DEVELOPMENT OF A DECISION SUPPORT SYSTEM FOR RUNOFF WATER STORAGE AND IRRIGATION – CASE STUDY OF COMMON BEAN AT UKWE, MALAWI

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A DISSERTATION SUBMITTED IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF AGRICULTURE, MOROGORO, TANZANIA.

2015

EXTENDED ABSTRACT

Temporally and spatially poor rainfall distribution in sub-Saharan Africa (SSA) has had serious repercussions on crop production resulting in high negative consequences on food production and financial returns for farmers. Harvesting and storing of rainwater for irrigation of crops (such as cereals and legumes) is, therefore, needed. One of the important legumes in sub-Saharan Africa, which serves as both food and cash crop, is the common bean (*Phaseolus vulgaris,* L). Demand for common bean in SSA outstrips production due to erratic and inadequate rainfall which results in yield reduction or loss of harvests. It is widely known in many SSA areas, such as Central Malawi Plains, that positive relationship between harvested watershed runoff and rainfall prevails, and that runoff water harvesting technique can contribute to food security through irrigation of beans and maize. However, among reviewed agro-hydrological models there is none being functional for relative processing of rainwater runoff, open surface water long-term storage and irrigation of common beans. Consequently, no decision support system concerning these processes is in use by farmers and agricultural field staff.

The study using common bean at Ukwe Area, as a case study crop and site respectively, for semi-arid SSA, relates runoff, water storage and its potential irrigation field area. Main methodology involved assessment of catchment area attributes for runoff rainwater, measuring and calculating of volume of water harvested and determination of irrigation water and crop water productivity. A number of instruments were used for surveying the catchment characteristics and measuring prevailing climate conditions, reservoir water volumes and crop parameters.

The study also premised on development of an agro-hydrological model component for strategic and tactical decision making to provide 'what if' solutions for the above-mentioned relationships. It was based on conceptualization, documentation and description, program coding and use of subroutines through incorporation of irrigation and socio-economic subroutines to *Nedbor Afstromnings* Model (NAM). Furthermore, the study focused on designing and validating a Decision Support System (DSS) for synchronization of catchment characteristics, reservoir capacity and irrigable field size. Results are conclusive that rainfall in the drought prone areas is unreliable and poorly distributed over a season, and is also frequented by dry spells. Findings showed that runoff water was highly related to seasonal rainfall amount with confidence limit (R^2) of 0.75.

It is illustrated that drought prone areas are sometimes flood prone as well. Total volume of water harvested led to estimation of field area at common bean water productivity of 0.71 g/L, slightly lower than values of higher than 1 g/L reported in Malawi and elsewhere. Socio-economic analysis demonstrated higher yield from irrigation than from rain-fed production, but fewer farmers expressed maximum willingness to be paying the current annual water harvesting contribution cost of US$ 17. Modified NAM demonstrated effectiveness in simulating rainfall - runoff, runoff-reservoir water volume, and volume - bean crop field size relationships. This was achieved through adjustment of the model parameters and time constants. With optimization of catchment parameters and runoff routing constants the model effectively simulated runoff with computed value magnitudes largely matching the measured values, from minimum of 0.5 m^3/day in drought year of 1988 to the highest 16 m^3/day in the highest rainfall in 1987. The added component of sub-routines for reservoir water losses and uses enables the model to simulate compute seasonal water balance and crop water productivity. The model is therefore agro-hydrological tool for making informed prediction relating to runoff, open rainwater storage and irrigation crop water productivity.

The developed Decision Support System, based on excel spreadsheet operation, reliably relates irrigation water to gross runoff rainwater stored (70%). For two dry season crop production cycles, at the same crop water productivity of 0.7 g/L, potential crop command field area of 1.5 ha is simulated. It is established that stakeholders can use the DSS developed information to support their decisions in planning field area for farmers based on reservoir capacity or build a reservoir to suffice crop land area to mitigate drought and dry spell impacts.

Key words: beans, agro-hydrological model, socio-economic analysis, decision support System

DECLARATION

I, DARWIN DODOMA SINGA, do hereby declare to the Senate of Sokoine University of Agriculture, that this dissertation is my own original work, and has never been submitted, nor concurrently being submitted for a degree award in any other University.

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11th November, 2015
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ACKNOWLEDGEMENTS

My profound gratitude is to God, the Highest, within and beyond the universe, for His graceful gift of life and knowledge that have made this work possible.

My sincere thanks are due to my supervisors, Prof. S. D. Tumbo, and Prof. H. F. Mahoo from the Department of Agricultural Engineering and Land Planning and Prof. F. B. Rwehumbiza from Department of Soil Science, Sokoine University of Agriculture (SUA), and Prof. M. Lowole from the Lilongwe University of Agriculture and Natural Resources (LUANