clay	1:1 to 2:1
Clay loam	1.5:1to 2:1
Sandy loam	2:1to 2.5:1
Sandy	3:1

Source: FAO, 2011

CHAPTER FOUR

RESULTS AND DISCUSSION.

4.1 Crop Water Requirement

4.1.1 Crop Data

The crops under observation during the study period were garden pea (*Pisum sativum*), sweet pepper (*Capsicum annuum*) and tomato (*Lycopersicum esculentum*). The various lengths of growth stages are shown in the Table 4.1. The length of the growing season depends on rainfall, evaporation and temperature, soil factors and crop factors (Mohanty, 2015). Among the crops under study, sweet pepper took the longest time of 115 days from planting date to harvest, tomato took 100 days and garden pea took 90 days. The crops were observed under four stages of growth, namely; Initial, development, mid-season and late season stages. For tomatoes, a proper watering system in order to grow and provide optimal yields. The factors that must be considered in watering the tomatoes are soil moisture and air temperature. The soil moisture needed for planting tomatoes is between 60% to 80% with a temperature rate between 24 to 28 ^{0}C (Ma Y, *et al.*, 2016). For garden pea, best yields and quality are achieved in cool and moist growing conditions. They grow reasonably well between 10 and 30°C with an optimum of 20°C. Temperatures above 30°C will cause poor pollination, early maturity and lower yields. Sweet peppers can tolerate daytime temperatures over 30°C, as long as night temperatures are within 21–24°C. Sweet peppers are photoperiod and humidity-insensitive (daylength and relative humidity do not affect flowering or fruit set). Sweet pepper grows best in a loam or silty-loam soil with good water-holding capacity. But they can grow on many soil types, as long as the soil is well drained. Soil pH should be between 5.5 and 6.8 (Gora *et al.*, 2019*)*

Table 4.1: Actual Lengths of Crop Developmental Growth Stages for the Three Crops in the Study

Crop	Crop growth periods (days)				
	Total growing season (days)	Init. (L_{ini})	Dev. (L_{dev})	Mid (L_{mid})	Late (L_{late})
Garden pea (*Pisum sativum*)	90	15	25	35	15
Sweet pepper (*Capsicum annuum*	115	20	35	40	20
Tomato (*Lycopersicum sculentum*)	100	20	25	30	25

Source: Observation from study areas

4.1.2 Climatic Data

The climatic data and the reference evapotranspiration for the three crops are presented in Table 4.2 and Table 4.3. The total ET_o on average was 3.84 mm for Kambirwa and 3.85 mm/day for Gituamba and Maragua ridge, while total wind speed was 103 km for all sites. For Gituamba and Maragua ridge the climatic factors were almost similar since the attitude was nearly at the same level at 1340.7 and 1351.6 metres respectively. The average sunshine hours were 6.7. This meant that the sky was cloudy at most times of the day in all sites. The minimum and maximum temperatures were 11.7 °C and 28 °C which was ideal for optimal growth of all the crops studied under the prevailing rainfall and other climatic factors. The two tables (4.2 and 4.3) also show the total effective annual rainfall of the study areas which was 842.6mm. This was estimated as 69.9 per cent of the rainfall i.e. 842.6 mm per annum out of the total average annual rainfall 1204.1 mm and the losses estimated as 30 per cent of rainfalls in the study area. The effective precipitation was high in November and April, the time the growing season commences for the short rains and Long rains respectively. This effective rainfall decreased to 52.6 mm in January and at harvest in March, rainfall increased to 74.9 mm. Excess rain is not conducive to maturity as it damages the crop. FAO-AGL. (2002) indicated crop damage would occur due to excess rainfall. The three horticultural crops under study in this area, requires a relatively cool, dry climate for high yield and premium quality though it is adapted to a wide range of climatic conditions from temperate to hot and humid tropical (Njonga, 2009)

Table 4.2: Climate Characteristics, Rainfalls, and Et_0 of Kambirwa in Maragua Watershed

Month	Min Temp °C	Max Temp °C	Humidity%	Wind km/day	Sun hours	Rad MJ/m²/day	ETo mm/day	Rain mm	Eff Rain mm
January	11.2	28.5	71	116	9.7	23.5	4.51	58	52.6
February	11.4	30	62	142	9.5	24.1	5.06	71	62.9
March	12.2	30.2	57	105	7.2	20.8	4.55	87	74.9
April	12.6	28.6	72	111	6.7	19.5	4.06	294	154.4
May	12.2	27.4	84	61	5.7	17	3.28	135	105.8
June	11.2	26.4	83	45	5.8	16.6	3.07	4.2	4.2
July	10.7	25.2	72	58	3.8	14	2.76	8.3	8.2
August	10.5	25.4	67	64	4.2	15.2	3.02	8.1	8
September	10.8	27.7	66	109	6.1	18.8	3.89	30.1	28.7
October	11.9	29.1	75	142	7.4	20.7	4.27	62.1	55.9
November	13.7	29.4	82	115	6.5	18.8	3.85	221.2	142.9
December	11.6	27.6	85	168	7.2	19.5	3.8	225.1	144
Total								1204.1	
Average	11.7	28	73	103	6.7	19	3.84		842.6

Table 4.3. Climate Characteristics, Rainfalls, And ET_0 of Gituamba and Maragua Ridge in Maragua Watershed

Month	Min Temp°C	Max Temp°C	Humidity %	Wind km/day	Sun hours	Rad MJ/m²/day	ETo mm/day	Rain mm	Eff rain mm
January	11.2	28.5	71	116	9.7	23.8	4.59	58	52.6
February	11.4	30	62	142	9.5	24.2	5.1	71	62.9
March	12.2	30.2	57	105	7.2	20.8	4.56	87	74.9
April	12.6	28.6	72	111	6.7	19.4	4.04	294	154.4
May	12.2	27.4	84	61	5.7	16.8	3.24	135	105.8
June	11.2	26.4	83	45	5.8	16.3	3.02	4.2	4.2
July	10.7	25.2	72	58	3.8	13.8	2.72	8.3	8.2
August	10.5	25.4	67	64	4.2	15.1	2.99	8.1	8
September	10.8	27.7	66	109	6.1	18.7	3.89	30.1	28.7
October	11.9	29.1	75	142	7.4	20.9	4.31	62.1	55.9
November	13.7	29.4	82	115	6.5	19	3.91	221.2	142.9
December	11.6	27.6	85	168	7.2	19.8	3.86	225.1	144
Total								1204.1	842.6
Average	11.7	28	73	103	6.7	19.1	3.85		

4.1.3 Crop Water Requirement of Garden Pea, Sweet Pepper and Tomatoes

The crop water requirements and crop evapotranspiration are closely linked to each other since the water lost through evapotranspiration is the water replaced to the plant to cater for its growth up to maturity. The difference between them is that crop evapotranspiration represents the water losses that occur, while the crop water requirement indicates the amount of water that should be supplied accounting for the water losses. In fact, this amount of water corresponds to the effective irrigation water supply to a certain crop in order to reach the maximum yield. Crop water requirement is a given amount of water lost due to crop evapotranspiration (ETc). The tables 4.4, 4.5 and 4.6 show the crop water requirement and the irrigation requirement of the three different crops during the study period. From the results, Kc at initial stage was the lowest, and began to increase at the development stage then was highest at late season stage and then began to decrease at the late season stage. The Kc at this initial stage was lower as compared with the other stages since this was just at initial stage of canopy formation so there was much water required for use during the crop initial stages of growth. This is explained by the fact that when atmospheric evaporation demand is on the higher side, the higher the rate at which soil dries and therefore the crop coefficient is low (Burdack, 2014). ET_c is seen to be low at the initial stage of growth cutting across all crops. The ETc begins to rise at the development stage and maintains the high levels at the mid-season stage and goes down at the late season stage. The high ETc in development and mid-season stage is explained by effective full groundcover approx. 70-80% and also rapid growth and therefore requires a lot of water since it is the time the ground is shaded and transpiration is more than evaporation in the plant due to increased canopy. The late season stage has lower values of both Kc and ETc since the crops begin to shed their leaves leading to less ground cover, hence less water requirements. The ETc values for the garden pea, sweet pepper and tomato were 395.6, 460.1 and 432.7 mm per the growing season respectively which is within the range provided by FAO, 2008 (Appendix 5). The irrigation requirements were 181.4, 216.6 and 187 mm per season for garden pea, tomato, and sweet pepper respectively. The results indicate increasing ETc throughout the growth stages which is high at the mid-season stage and starts to decrease slightly at the later stages. Generally, the ETc varied significantly throughout the development cycle of the crops majorly due to the prevailing climatic conditions and the development of the crop during the growth stages. The dominant factors affecting evapotranspiration are solar thermal radiation and temperature, relative humidity and the wind, and in general, the magnitude of evapotranspiration will increase as temperature, solar thermal radiation, humidity, and wind speed grow larger. The effect of solar Thermal radiation on evapotranspiration is through the process of photosynthesis. The growth cycle of the plant normally requires the circulation of water through the root-stem-leaf system. The circulation of the water travel from the roots to the leaves and accelerates with an increasing amount of solar thermal radiation to the vegetation concerned. The effect of temperature on evapotranspiration can be said to be directly related to the intensity and duration of solar radiation. (Kang *et al.*, 2018), (Banik & Raman, 2014). However, further research is needed that the temperature that will affect the evapotranspiration is the leaf temperature and not the air temperature around the leaves.

The largest crop water requirement occurs in the midseason and part of late season phase. While the lowest water demand value occurs in the initial stage because at this time the plants have not formed canopy to enhance transpiration. The late season stage also has a low crop water requirement since crops are mature so water is not much needed. The plants need the most water when it occurs in the process of forming the fruit as requires more energy to make fruit formation in the phase towards the late-season. The value of water demand is reduced because of the process of fruit ripening. The growth of the crop has been maximized so that no longer develop the growth process and approaching the harvest phase ().

Table 4.4: Crop Water Requirement (ETc) for Garden Pea in Kambirwa

Month	Decade	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	2	Init	0.5	2.29	2.3	1.3	2.3
Jan	3	Init	0.5	2.38	26.1	15.5	10.6
Feb	1	Deve	0.57	2.86	28.6	19.8	8.9
Feb	2	Deve	0.83	4.32	43.2	20.9	22.2
Feb	3	Deve	1.07	5.32	42.6	22.3	20.3
Mar	1	Mid	1.16	5.5	55	21.5	33.5
Mar	2	Mid	1.16	5.29	52.9	21.8	31.1
Mar	3	Mid	1.16	5.08	55.9	31.7	24.3
Apr	1	Late	1.15	4.85	48.5	46.7	1.8
Apr	2	Late	1.12	4.5	40.5	51.8	0
					395.6	253.1	142.5

Table 4.5: Crop Water Requirement for Tomato in Maragua Ridge

Month	Decade	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	2	Init	0.6	2.75	24.8	11.5	12
Jan	3	Init	0.6	2.86	31.4	15.5	15.9
Feb	1	Deve	0.72	3.62	36.2	19.8	16.4
Feb	2	Deve	0.95	4.94	49.4	20.9	28.5
Feb	3	Mid	1.14	5.66	45.3	22.3	23
Mar	1	Mid	1.16	5.52	55.2	21.5	33.7
Mar	2	Mid	1.16	5.31	53.1	21.8	31.3
Mar	3	Late	1.15	5.05	55.5	31.7	23.8
Apr	1	Late	1.03	4.32	43.2	46.7	0
Apr	2	Late	0.88	3.56	35.6	57.5	0
Apr	3	Late	0.8	3.03	3	5	3
					432.7	274.1	158.6

Table 4.6: Crop Water Requirement for Sweet Pepper in Gituamba

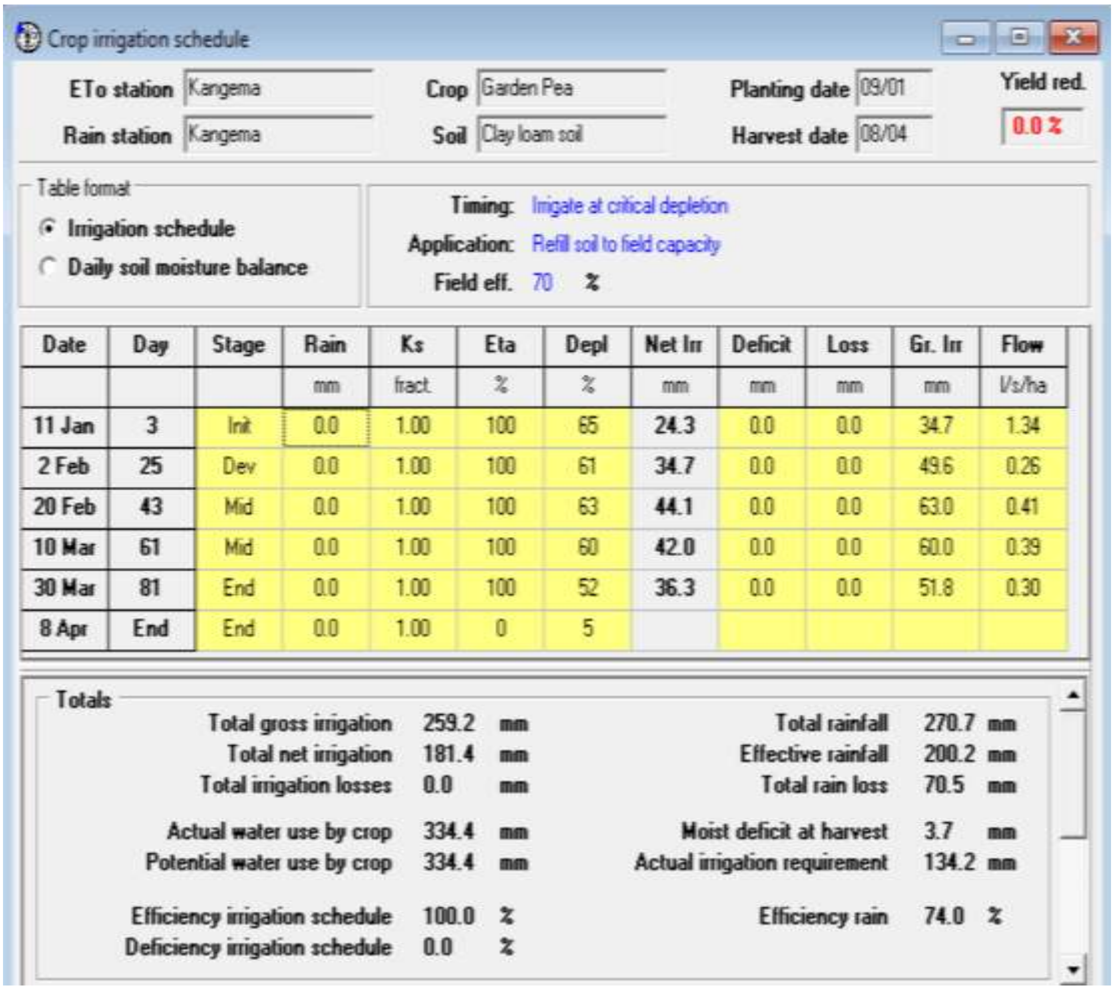
Month	Decade	Stage	Kc coeff	ETc mm/day	ETc mm/dec	Eff rain mm/dec	Irr. Req. mm/dec
Jan	1	Init	0.6	2.61	2.6	2.4	2.6
Jan	2	Init	0.6	2.75	27.5	12.7	14.8
Jan	3	Deve	0.6	2.87	31.6	15.5	16.1
Feb	1	Deve	0.7	3.48	34.8	19.8	15
Feb	2	Deve	0.82	4.29	42.9	20.9	22
Feb	3	Deve	0.94	4.7	37.6	22.3	15.3
Mar	1	Mid	1.04	4.92	49.2	21.5	27.7
Mar	2	Mid	1.05	4.79	47.9	21.8	26.1
Mar	3	Mid	1.05	4.61	50.7	31.7	19
Apr	1	Mid	1.05	4.43	44.3	46.7	0
Apr	2	Late	1.03	4.18	41.8	57.5	0
Apr	3	Late	0.96	3.64	36.4	50.1	0
May	1	Late	0.91	3.19	12.8	16.9	0
					460.1	339.8	120.3

Init = initial; Deve = development; Mid = Mid-season; Late = Late season stage; Eff = effective rain, Irr. Req = irrigation requirements, Kc = crop coefficient, ETc = crop evapotranspiration

4.14 Net Irrigation Requirement (NIR) and Irrigation Schedule.

In order to improve irrigation water management in the field the knowledge of irrigation water requirements and irrigation time scheduling is key. The CROPWAT model provides agriculturists with the opportunity to design an indicative irrigation schedule and evaluate field irrigation program in terms of efficiency of water use and yield reduction and Simulate field irrigation program under water deficiency conditions, rain-fed conditions, and supplementary irrigation. Irrigation water management is simply monitoring the amount, timing, and rate of irrigation in an effective and strategic manner to minimize wastage of water or over irrigating the crops (FAO_UN, 2018). Figures 4.1, 4.2 & 4.3 illustrate the field crop irrigation schedules for the garden pea, tomato and sweet pepper grown in the respective study areas. The total gross irrigation and net irrigation for garden pea are 259.2 mm and 181.4 mm with six irrigation schedules, 309.4 mm and 216.6 mm for tomato with six irrigation schedules and 262.2 mm and 187.0 mm for sweet pepper with five irrigation schedules.

This figures obtained for gross irrigation and net irrigation corresponds to values in FAO guidelines for crop water requirement and irrigation requirement and also conforms to the soil types and the rainfall as per the conditions given in the guidelines.

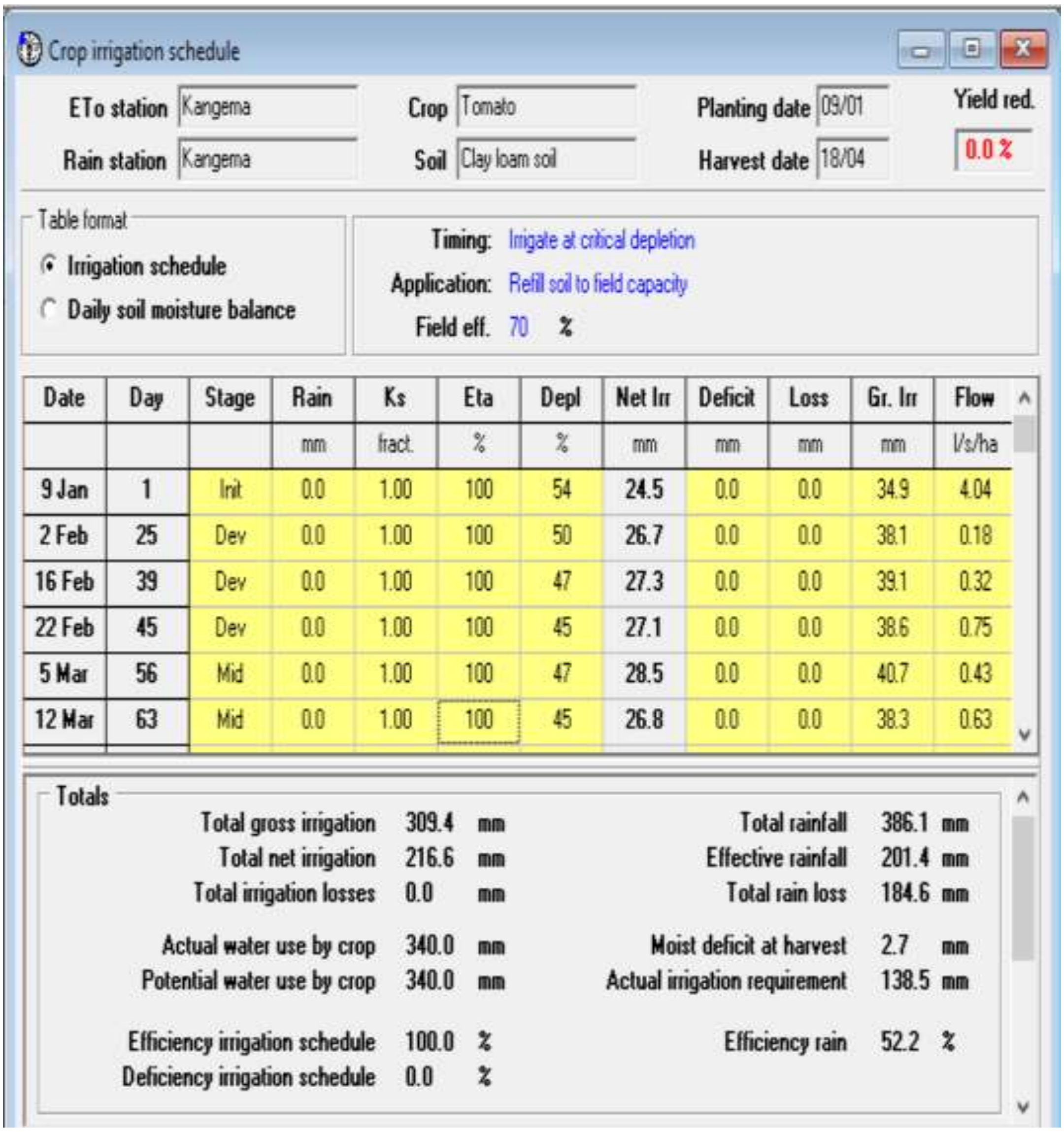


Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
11 Jan	3	Init	0.0	1.00	100	65	24.3	0.0	0.0	34.7	1.34
2 Feb	25	Dev	0.0	1.00	100	61	34.7	0.0	0.0	49.6	0.26
20 Feb	43	Mid	0.0	1.00	100	63	44.1	0.0	0.0	63.0	0.41
10 Mar	61	Mid	0.0	1.00	100	60	42.0	0.0	0.0	60.0	0.39
30 Mar	81	End	0.0	1.00	100	52	36.3	0.0	0.0	51.8	0.30
8 Apr	End	End	0.0	1.00	0	5					

Totals

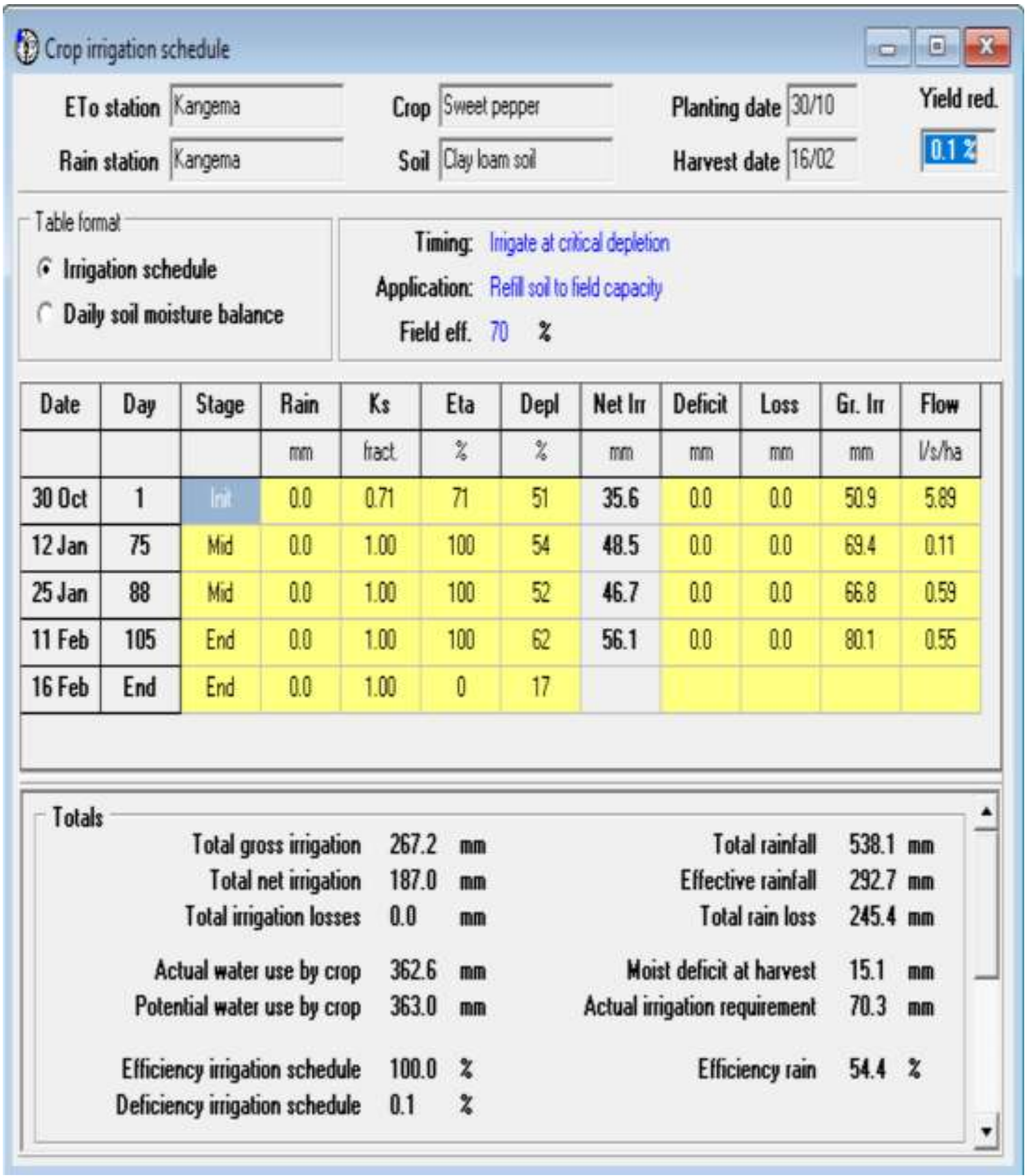
Total gross irrigation	259.2	mm	Total rainfall	270.7	mm
Total net irrigation	181.4	mm	Effective rainfall	200.2	mm
Total irrigation losses	0.0	mm	Total rain loss	70.5	mm
Actual water use by crop	334.4	mm	Moist deficit at harvest	3.7	mm
Potential water use by crop	334.4	mm	Actual irrigation requirement	134.2	mm
Efficiency irrigation schedule	100.0	%	Efficiency rain	74.0	%
Deficiency irrigation schedule	0.0	%			

Figure 4.1: Field Crop Water Schedules for Garden Pea



Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
9 Jan	1	Init	0.0	1.00	100	54	24.5	0.0	0.0	34.9	4.04
2 Feb	25	Dev	0.0	1.00	100	50	26.7	0.0	0.0	38.1	0.18
16 Feb	39	Dev	0.0	1.00	100	47	27.3	0.0	0.0	39.1	0.32
22 Feb	45	Dev	0.0	1.00	100	45	27.1	0.0	0.0	38.6	0.75
5 Mar	56	Mid	0.0	1.00	100	47	28.5	0.0	0.0	40.7	0.43
12 Mar	63	Mid	0.0	1.00	100	45	26.8	0.0	0.0	38.3	0.63

Figure 4.2: Field Crop Water Schedules for Tomato



Date	Day	Stage	Rain	Ks	Eta	Depl	Net Irr	Deficit	Loss	Gr. Irr	Flow
			mm	fract.	%	%	mm	mm	mm	mm	l/s/ha
30 Oct	1	Init	0.0	0.71	71	51	35.6	0.0	0.0	50.9	5.89
12 Jan	75	Mid	0.0	1.00	100	54	48.5	0.0	0.0	69.4	0.11
25 Jan	88	Mid	0.0	1.00	100	52	46.7	0.0	0.0	66.8	0.59
11 Feb	105	End	0.0	1.00	100	62	56.1	0.0	0.0	80.1	0.55
16 Feb	End	End	0.0	1.00	0	17					

Figure 4.3: Field Crop Water Schedules for Sweet Pepper

4.2 Runoff Estimation

4.2.1 Watershed Delineation

The figure 4.4 shows the output of the delineated watershed of the study areas.

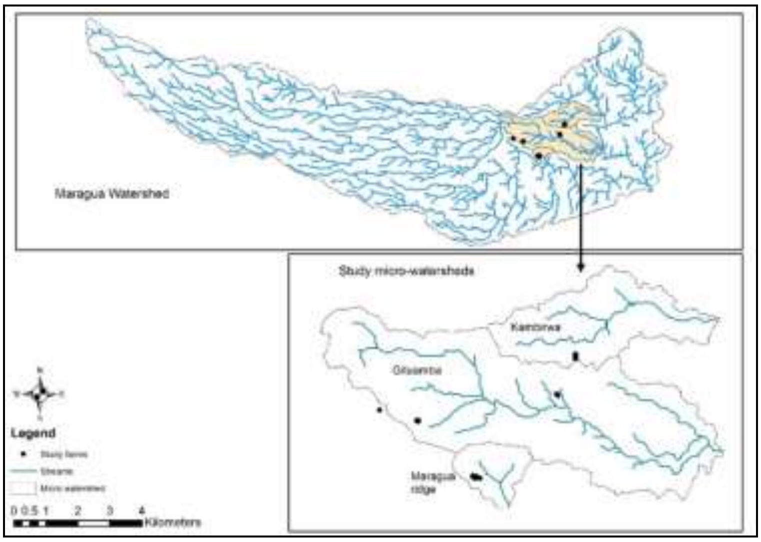


Figure 4.4: A Map of Micro-Watersheds Representing the Study Farms

After delineating the watershed, a working boundary was created as a shape file in ArcGIS covering the watershed and areas around. This was to ensure that the data created covered all the study sites.

4.2.2 Soil Data

The soil data required included; Soil texture and soil depth to bedrock. All these files were downloaded from the soil grids site by ISRIC at a resolution of 250m.

4.2.1.1 Soil Texture

The figure 4.5 and 4.6 shows the different soil textures covering the Maragua watershed. The results indicate that soils of clay loam texture dominated the study area on the upper area falling under hydrologic soil group D while sandy clay loam dominated the lower areas which falls under Hydrologic soil group C as shown in the table 4.7. Pure clay soils were highly dominant taking a good percentage of the Maragua watershed.

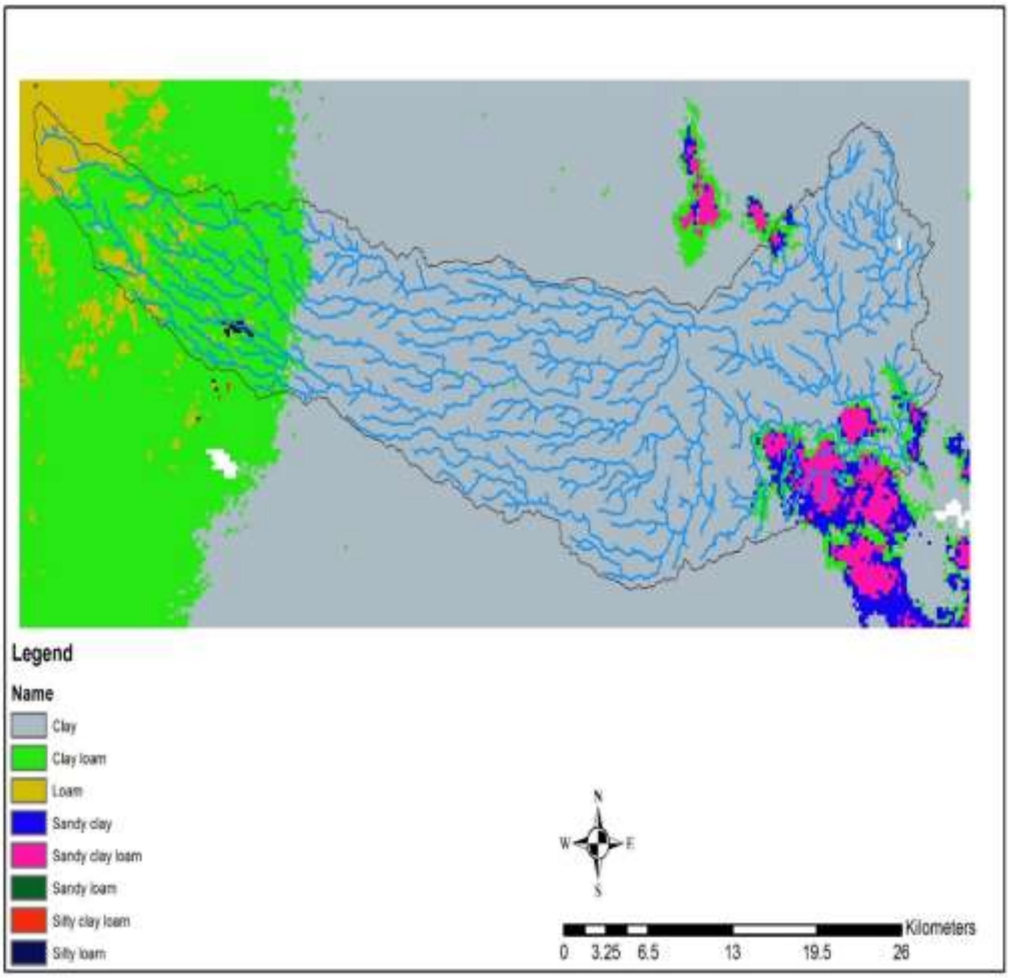


Figure 4.5: A map showing the Different Soils Textures within Maragua Watershed

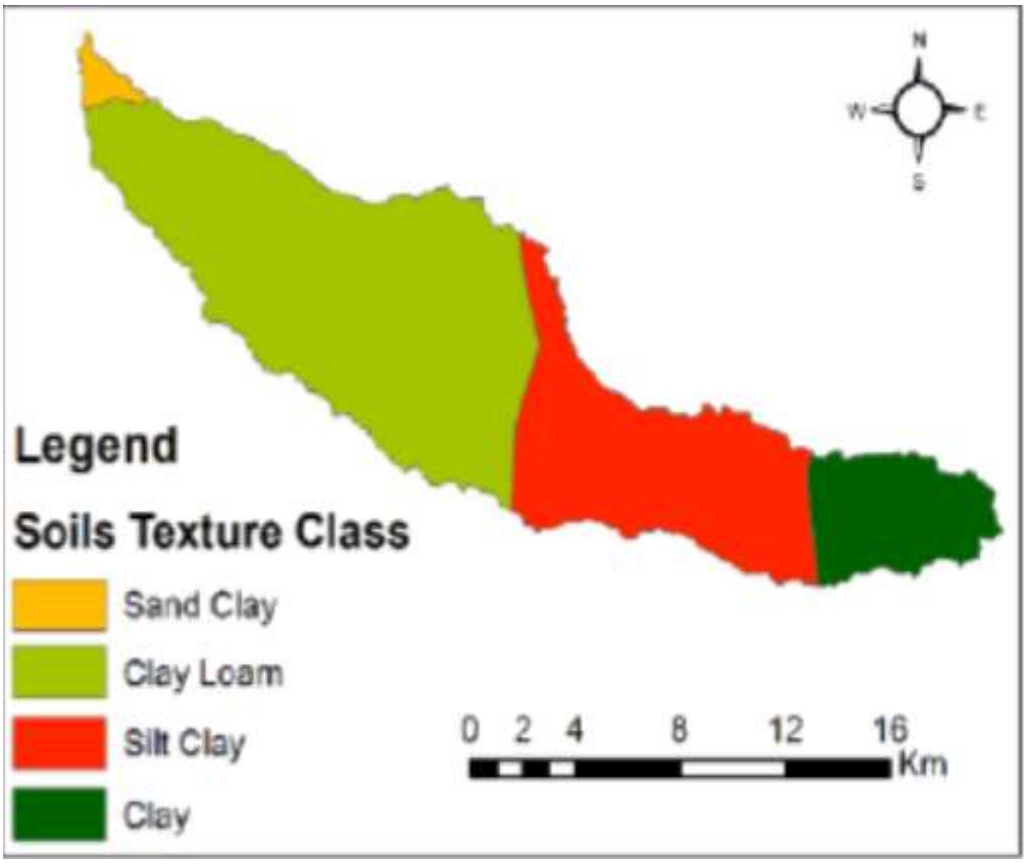


Figure 4.6: A Map Showing the Different Soils Textures within Maragua watershed

Table 4.7: Hydrological Soil Groups Showing Infiltration Rates within the Maragua Watershed

Soil	Infiltration rate (mm/hr)	HSG
Clay	1-5	D
Clay loam	5-10	D
Sandy clay loam	20-30	C
Silt loam	15-20	C
Sandy clay	20-30	C
Silt clay loam	10-15	C

4.3 Soil Depth to Bedrock

Absolute soil depth to bedrock in cm was downloaded from the ISRIC website and clipped to the working boundary. The results are as shown in figure 4.7.

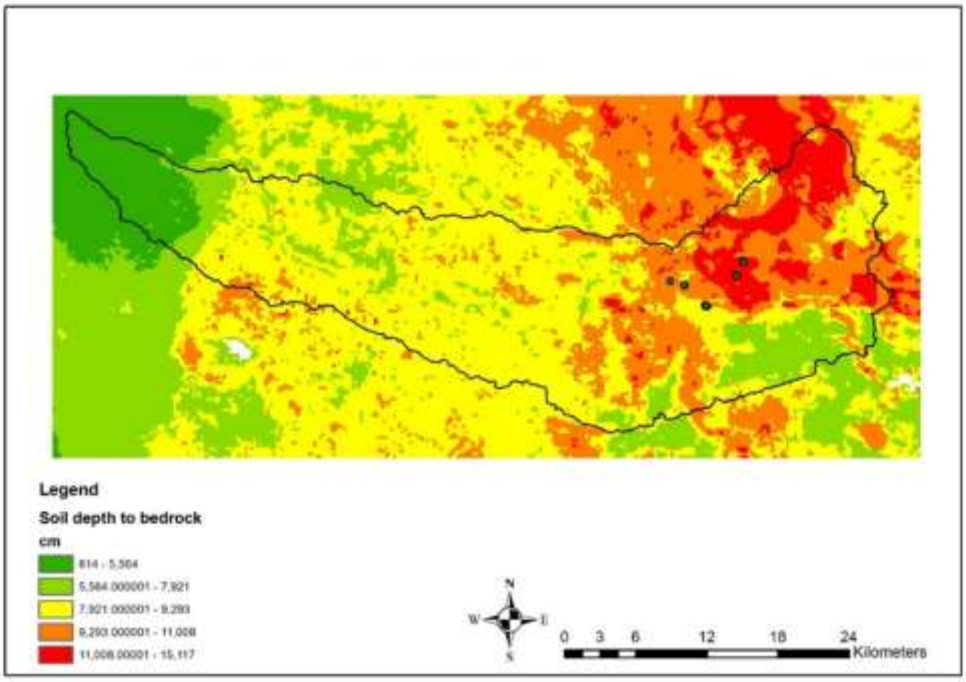


Figure 4.7: A Map Showing the Layers of Soil Depth to Bedrock

4.4 Land Use Cover Map

The figure 4.8 shows the different land use land cover types that were as a result of image classification. From the results in Figure 4.8, the area was dominated by cropland. On the micro watersheds which represent the areas under study, there were only three land cover types including built-up areas, cropland and water. Of the three, the crop land dominated the larger part of the study area with an area of 48.8061 km^2, built-up areas with 3.4272 km^2 and water with the least area occupying 0.0027 km^2. The table 4.8 shows the specific areas covered by the different land cover types within the Maragua watershed and the three micro-watersheds respectively.

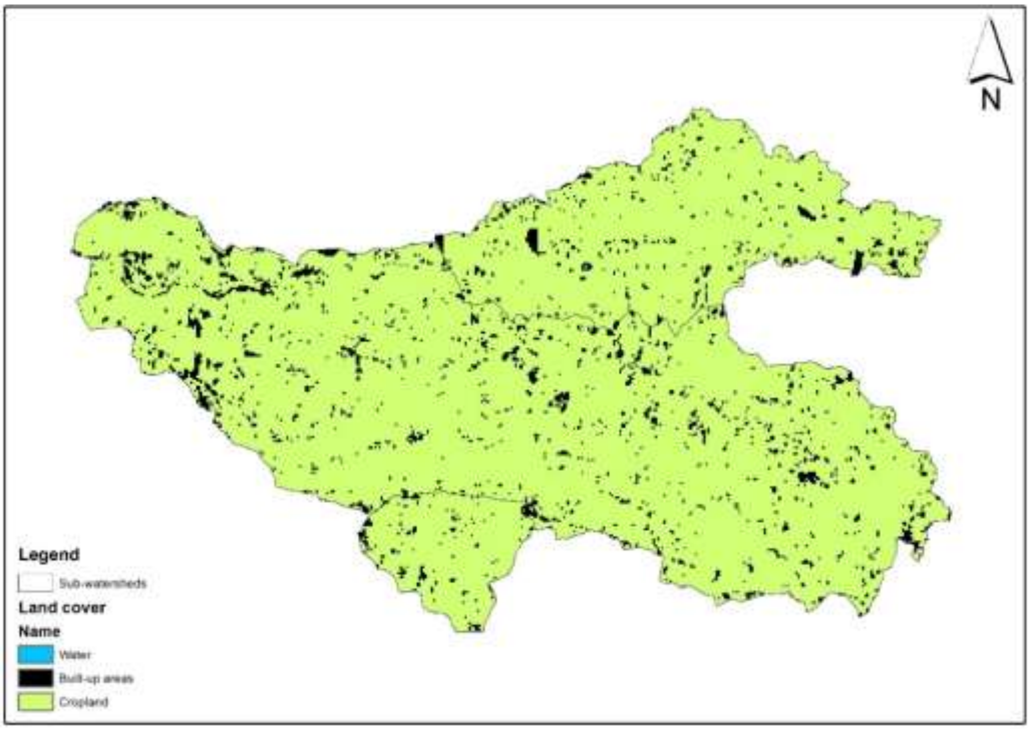


Figure 4.8: A Map Showing the Different LULC Types Within the Micro-Watersheds

Table 4.8: Areas of the specific LULC types in m^2, km^2 and Ha in the Micro-watersheds

FID	Name	Area (m^2)	Area (km^2)	Area (Ha)
0	Built-up areas	3427200	3.4272	342.72
1	Cropland	48806100	48.8061	4880.61
2	Water	2700	0.0027	0.27

4.4.1 Land Use Maps for Specific Micro Watersheds

The table 4.9 shows the results of the land use land cover maps after classification and extraction from the Maragua watershed and defines the classes obtained from the studied micro-watersheds that is Kambirwa, Maragua ridge and Gituamba. The different land use classes were built-up areas, water and crop land. Of the three, water was found to occupy the least area which was only found in Kambirwa micro-watershed with an area of 0.0027 km^2. Cropland and Built-up areas was found in the three where cropland occupied the largest area with (34.39 km^2) in Gituamba, 11.37 km^2 in Kambirwa and the least in in Maragua Ridge with an area of 3.05 km^2 and built-up areas with 2.51 km^2 in Gituamba, 0.72 km^2 in Kambirwa and 0.19 km^2 in Maragua ridge respectively.

Table 4.9: Statistics for LULC areas (m2, km2) for the different Micro-Watersheds

Land cover types	**Area of Land cover type in m^2 (km^2)**		
	Gituamba	**Kambirwa**	**Maragua ridge**
Built-up areas	2513700 (2.51)	720900 (0.72)	192600 (0.19)
Cropland	34388100 (34.39)	11369700 (11.37)	3048300 (3.05)
Water	0	2700 (0.0027)	0
Total Area	3690.18	1209.33	324.09

4.4.2 Rainfall Data

Rainfall data was downloaded from WorldClim i.e. annual precipitation based on historical rainfall data collected over a period of 30 years (Fick & Hijmans, 2017). This was clipped to the working boundary area and the output was as shown in figure 4.9. The results show that the study area had an annual precipitation ranging between 790 and 1050 mm. this indicates that the area is a low rainfall zone which requires supplemental irrigation to take crops to maturity.

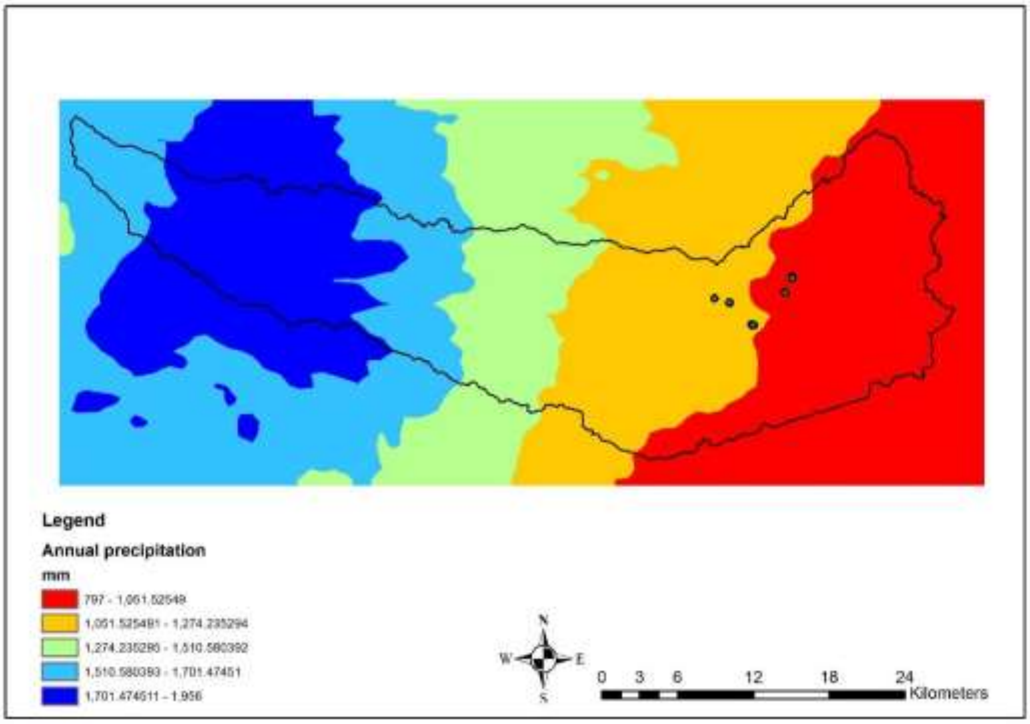


Figure 4.9: A Map Showing Annual Precipitation in Maragua Watershed

4.4.3 Curve Number and Creation of Curve Number Maps for the Micro Watersheds

The results in Table 4.10, 4.11 and 4.12 show that the highest curve number was 100 for water as a land cover category and the lowest was 87 for the crop land. The results show that there was only clay soil texture falling under hydrological soil group D. This is as a result of the land use categories mapped out from the different study farms. The CNs in the tables represent LULC classes falling in hydrological group D. The tables shows the values of CN as they were assigned to the respective combined attribute generated from the overlaid maps (land use and hydrological soil groups) for Gituamba, Maragua and Kambirwa. The water covered areas indicate a higher curve number of 100 indicating a high runoff potential as compared to cropland and built-up areas where the Curve number ranges between 100 and 87 indicating a low runoff because of high abstraction from the crops and buildings respectively.

Table 4.10: CN Lookup Table LU_Value used to assign AMC II CN to Soil_Landuse Complex_Maragua ridge

LU_Value	Description	A	B	C	D
1	Cropland	69	78	83	87
2	Built-up areas	77	86	91	94

Table 4.11: CN Lookup table LU_Value used to assign AMC II CN to Soil_Landuse Complex_Kambirwa

LU_Value	Description	A	B	C	D
1	Cropland	63	75	83	87
2	Built-up areas	77	86	91	94
3	Water	100	100	100	100

Table 4.12: CN Lookup table LU_Value used to assign AMC II CN to Soil_Landuse Complex_Gituamba

LU_Value	Description	A	B	C	D
1	Cropland	67	78	85	89
2	Built-up areas	77	86	91	94

4.4.4 Runoff Depth and Runoff Volume Calculation

For modelling purposes, watersheds were considered to be AMC II, which is essentially an average moisture condition (Parvez *et al*., 2020). The values of runoff depth, Q were calculated using equation 3.4 whereby the value of surface retention was calculated using equation 3.6 then replaced in the former equation to get Q. The results in table 4.13 shows that from the cropland, the runoff depth was the lowest since the abstraction was also high meaning that less runoff was realized from the crop covered areas and the water covered area was the highest though it was only found in Kambirwa Micro-watershed. The values of runoff depth obtained were 823.99mm, 848.77mm for Kambirwa, 831.37mm and 848.77mm for Gituamba and 823.99mm and 848.77mm for Maragua ridge for cropland and built-up areas. The runoff volume calculated from the area and depth of runoff indicates that the crop land had the highest volume of runoff since it occupied the largest area among the three land use classes which was at 9,368,519.10 m^3, 2,858,923.47 m^3, 2,511,768.72 m^3, for Kambirwa, Gituamba and Maragua ridge micro-watersheds respectively.

Table 4.13: Runoff Depths and Volumes from the Different Micro-watersheds under the Various Classes

Soil_lu Complex	Land use	CN for AMC II	Area to be irrigated (m^2)	% area	Rainfall, P(mm)	Surface Retention, S	Runoff Depth, Q	Runoff Volume, m^3
Kambirwa	Crop land	87	11369700	94.04	867.93	37.95	823.99	9,368,519.10
	Built-up areas	94	720900	5.96	867.93	16.21	848.77	611,878.29
	Water	100						
	Total Area			100				
Gituamba	Cropland	89	3438810	93.19	867.93	31.39	831.37	2,858,923.47
	Built-up areas	94	2513700	6.81	867.93	16.21	848.77	2,133,553.15
	Total Area			100				
Maragua	Cropland	87	3048300	94.06	867.93	37.95	823.99	2,511,768.72
ridge	Built-up areas	94	192600	5.94	867.93	16.21	848.77	163,473.10
				100				

4.5 Design Criteria for the Farm Ponds

4.5.1 Water Demand Analysis

Based on the survey which was conducted, it was found out that the water demand was only for crops irrigation during the dry period. The water demand was therefore estimated from the irrigation water requirement per season as follows;

The water requirement for garden pea, sweet pepper and tomato which were the main crops under irrigation in the area were **395.6, 460.1 and 432.7** mm/ season respectively and the irrigation requirements were **181.4, 216.6** and **187.0** mm/season. In this case the irrigation requirement was used since the water to be harvested will be used for supplemental irrigation. The calculation of the water required for the entire season are presented in Table 4.14.

Table 4.14: Volume of Water Required for Crop Irrigation in the Three Sites

Study area	Crop area (m^2)(Ha)	Irrigation water demand mm/ season (m/season)	Total volume of Irrigation water demand (m^3/season)
Kambirwa	25152 (2.515)	181.4 (0.181)	4552.5
Gituamba	19240 (1.924)	216.6 (0.217)	4175.1
Maragua ridge	17530 (1.753)	187.0 (0.187)	3278.1

From the Table 4.14, the total volume of irrigation water demand for the irrigated area for Kambirwa, Gituamba and Maragua ridge is **4552.5, 4175.1** and **3278.1 m^3** per season respectively. This was calculated from the respective crop area and irrigation water required for the crop. This then means that the farm pond should be able to meet this demand during the dry months of the crop season.

4.5.2 Evaporation Losses

The evaporation losses was calculated using equation 4.1, 4.2, 4.3. From a study carried out by woodhead (1968) show that E_0 for Murang'a which is the study area is 1885 mm per year. The average surface area of the ponds taken as 1025, 925 and 895 m^2 for Kambirwa, Gituamba and Maragua ridge respectively. The areas were calculated from the survey drawings taken during data collection on the site reconnaissance survey. The E_{vol} for the three sites is therefore given in table 4.15. The values were calculated based on a four months season and the values obtained were 0.636, 0.576 and 0.552 m^3 as in Table 4.15.

Maragua	1358	193	193	195	156	145	124	113	114	153	177	155	167	1885

Data from "Studies of Potential Evaporation in Kenya", T. Woodhead, 1968

$$E_{vol} = 0.1025 * 0.0052 * 10 = 0.0053 \quad (4.1)$$

$$E_{vol} = 0.0925 * 0.0052 * 10 = 0.0048 \quad (4.2)$$

$$E_{vol} = 0.0895 * 0.0052 * 10 = 0.0046 \quad (4.3)$$

Table 4.15: Maximum Evaporative Loss (Evol) m^3 per year in the Three Sites

Study area	Maximum pond surface area in m^2	Maximum pond surface area in ha	Maximum evaporative loss (Evol) m^3 per day	Maximum evaporative loss (Evol) m^3per season (4 months)
Kambirwa	1025	0.1025	0.0053	0.636
Gituamba	925	0.0925	0.0048	0.576
Maragua ridge	895	0.0895	0.0046	0.552

4.5.3 Seepage losses

This was calculated using the equation **4.4, 4.5, 4.6** and therefore the seepage losses for the three sites were calculated as in Table 4.16 for Kambirwa, Gituamba and Maragua ridge respectively. The value of hydraulic conductivity was taken from Table 3.6 in the previous chapter as $1 * 10^{-5}$ which depicts the soils of the project area as semi-permeable since it was the category of HSG C&D. The seepage losses therefore were calculated as in table 4.16. The values of seepage losses per season were 10.68, 9.60, and 9.24 m^3 in Kambirwa, Gituamba and Maragua ridge respectively.

$$S_{vol} = 1 * 10^{-5} * 0.1025 * 86400 = 0.089 \tag{4.4}$$

$$S_{vol} = 1 * 10^{-5} * 0.0925 * 86400 = 0.080 \tag{4.5}$$

$$S_{vol} = 1 * 10^{-5} * 0.0895 * 86400 = 0.077 \tag{4.6}$$

Table 4.16: Maximum Seepage Loss (Evol) m^3 per year in the Three Sites

Study area	Maximum pond surface area	Maximum seepage loss (Svol) m^3 per day	Maximum seepage loss (Svol) m^3 per season
Kambirwa	1025	0.089	10.68
Gituamba	925	0.080	9.60
Maragua ridge	895	0.077	9.24

4.5.4 Total Water Demand

This was calculated by summing up irrigation water demand, maximum evaporative losses and seepage losses as in Table 4.17. The total estimated water demand for the three sites were found to be 3619.5 m^3, 3079.7 m^3 and 2122.7 m^3 per year. This therefore means that every farm pond designed and constructed should be able to meet this demand during the dry period of the year for the three different sites.

Table 4.17: Total Water Demand in m^3 Per Year in the Three Sites

Study area	Total volume of Irrigation water demand (m^3/year)	Maximum evaporative loss (Evol) m^3/season	Maximum seepage loss (Svol) m^{3}per season	Total water demand in m^{3}per season
Kambirwa	4552.5	0.636	10.68	4563.8
Gituamba	4175.1	0.576	9.60	4185.3
Maragua ridge	3278.1	0.552	9.24	3287.9

4.5.5 Estimation of Dead Storage

This was calculated as a percentage of the total water demand as shown in Table 4.18. The dead storage of the three sites 228.2 m^3, 209.3 m^3 and 164.4 m^3 in Kambirwa, Gituamba and Maragua Ridge respectively. Dead storage = 5 % of Total water demand. The FAO manual for the construction of small dams recommends 4-5 percent of the total water demand as the dead storage.

Table 4.18: Estimated Dead Storage in m^3 per Year

Study area	Total water demand m^{3}per year)	Dead storage m^{3}per year
Kambirwa	4563.8	228.2
Gituamba	4185.3	209.3
Maragua ridge	3287.9	164.4

Therefore the storage capacities of the pond were calculated as 4792.1, 4394.6 and 3452.3 m^3 respectively. This means that the farm ponds will be able to hold water amounting to the listed volumes as shown in Table 4.19.

Table 4.19: Estimated Total Storage Capacity in m^3per year

Study area	Total water demand m^3 per year	Dead storage m^3 per year	Storage capacity of the farm ponds in m^3
Kambirwa	4563.8	228.2	4792.1
Gituamba	4185.3	209.3	4394.6
Maragua ridge	3287.9	164.4	3452.3

4.5.6 Spill Way Design Criteria

i. Determination of Peak Discharge

This was achieved by first calculating of peak discharge using equation 4.9. This was achieved by first calculating the Time of concentration in hours using equation 3.12 from the previous chapter and using data in the Table 4.20, 4.21 and 4.22 which was then used in the discharge equation to calculate peak discharge for the spillway of the three farm ponds.

Table 4.20: Available Data for Calculation of Peak Discharge for Gituamba Sub-Watershed

L	1.54 km obtained from Google earthpro
Kr	0.35 (Cultivated, absorbent soil)
T	12 hrs.
F	12 * 15 = 180
R	$R = \left[\frac{t+1}{t}\right].F = \left[\frac{12+1}{12}\right] 180 = 195$
Kr.R	$K_r\,.\ R = 0.35 \times 195 = 68.25$
C	0.170 From figure 3.6 from chapter 3
a	1.25 km^2
f(a)	0.798 From figure 3.7 from chapter 3
s	The average slope of the catchment from Google earth is 2.0 %

Thus, from equation 3.10;

$$= \frac{0.170 \times \ 1.54^2}{68.25 \times 0.02 \times 0.798} = \frac{0.403}{1.08927}$$

$$\frac{T_c^{\,3}}{T_c + 1} = 0.37$$

Therefore: $T_c^{\,3} = 0.37\ (T_c + 1)$ and $T_c^{\,3} - 0.37\ T_c - 0.37 = 0$

Solving the equation $T_c =$ 0.89 hrs.

Having estimated the value of T_c, the estimated maximum rainfall intensity (*I*) is calculated with the following equation:

$$I = \frac{R}{Tc+1}\ mm\ /hr \quad (4.7)$$

And the average rainfall intensity *I* as;

$$I \ = \frac{195}{0.4 + \ 1} = 139.28\ mm/hr$$

Fitting the value to this equation 4.8, then i becomes;

$$i = I \times f(a) \quad (4.8)$$

$$= 139.28 \times 0.798 = \ 111.15\ mm/hr$$

The above data is then fitted into the rational formula to obtain the peak discharge

$$Q \quad = \frac{K_r .i .a}{3.6} m^3/sec \tag{4.9}$$

$$Q \quad = \frac{\frac{0.35 \times 111.15 \times 0.25}{3.6}}{60} m^3/sec$$

$$\mathbf{Q \quad = 0.045\ m^3/sec}$$

Table 4.21: Available Data for Calculation of Peak Discharge for Kambirwa Sub-Watershed

L	**0.74 km**
Kr	0.35 (Cultivated, absorbent soil)
T	12 hrs.
F	12 * 15 = 180, value 15 obtained from Rainfall intensity map Fig. 3.10
R	$R = \left[\frac{t+1}{t}\right].F = \left[\frac{12+1}{12}\right] 180 \ = 195$
Kr.R	$K_r\ .\ R = \ 0.35 \times 195 \ \ = 68.25$
C	0.170 From figure 3.8
a	0.75 km^2
f(a)	0.800 From figure 3.9
s	The average slope of the catchment from Google earth is 1.0 %

Thus,

$$= \frac{0.170 \times 0.74^2}{0.35 \times 195 \times 0.01 \times 0.800} = \frac{0.093092}{0.546} = 0.17$$

Hence, $$\frac{T_c^3}{T_c + 1} = 0.17$$

Therefore: $T_c^3 = 0.17\,(T_c + 1)$ and $T_c^3 - 0.17\,T_C - 0.17 = 0$

Solving the equation $T_C = 0.66$

Having established the value of T_c, the estimated maximum rainfall intensity (*I*) is calculated with the following equation 3.12 and the average rainfall intensity *i* as equation 3.13

$$I = \frac{195}{0.66 + 1} = 117.47\ mm/hr$$

$$i = 117.47 \times 0.800 = 93.98\ mm/hr$$

The above data is then fitted into the rational formula (equation 3.14) to obtain the peak discharge

$$Q_{Sp} = \frac{\frac{0.35 \times 93.98 \times 0.75}{3.6}}{60} m^3/sec$$

$$\mathbf{Q_{Sp} = 0.114\ m^3/sec}$$

Table 4.22: Available Data for Calculation of Peak Discharge Maragua Ridge Sub-Watershed

L	**0.62 km**
Kr	0.35 (Cultivated, absorbent soil)
T	12 hrs.
F	12 * 15 = 180, value 15 obtained from Rainfall intensity map Fig. 3.10
R	$R = \left[\frac{t+1}{t}\right].F = \left[\frac{12+1}{12}\right]180 = 195$
Kr.R	$K_r\,.\,R = 0.35 \times 195 = 68.25$
C	0.170 From figure 3.8
a	0.64 km^2
f(a)	0.800 From figure 3.9
s	The average slope of the catchment from Google earth pro is 3.0 %

Thus,

$$= \frac{0.170 \times 0.62^2}{0.35 \times 195 \times 0.03 \times 0.800} = \frac{0.065348}{1.638}$$

$$\frac{T_c^{\,3}}{T_c + 1} = 0.04$$

Therefore: $T_c^{\,3} = 0.04\,(T_c + 1)$ and $T_c^{\,3} - 0.04\,T_C - 0.04 = 0$

Solving the equation $T_c = 0.38$

Having established the value of T_c, the estimated maximum rainfall intensity (*I*) is calculated with the following equation 3.12 and the average rainfall intensity *i* as in equation 3.13;

$$I = \frac{195}{0.38 + 1} = 141.30\ mm/hr$$

$$i = 141.30 \times 0.800 = 113.04\ mm/hr$$

The above data is then fitted into the rational formula (equation 3.14) to obtain the peak discharge

$$Q_{Sp} = \frac{\frac{0.35 \times 113.04 \times 0.64}{3.6}}{60} m^3/sec$$

$$\mathbf{Q_{Sp} = 0.117\ m^3/sec}$$

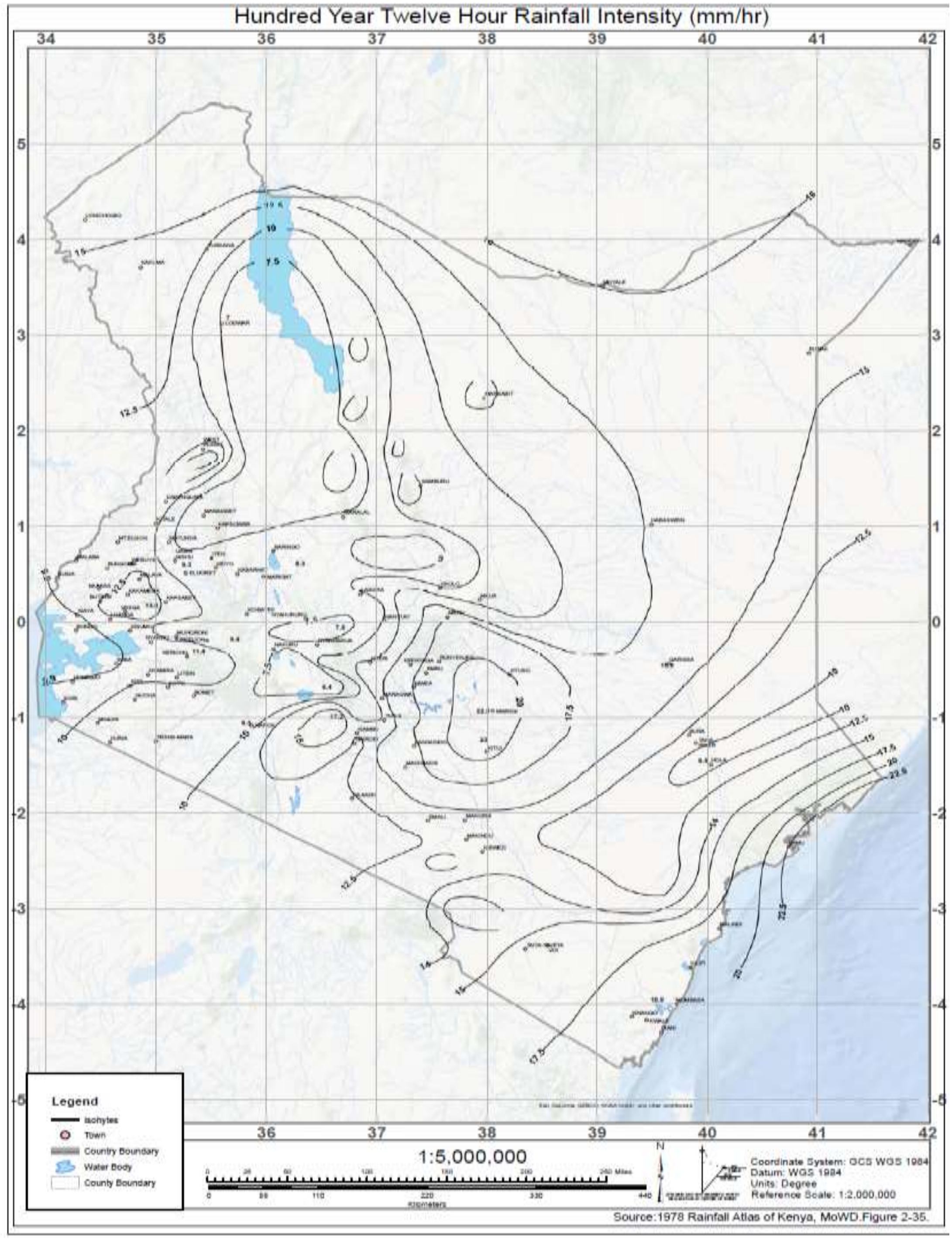


Figure 4.10: Rainfall Intensity Map for a 100 - Year Return Period

From the calculation the peak discharge for the spillway was 0.045, 0.114 and 0.117 m^3/sec for Gituamba, Kambirwa and Maragua ridge respectively . The difference in discharge values was as a result of the slope in Gituamba than the other study sites.

4.5.6.1 Inflow Spillway Channel

Since recommended slopes for inflow spill way channels range from 0.3 % to 1 % with a widening inflow inlet or mouth, then for this design an inflow channel slope of **0.3 %** is adopted, all the way to the spill way crest.

4.5.6.2 Outflow Spillway Channel

Spill way dimensions' values with a slope less than 0.005 and a depth of between 0.3 and 0.45 are recommended from the design guidelines. After performing iteration to determine the adequate flow velocity the following results in table 4.23, 4.24 and 4.25 were obtained for each study farms;

In this case a flow velocity of 2.5 m/s and 2m/s was adopted for Gituamba, Kambirwa and Maragua ridge respectively. The 2 m/s velocity was for the Kambirwa and Maragua ridge. The values of discharge were obtained from the peak discharge obtained from the calculations in section 4.3.7. The value of n was obtained from the appendix III between 0.015 - 0.02 with lined channel finished, with gravel on bottom.

Table 4.23: Iterations for the Value of Depth for Gituamba Sub Watershed Pond

	v	Q	Q/v	n (earth)		vn	
	2.5	0.045	0.018	0.017		0.0425	
		Iterations for d					
No	d	b = (Q/v)/d	P= 2*(2*d*d)^(1/2)+b	A=d(d+b)	R=A/P	R^(2/3)	i=(vn/(R^(2/3))^2
1	1	0.018	2.846	1.018	0.358	0.504	0.0071
2	0.8	0.023	2.286	0.66	0.289	0.437	0.0095
3	0.6	0.03	1.727	0.38	0.22	0.364	0.0136
4	0.4	0.045	1.176	0.18	0.153	0.286	0.0221
5	0.35	0.05	1.114	0.14	0.126	0.251	0.0287
6	0.38	0.05	1.124	0.16	0.142	0.272	0.0244
7	0.45	0.04	1.313	0.22	0.168	0.304	0.0195

Table 4.24: Iterations for the Value of Depth for Kambirwa Sub Watershed Pond

tm	**v**	**Q**	**Q/v**	**n (lined channel finished, with gravel)**		**vn**	
	2	0.114	0.057	0.017		0.034	
		Iterations for d					
No	d	b = (Q/v)/d	P= 2*(2*d*d)^(1/2)+b	A=d(d+b)	R=A/P	R^(2/3)	i=(vn/(R^(2/3))^2
1	1	0.057	2.89	1.057	0.367	0.512	0.0044
2	0.8	0.071	2.33	0.697	0.299	0.447	0.0058
3	0.6	0.095	1.79	0.417	0.233	0.378	0.0080
4	0.4	0.143	1.27	0.217	0.171	0.308	0.0012
5	0.35	0.163	1.15	0.180	0.157	0.291	0.0137
6	0.38	0.150	1.22	0.201	0.165	0.301	0.0128
7	0.45	0.127	1.40	0.260	0.186	0.326	0.0109

Table 4.25: Iterations for the Value of Depth for Maragua Ridge Sub Watershed Pond

tm	v	Q	Q/v	n (lined channel finished, with gravel)		Vn	
	2	0.117	0.059	0.017		0.034	
		Iterations for d					
No	d	b = (Q/v)/d	P= 2*(2*d*d)^(1/2)+b	A=d(d +b)	R=A/P	R^(2/3)	i=(vn/(R^(2/3))^2
1	1	0.059	2.887	1.059	0.367	0.512	0.0044
2	0.8	0.074	2.337	0.699	0.299	0.447	0.0058
3	0.6	0.098	1.795	0.419	0.233	0.378	0.0081
4	0.4	0.148	1.279	0.219	0.171	0.308	0.0122
5	0.35	0.169	1.159	0.812	0.700	0.788	0.0019
6	0.38	0.155	1.230	0.203	0.165	0.667	0.0026
7	0.45	0.131	1.404	0.261	1.186	1.121	0.0091

From the iteration exercise, the appropriate bottom width of the spillway should be 11.5 m, 8.6 m and 8.8 m, as this figure corresponds to a slope of 0.005, 0.004, and 0.004 for Gituamba, Kambirwa and Maragua ridge respectively which is less than the recommended **0.005** and a depth of **0.4**, which falls within the recommended rage of **0.3 to 0.45**.

4.5.6.3 Spill Way Type Selection (Channel Geometry)

A trapezoidal spillway, with a side slope of 1 is recommended. Such spillways have the following geometric qualities in Table 26.

Table 4.26: Geometric Qualities of a Trapezoidal Spillway

X- sectional area	Wetted perimeter	Hydraulic radius	Top width
$A = bd + Zd^2$	$P = b + 2d\sqrt{1+Z^2}$	$R = \frac{A}{p} = \frac{bd + Zd^2}{b + 2d\sqrt{1+Z^2}}$	$w = b + 2dZ$

Fitting in the values of breadth and depth, for the three farm ponds then;

W= b + 2dz = 11.5 + (2*0.4*1) = 12.3m

W= b + 2dz = 8.6 + (2*0.4*1) = 9.4m

W= b + 2dz = 8.8 + (2*0.4*1) = 9.6m

Thus, the top widths of the spill way channels becomes **12.3, 9.4** and **9.6.**

Bottom widths **= 11.5, 8.6 and 8.8**

4.3.6.4 Spill Way Approach Depths

From equation 12-7 in the practice manual for small dams.

Flow per unit width (q) is given by the equation 4.10 as;

$$q = Q/b \tag{4.10}$$

Where Q is the flow rate (9.65, 6.85 and 7.03)

b is the bottom width (11.5, 8.6 and 8.8)

Fitting the data into the equation gives

= 9.65/11.5

= **0.84 m^2/s**

= 6.85/8.6

= 0.8 m^2/s

= 7.03/8.8

= 0.8 m^2/s

Critical depth (H_c) is given by the equation 4.11 as;

$$H_C = [q^2/g]^{\frac{1}{3}} \quad (4.11)$$

Where q is flow per unit width (**0.84**, **0.8** and **0.8**)

g is force of gravity (**9.81**)

Fitting into the equation3.15 gives

$H_{CG} = (0.84^2 /9.81)^{1/3}$

= 0.42m

$H_{CK} = (0.8^2 /9.81)^{1/3}$

= 0.40m

$H_{CM} = (0.8^2 /9.81)^{1/3}$

= 0.40m

The **depth of approach** is given the equation 4.12 as

$$H_A = 1.5 * H_c \quad (4.12)$$

$H_{AG} = 1.5 * 0.42$

=0.624m

$H_{AK} = 1.5 * 0.402$

=0.603m

$H_{AM} = 1.5 * 0.402$

=0.603m

Note: The symbols G, K and M denotes Gituamba, Kambirwa and Maragua ridge respectively.

The **normal water depth** is given by equation 4.13 as;

$$H_N = H_A - \frac{\frac{5}{4} * V^2}{2g} \quad 4.13$$

Fitting into equation gives;

Gituamba = $0.624 - \frac{\frac{5}{4} * 2.5^2}{2 * 9.81}$

= **0.226m**

Kambirwa = $0.60 - \frac{\frac{5}{4} * 2^2}{2 * 9.81}$

= 0.345m

Maragua ridge $= 0.60 - \frac{\frac{5}{4} * 2^2}{2 * 9.81}$

= **0.345m**

Since the **normal water depth** is less than the **critical depth** therefore the flow is subcritical.

4.5.7 Slopes

The table 4.26 shows the values of slopes which were obtained from the corresponding soil type. The values obtained for the side slope were 1.5:1 to 2:1 since all the sites had the same type of soil which was clay loam as obtained from the soil data.

Table 4.26: Values of Recommended Slope Versus the Soil Type

Soil type	Soil type	Slope (Horizontal : Vertical)
Kambirwa	Clay loam	1.5:1 to 2:1
Gituamba	Clay loam	1.5:1 to 2:1
Maragua ridge	Clay loam	1.5:1 to 2:1

CHAPTER FIVE

CONCLUSION AND RECOMMENDATION.

5.1 Conclusion

The study revealed that CropWAT model coupled with accurate area climate, soils and crop data can be used to consistently establish the irrigation water requirement for the region. Among the three crops under study, sweet pepper had the highest amounts of evapotranspiration and water requirements and more frequent irrigation schedules than the other two crops. The ETc values for the garden pea, sweet pepper and tomato were 395.6, 460.1 and 432.7 mm/season respectively which is within the range provided by FAO, 2008. The irrigation requirements were 181.4, 216.6 and 187 mm/season for garden pea, tomato, and sweet pepper respectively. The ET_c was found to be high during the development and mid-season stage. This is because most plants need the most water when it occurs in the process of forming the fruit as requires more energy to make fruit formation in the phase towards the late-season.

The calculation of runoff using SCS-CN by the ArcGIS approach provides reliable method for computing the CN values, which combines Land use and Hydrological soil group. The computation of the CN values was the key to a successful SCS-CN modelling. The results demonstrated that the SCS-CN method by using satellite imagery data to estimate runoff is convenient and effective. The runoff volume calculated from the area and depth of runoff indicates that the crop land had the highest volume of runoff since it occupied the largest area among the three land use classes which was at 9,368,519.10 m^3, 2,858,923.47 m^3, 2,511,768.72 m^3, for Kambirwa, Gituamba and Maragua ridge micro-watersheds respectively. This runoff come from the entire sub watersheds which will supply water to the farm ponds in the area. The values indicate that there is enough runoff to be harvested to the farm ponds.

From the design criteria developed for farm ponds, farmers are able to construct the right size of farm pond based on their catchment area and the crop to irrigate. From these results a farmer can determine when to irrigate and depending on the amount of water stored in a farm pond determine how to apportion the water in the different crop development stages. The irrigation water demand for the irrigated area for Kambirwa, Gituamba and Maragua ridge is **4552.5, 4175.1** and **3278.1 m^3** per season respectively. This was in line with the water usage for the crops observed during this season.

5.2 Recommendations from Research

- CropWat model as a suitable decision support tool for policy makers and investors on irrigation and water resources in the region with regard to irrigation water management. It further recommends that governments and other development agencies needs to invest in training and awareness creation on effective irrigation water management and rainwater harvesting techniques for smallholder farmers of the area.

5.3 Recommendations for Further Research

- Further research on the economics of water use and technical aspects of running different irrigation systems be undertaken. With this information farmers and irrigation planners can make wise decisions on the appropriate irrigation system to adopt and choose or recommend the most profitable crops to be grown in a particular area based on the findings.
- Further research is required to determine water productivity for supplemental irrigated crops as well as deficit irrigation under specific crop management practices. Through such a study, the farmers will be able to determine the exact amount applied as well as the best crop management practices to give maximum farm productivity.

REFERENCES

Abtew, W., & Melesse, A. (2013). *Evaporation and Evapotranspiration: Measurements and Estimations*. Dordrecht: Springer Netherlands.

Ahmad, I., Verma, V., & Verma, M. K. (2015). Application of the Curve Number Method for Estimation of Runoff Potential in GIS, *Environment, 80*, 16–20. https://doi.org/10.7763/IPCBEE.

Ahmed, B., & Gemeda, F. (2021). Design, construction and evaluation of runoff water harvesting pond for smallholder farming. *International Journal of Research -Granthaalayah, 9*(9), 30–39. https://doi.org/10.29121/ granthaalayah. v9.i9.2021.4223

Al- Jabari, S., Abu, M. S., & Al - Mimi, Z. (2009). Estimation of runoff for an agricultural watershed using SCS curve number and GIS. *Thirteenth International Water Technology Conference*, (January 2003), 1213–1229.

Allen, R. G., & Food and Agriculture Organization of the United Nations. (1998). *Crop evapotranspiration: Guidelines for computing crop water requirements.* Rome: Food and Agriculture Organization of the United Nations.

Arvind, C. P. (2017). *Geospatial technique for runoff estimation based on SCS-CN Method in Upper South Koel River Basin of Jharkhand in India. Int. j. hydrol*, *1*(7), 213-220.

Arcement, G. J., & Schneider, V. R. (1989). *Guide for selecting Manning's roughness coefficients for natural channels and flood plains* (Vol. 2339). Washington, DC: US Government Printing Office.

Asmita, K., Lakhote, B., & Baisware, N.Z. (2014). Analysis of Rainfall-Runoff for Agricultural Watershed Area. *IOSR Journal of Environmental Science, Toxicology and Food Technology*. *8*. 58-65.

Athavale, R.N. (2003). *Water harvesting and sustainable supply in India. Environment & development series,* India: Centre for Environment Education.

Baker, T., Kiptala, J., Olaka, L., Oates, N., Hussain, A., & Mccartney, M. (2015). Baseline Review and Ecosystem Services Assessment of the Tana River Basin, Kenya. (Vol. 165). International Water Management Institute (IWMI). https://doi.org/10.5337/2015.223.

Banik, P. & Ranjan, S. (2014). CROPWAT Crop Water Assessment of Plain and Hilly Region Using CROPWAT Model, *Int. J. Sustainable Mater. Process. ECO-Efficient-IJSMPE, 1*(3), 1–9.

Barikar, Dr. U. (2012). Farm Ponds: A Climate Resilient Technology for Rainfed Agriculture Planning, Design and Construction. National Initiative on Climate Resilient Agriculture Central Research Institute for Dryland Agriculture. *Technical Bulletin*. 1-60.

Bates, B., Zbigniew Kundzewicz, A. W., Wu, S., & Palutikof, J. (2008). Climate change and water. *Technical Paper of the Intergovernmental Panel on Climate Change. Geneva*.

Bengtsson, M. & Orjan, S. (2004). Climate of competition, clusters and innovative performance, *Scandinavian Journal of Management, 20*(3), 225-244.

Blöschl, G. (2013). *Runoff prediction in ungauged basins: Synthesis across processes, places and scales*. Cambridge: Cambridge University Press.

Bos, M. G. (2009). *Water requirements for irrigation and the environment*. Dordrecht: Springer.

Bot, A., Benites, J., & Food and Agriculture Organization of the United Nations. (2005). *The importance of soil organic matter: Key to drought-resistant soil and sustained food production*. Rome: Food and Agriculture Organization of the United Nations.

Burdack, D. (2014). *Water management policies and their impact on irrigated crop production in the Murray-Darling basin, Australia*. Potsdam: Univ. Press.

Bush, M. J. (2017). Climate Change Adaptation in Small Island Developing States. New York: John Wiley & Sons.

Calderon Palma, H. L. (2018). Surface and subsurface runoff generation processes in a poorly gauged tropical coastal catchment: a study from Nicaragua; Dissertation, UNESCO-IHE Institute for Water Education, Delft: Delft University of Technology.

Calhoun, Y., & Seideman, D. (2005). *Water pollution.* Philadelphia: Chelsea House Publishers.

Chellaney, B. (2013). *Water, peace, and war: Confronting the global water crisis*. New Jersey: Rowman & Littlefield.

Chen, Y., Zhou, C., Li, D., Rong, G. & Qinghui, J. (2012). A new classification of seepage control mechanisms in geotechnical engineering. *Joumal of Rock Mechanics and Geotechnical Engineering. 2010*. 10.3724/SP.J.1235.2010. 00209.

Chin, D. A. (2000). *Water-Resources Engineering*. New Delhi: Prentice-Hall.

Chow, V.T., (1959). *Open-channel hydraulics*, New York: McGraw-Hill.

David, M., & International Water Management Institute. (2007). Water for Food, Water for Life: A Comprehensive Assessment of Water Management in Agriculture. London: Earthscan pub.

DeBusk, K., & Hunt, W. (2014). Rainwater Harvesting: A Comprehensive Review of Literature, *Report. No. 425*, (425), 164.

Evans, R. (2002). An alternative way to assess water erosion of cultivated land–field-based measurements: And analysis of some results. *Appl. Geogr. 22*, 187–207.

FAO, (2017). CropWAT, Land and Water. Retrieved from http://www.fao.org/land-water/databases-

FAO, (2016). *FAOSTAT. Food and Agriculture Organization of the United Nations*, Rome: FAO.

FAO. (2008). *Global map of monthly reference evapotranspiration –GeoNetwork: grid database*, Rome: FAO.

FAO_UN. (2018). *Guidelines on irrigation investment projects*. Rome: FAO.

FAO (2011). The state of the world's land and water resources for food and agriculture (SOLAW) - Managing systems at risk, Food and Agriculture Organization of the United Nations / Earthscan, Rome / London, Retrieved from http://www.fao.org/nr/solaw/en/.

FAO-AGL. (2002). Crop Description and Climate. Land and Water development division. *Agriculture* 21.

Fauraes, J. M., Steduto, P., & Hoogeveen, J. (2012). *Coping with water scarcity: An action framework for agriculture and food security*. Rome: Food and Agriculture Organization of the United Nations.

Fick, S.E. & Hijmans, RJ. (2017). WorldClim 2: new 1km spatial resolution climate surfaces for global land areas. *International Journal of Climatology 37*(12), 4302-4315.

Fitts, C. R., & Elsevier. (2013). *Groundwater science*. Amsterdam: Academic Press.

Foley, M. (2019). *Farming for the long haul: Resilience and the lost art of agricultural inventiveness*. Chelsea: Chelsea Green Publishing.

Geertsma, R. Wilschut, L. & Kauffman, J. (2009). *Baseline Review of the Upper Tana, Kenya*. Nairobi: Agriculture Ecosystems & Environment.

Gonzalez Barrios, J. L., Viramontes, D., Vauclin, M., Esteves, M., & Descroix, L. (2001). Influence of soil surface features and vegetation on runoff and erosion in the Western Sierra Madre. *Catena*, *43*(2), 115–135. https://doi.org/10.1016/S0341-8162(00)00124-7

Gora, J. S., Verma, A. K., Singh, J., & Choudhary, D. R. (2019). Climate change and production of horticultural crops. In *Agricultural Impacts of Climate Change 1,* 45-61.

Gould, J., & Nissen-Petersen, E. (1999). *Rainwater catchment systems for domestic supply: Design, construction and implementation*. London: Intermediate Technology.

Grismer, M., Orang, M., & Richard, M. (2002). Pan Evaporation to Reference Evapotranspiration Conversion Methods. *Journal of Irrigation and Drainage Engineering-asce – (J IRRIG DRAIN ENG-ASCE). 128.* 10.1061/ (ASCE) 0733-9437(2002)128:3(180).

Hashem, A., Engel, B., Bralts, V., Radwan, S. & Rashad M (2016), Performance Evaluation and Development of Daily Reference Evapotranspiration Model, *Irrigation Drainage System Eng 2016*.

Hatibu, N., & Mahoo, H. (1999). Rainwater harvesting technologies for agricultural production : A case for Dodom , Tanzania. *Network*, 161–171.

Hengl, T., De Jesus, J. M., Heuvelink, G. B. M., Gonzalez, M. R., Kilibarda, M., Blagotić, A. & Kempen, B. (2017). SoilGrids 250m: Global gridded soil information based on machine learning. In *PLoS ONE, 12*. https://doi.org/10.1371/journal.pone.0169748

International Fund for Agricultural Development, IFAD. (2012). *Upper Tana catchment natural resource management project report, east and southern Africa division, project management department.* Nairobi: IFAD.

In Farooq, M., & In Siddique, K. H. M. (2016). *Innovations in Dryland Agriculture*. Cham: Springer International Publishing.

Jacobs, J., Angerer, J., Vitale, J., Srinivasen, R., Kaitho, R., Stuth, J., & Clarke, N. (2004). Exploring the potential impact of reforestation on the hydrology of the Upper Tana River Catchment and the Masinga Dam, Kenya. *Impact Assessment Group, Cent. for Natural Resource Information Technol., Texas A&M Univ., College Station*.

Jacobsen, M., Webster, M., & Vairavamoorthy, K. (2012). *The future of water in African cities: Why waste water?* Washington, D.C: The World Bank.

Jolley, J., Tucillo, M. E., Young, M. L., Barrett, M. E., Lantin, A., United States., National Academies of Sciences, Engineering, and Medicine (U.S.)., Airport Cooperative Research Program. (2017). *Green store water infrastructure*. *Sustainability*, *10*(12), 4388.

Johl, S. S. (2014). Irrigation and Agricultural Development: Based on an International Expert Consultation, *Baghdad, Iraq, 24 February - 1 March 1979*. Kent: Elsevier Science.

Kenya & International Monetary Fund. (2010). *Kenya: Poverty reduction strategy paper*. Nairobi: Kenya & International Monetary Fund.

Khopade, D.K., & Oak. R.A. (2014). Oak Estimation of Runoff Yield for Nira Deoghar Catchment Using Different Empirical Equations. *The International Journal of Engineering and Science (IJES) 3*(6), 2319 – 1813.

Kimeli, N. (2017). Application of GIS for Estimation of Water Runoff Volume in Water Collection Sites Case Study: Northern Collector Water Tunnel. *American Journal of Geographic Information System*, *6*(5), 169–177.

KNBS, (2019). *Kenya Population and Housing Census Reports*. Nairobi: KNBS.

Leal, F. W. (2011). *The economic, social and political elements of climate change*. Berlin: Springer.

Kang S., Li X., Zhang X., & Li F., (2018). Deficit irrigation provokes more pronounced responses of maize photosynthesis and water productivity to elevated CO2, Agric. *Water Manag.*, *195*, 71–83,

Lindqvist, A.K., (2005). *Water from ponds, pans and dams: A manual on planning, design, construction and Maintenance. Technical handbook No. 32.* Nairobi: Regional Land Management Unit (RELMA)/World Agroforestry Centre Eastern and Central Africa Regional Programme. Retrieved from www.**worldagroforestry**.org/.../MN13546.pdf

Ma, Y., Qu, L., Wang, W., Yang, X., & Lei, T. (2016). Measuring soil water content through volume/mass replacement using a constant volume container. *Geoderma*, *271*, 42-49.

Magar, R.B. & Jothiprakash, V. (2012). *Multi-time-step ahead daily and hourly intermittent reservoir inflow prediction by artificial intelligent techniques* *using lumped and distributed data, Journal of Hydrology*, (450–451), 293-307. https://www.sciencedirect.com/science/article/pii/S0022169412003459)

Mati, B. M., (2018). Water Harvesting in Practice: Towards Building Resilient Livelihoods in Semi-Arid Zones. *Field Practitioners Guide 2*.

Mati, B. M. (2012). *Runoff Harvesting for Crop Production: Practical Solutions for Dr land Agriculture.* Training Manual 1. Nile Basin Initiative (NBI), Nile Equatorial Lakes Subsidiary Action Programme (NELSAP)-Regional Agricultural and Trade Programme (RATP), Bujumbura, Burundi.

Mandel, S. (2014). *Groundwater Resources: Investigation and Development*. Saint Louintris: Elsevier Science.

Masoumeh, N., Mohammad S., Saeid. E., Kaveh. O., Vijay P., & Nicolas R., (2019). Evaluation of Radiation Methods for Calculating the Water Requirement of Grass in Two Different Climates using REF-ET Software, *International Journal of Constructive Research in Civil Engineering (IJCRCE). 5*(1), 1-7.

Mishra, S. K., & Singh, V. P. (2003). *Soil Conservation Service Curve Number (SCS-CN) Methodology*. Dordrecht: Springer Netherlands.

Mishra, S. K., & Singh, V. P. (2004). Long-term hydrological simulation based on the Soil Conservation Service curve number. *Hydrological Processes*, *18*(7), 1291-1313.

Mohanty, M. S. (2015). *Crop growth simulation modelling and climate change*. Jodhpur: Scientific publisher (India).,.

Molden, D., Oweis, T. Y., Pasquale, S., Kijne, J. W., Hanjra, M. A., Bindraban, P. S., & Upadhyaya, A. (2007). *Pathways for increasing agricultural water productivity.* Sokoine: Sokoine University of Agriculture.

Morgan, R. P. C. (2004). *Soil Erosion and Conservation*. Oxford: Blackwell Pub.

MUWASCO Project Report. (2017). Environmental *and Social Impact Assessment of Maragua Water Supply Project. LOG associates.* Morang'a: MUWASCO.

Muema, J. M., Kaluli, J.W., Gathenya, J.M., & Mwangi, B.M. (2018). 'Evaluation of Wetland Loss in Maragua Watershed, Murang ' a County , Kenya', *Journal of Sustainable Research in Engineering, 4*(4), 160–170.

Murang'a County Integrated Development Plan. (2018), *Water supply*, Morang'a: Murang'a County.

MWI, GOK. (2015). *Practice manual for small dams, pans and other water conservation structures in Kenya.* Nairobi: State Department for Water, Ministry of Water and Irrigation, Government of Kenya.

National Conference on Fifty Years of Indian Agriculture, Mohammad, A., Munir, A., Rehman, H., & Aligarh Muslim University. (2007). *Fifty years of Indian agriculture*. New Delhi: Concept Pub. Co

Njogy, I., & Kitheka, J. (2017). Assessment of the Influence of Rainfall and River Discharge on Sediment Yield in the Upper Tana Catchment in Kenya. Retrieved from repository.seku.ac.ke

Njonga, B. (2009). *Tomato: Conditions for successful production*. Nairobi: Farmer's voice.

Novak, C. A., Van Giesen, E., & DeBusk, K. M. (2014). *Designing rainwater harvesting systems: integrating rainwater into building systems*. New York: John Wiley & Sons.

Oweis, T., Hachum, A. & Kijne, J. (1999). *Water harvesting and supplemental irrigation for improved water use efficiency in dry areas.* Colombo, Sri Lanka: International Water Management Institute (IWMI).

Pandey, A., Mishra, S. K., Kansal, M. L., Singh, R. D., & Singh, V. P. (Eds.). (2021). *Water Management and Water Governance: Hydrological Modeling*. New Jersey: Springer.

Pandey, A., Chowdary, V., Mal, B., & Dabral, P. (2003). Estimation of runoff for agricultural watershed using SCS Curve Number and Geographic Information System. Retrieved from *http://www. gisdevelopment. net/application/agriculture/soil/pdf/48. pdf*

Panigrahi, B. (2011). *Irrigation systems engineering*. New Delhi: New India Pub. House.

Parvez, M. B., Thankachan, A., Chalapathi, K., Inayathulla, M., & Chithaiah, E. (2020). Geospatial technique for runoff estimation based on soil conservation service curve number method in upper Cauvery Karnataka. *Australian Journal of Science and Technology, 4*(1), 232-241.

Pereira, L. S., Cordery, I., & Iacovides, I. (2009). *Coping with water scarcity: Addressing the challenges*. Dordrecht: Springer.

Pereira, G., Allen, M., & Dirk, R. (2015). Crop evapotranspiration estimation with FAO56: Past and future, *Agricultural Water Management, 147,* 4-20, https://doi.org/10.1016/j.agwat.2014.07.031.

Pielke, S. R. A. (2013). *Climate Vulnerability Volume 4*. Burlington: Elsevier Science.

Reddy K. S., Manoranjan, K., Rao, K.V., Maruthi, V., Reddy, B.M.K., Umesh B., Ganesh Babu R., … & Venkateswarlu, B. (2012). *Farm Ponds: A Climate Resilient Technology for Rainfed Agriculture; Planning, Design and Construction.* Central Research Institute for Dryland Agriculture, Santoshnagar, Saidabad, Hyderabad-500059, Andhra Pradesh: CRIDA.

Allen, R.G. Pereira, L.S. &, Smith, D.R (1998). *Crop evapotranspiration: Guidelines for computing crop requirements.* Irrigation and Drainage paper No 56", Rome, Italy: FAO.

Seethapathi, P. V., Dutta, D., Siva, K. R., & N.R.D.M.S. Project (India). (2008). *Hydrology of small watersheds*. New Delhi: Natural Resources Data Management System, Dept. of Science & Technology, Ministry of Science & Technology, Govt. of India.

Shadeed, S., & Almasri, M., (2010). Application of GIS-based SCS-CN method in. *Water Science and Engineering*, *3*(1), 1–13. https://doi.org/10.3882/j.issn. 1674-2370.2010.01.001

Shaver, E., Horner, R. R., Skupien, J., May, C., Ridley, G., United States. & North American Lake Management Society. (2007). *Fundamentals of urban runoff management: Technical and institutional issues*. Madison, WI: North American Lake Management Society.

Silva, C. L., & Oliveira, C. A. S. (1999). Runoff measurement and prediction for a watershed under natural vegetation in central Brazil. *Revista Brasileira de Ciência do Solo*, *23*(3), 695-701. https://dx.doi.org/10.1590/S0100-06831999000300024

Singh, N., & Sharma, V. P. (2002). Patterns of rainfall and malaria in Madhya

Pradesh, central India. *Annals of Tropical Medicine & Parasitology*, *96*(4), 349-359.

Stephens, T. (2010). *Manual on small earth dams: a guide to siting, design and construction.* Food and Agriculture Organization of the United Nations (FAO), Rome: FAO.

Sweden. & World Agroforestry Centre. (2005). *Water from ponds, pans, and dams: A manual on design, construction, and maintenance*. Nairobi: Regional Land Management Unit.

TNC. (2015). Upper Tana-Nairobi Water Fund Business Case. Version 2, (September), 36. Retrieved from http://www.nature.org/ourinitiatives/ regions/ africa/upper-tana-nairobi-

Tollner, E. W. (2016). *Engineering hydrology for natural resources engineers*. New York: John Wiley & Sons.

UDFCD. (2007). Drainage Criteria Manual (V.1) Runoff. Drainage Criteria Manual. *Journal of Hydrologic Engineering*, *21*(3), 04015073.

UNEP. (2002). Freshwater stress and scarcity in Africa by 2025. Retrieved from http://www.unep.org/dewa/assessments/ecosystems/water/vitalwater/21.htm.

Urban Hydrology for SmallWwatersheds. (1986). Retrieved from http://www.unep.org/dewa/assessments/ecosystems/water/vitalwater/21.htm.

Vaezi, A. R., Bahrami, H. A., Sadeghi, S. H. R., & Mahdian, M. H. (2010). Modellingthe relationship between runoff and soil properties in dry-farming lands, NW Iran. *Hydrology and Earth System Sciences Discussions*, *7*(2), 2577–2607. https://doi.org/10.5194/hessd-7-2577-

2010.

Van, S. F., Alemayehu, H. T., Arroyo-Arroyo, F., Deligianni, A., Rao, K., & Woldearegay, K. (2021). *Green Roads for Water: Guidelines for Road Infrastructure in Support of Water Management and Climate Resilience*.

Vining, K. C., & Minnesota. (2004). *Simulation of runoff and wetland storage in the Hamden and Lonetree watershed sites within the Red River of the North Basin, North Dakota and Minnesota*. Reston, Va: U.S. Dept. of the Interior, U.S. Geological of Survey.

Wagener, T., Wheater, H & Gupta, H. (2004). Rainfall-Runoff Modelling In Gauged and Ungauged Catchments. 10.1142/9781860945397.

Waller, P., Yitayew, M., Waller, P., & Yitayew, M. (2016). Crop evapotranspiration. *Irrigation and Drainage Engineering*, 89-104.

Wani, S. P.; Rockstrom, J. & Oweis, T. (Eds.) (2009). *Rainfed agriculture: unlocking the potential*. Wallingford, UK: CABI; Patancheru, Andhra Pradesh, India: International Crops Research Institute for the Semi-Arid Tropics (ICRISAT); Colombo, Sri Lanka: International Water Management Institute (IWMI). 310p.

Wilschut, LI (2010). *Land Use Map of the Upper Tana, Kenya; Based on remote sensing. Green Water Credits Report 9 / ISRIC Report 2010/03*. Wageningen: ISRIC – World Soil Information.

Wood head, T. (1968). *Studies of Potential Evapotranspiration in Kenya.* Nairobi: East African Agriculture and Forestry Research Organization.

World Bank. (2010). *Reshaping economic geography*. Washington, D.C: World Bank.

Zhan, G. & Lin, S. (2009). Modified Blaney-Criddle method an empirical approach to estimate potential evaporation using air temperature', in AB Fourie & M Tibbett (eds), *Mine Closure 2009: Proceedings of the Fourth International Conference on Mine Closure*, Australian Centre for Geomechanics, Perth, pp. 461-471, https://doi.org/10.36487/ ACG _repo/908_35

APPENDICES

Appendix I: Percent of Moisture Based on Dry Weight of Soil

Soil type	Field capacity	Permanent wilting point	Available water per unit depth of soil, mm/m
Fine sand	3 - 5	1 - 3	20- 40
Sandy loam	5 -15	3- 8	40-110
Silt loam	12-18	6 -10	60-130
Clay loam	15-30	7-16	100-180
Clay	25-40	12-20	160-300

Lockhart & Wiseman, 2015

Appendix II: Return Period Criteria for Design Purposes

Return Period Criteria for Design Purposes			
Class of water storage structure	Minimum Return Period for Design of Spillway (WRM Rules 2007)	Recommended Minimum Return Period for Design of Spillway	Recommended Minimum Return Period for Design of Diversion Works, if required
A(Low risk)	1 in 50 years	1 in 50 years	1 in 5 years
B(medium risk)	1 in 100 years	1 in 100 - 500 years	1 in 10 years
C(High risk)	1 in 500 years	1 in 1000 years	1 in 15 years
(Source: WRM Rules 2007)			

Appendix III: Lined or Constructed Channels

	Minimum	Normal	Maximum
a. Cement			
1. neat surface	0.01	0.011	0.013
2. mortar	0.011	0.013	0.015
b. Wood			
1. planed, untreated	0.01	0.012	0.014
2. planed, creosoted	0.011	0.012	0.015
3. unplanned	0.011	0.013	0.015
4. plank with battens	0.012	0.015	0.018
5. lined with roofing paper	0.01	0.014	0.017
c. Concrete			
1. trowel finish	0.011	0.013	0.015
2. float finish	0.013	0.015	0.016
3. finished, with gravel on bottom	0.015	0.017	0.02
4. unfinished	0.014	0.017	0.02
5. gunite, good section	0.016	0.019	0.023
6. gunite, wavy section	0.018	0.022	0.025
7. on good excavated rock	0.017	0.02	
8. on irregular excavated rock	0.022	0.027	
d. Concrete bottom float finish with sides of:			
1. dressed stone in mortar	0.015	0.017	0.02
2. random stone in mortar	0.017	0.02	0.024
3. cement rubble masonry, plastered	0.016	0.02	0.024
4. cement rubble masonry	0.02	0.025	0.03
5. dry rubble or riprap	0.02	0.03	0.035
e. Gravel bottom with sides of:			
1. formed concrete	0.017	0.02	0.025
2. Random stone mortar	0.02	0.023	0.026
3. dry rubble or riprap	0.023	0.033	0.036
f. Brick			
1. glazed	0.011	0.013	0.015
2. In cement mortar	0.012	0.015	0.018
g. Masonry			

1. cemented rubble	0.017	0.025	0.03
2. dry rubble	0.023	0.032	0.035
h. Dressed ashlar/stone paving	0.013	0.015	0.017
i. Asphalt			
1. smooth	0.013	0.013	
2. rough	0.016	0.016	
j. Vegetable lining	0.03		0.5

Manning's n for Channels (Chow, 1959)

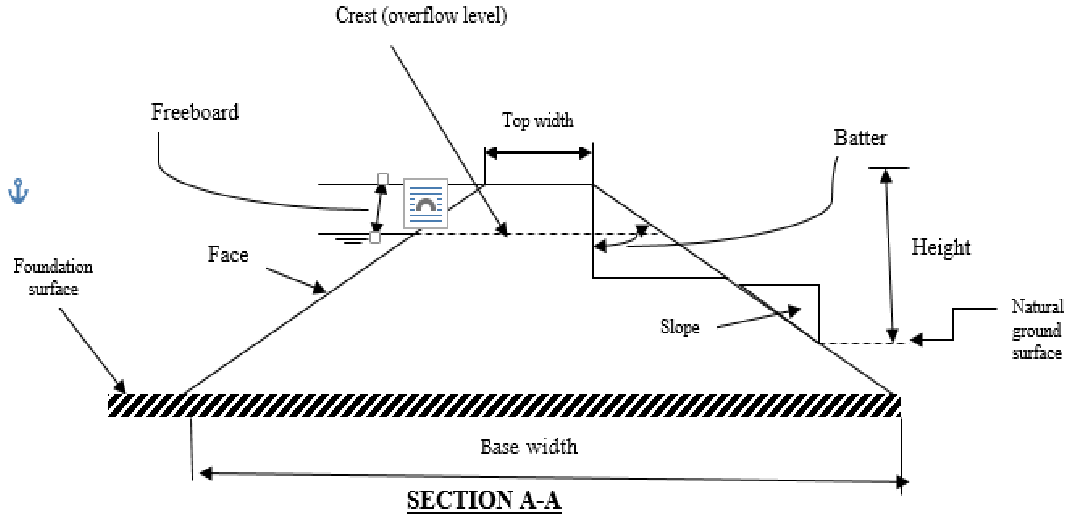
Appendix IV: Description and Curve Numbers for Cultivated Agricultural Lands

Cover type	Treatment	condition	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row (SR)	Poor	72	81	88	91
		Good	67	78	85	89
	SR + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	C + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	C&T+ CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	SR	Poor	65	76	84	88
		Good	63	75	83	87
	SR + CR	Poor	64	75	83	86
		Good	60	72	80	84
	C	Poor	63	74	82	85
		Good	61	73	81	84
	C + CR	Poor	62	73	81	84
		Good	60	72	80	83
	C&T	Poor	61	72	79	82
		Good	59	70	78	81
	C&T+ CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded	SR	Poor	66	77	85	89
or broadcast		Good	58	72	81	85
legumes or	C	Poor	64	75	83	85
rotation		Good	55	69	78	83
meadow	C&T	Poor	63	73	80	83
		Good	51	67	76	80

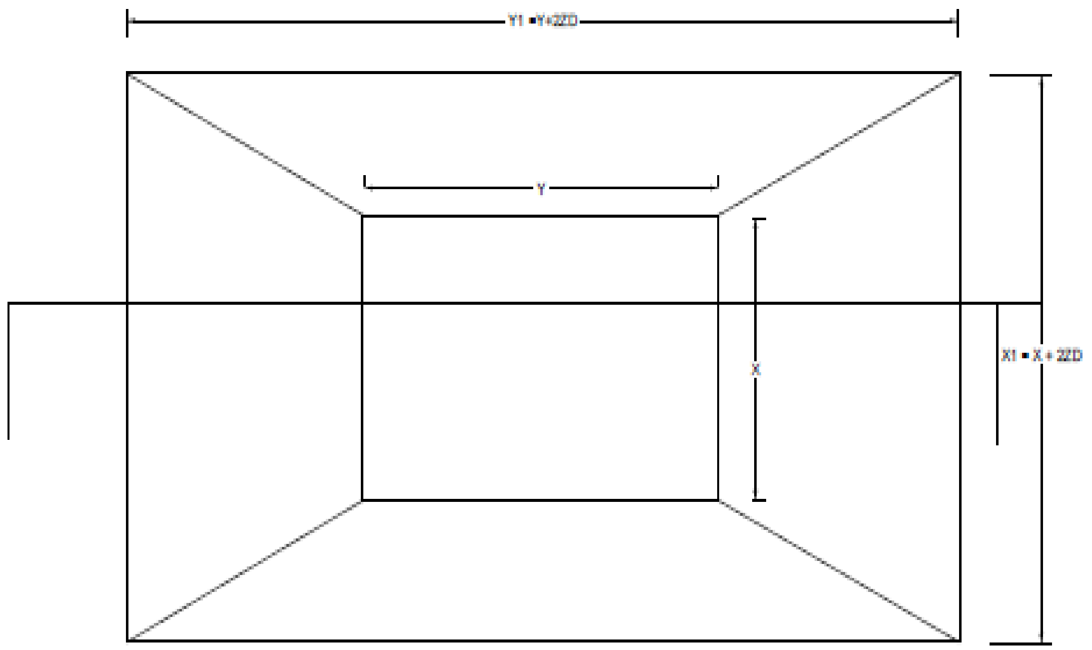
Appendix V: Approximate Values of Seasonal Crop Water Needs

Crop	Crop water need (mm/total growing period)
Alfalfa	800-1600
Banana	1200-2200
Barley/Oats/Wheat	450-650
Bean	300-500
Cabbage	350-500
Citrus	900-1200
Cotton	700-1300
Maize	500-800
Melon	400-600
Onion	350-550
Peanut	500-700
Pea	350-500
Pepper	600-900
Potato	500-700
Rice (paddy)	450-700
Sorghum/Millet	450-650
Soybean	450-700
Sugarbeet	550-750
Sugarcane	1500-2500
Sunflower	600-1000
Tomato	400-800

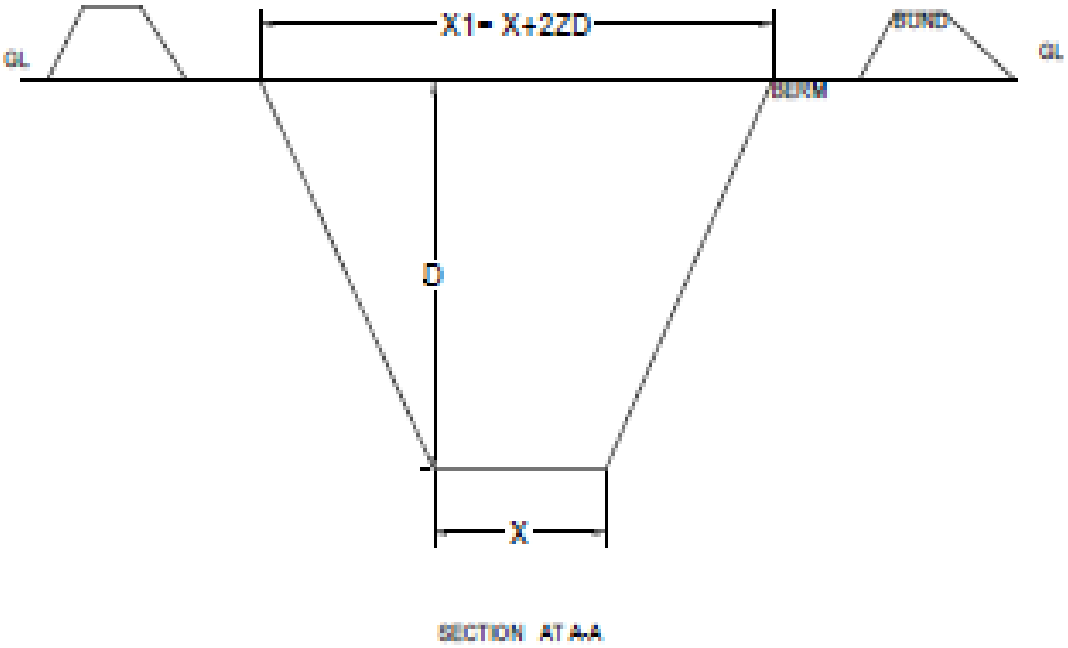
FARM POND DRAWINGS



Features of the farm pond



Plan view of the farm pond



Sectional View of The Farm Pond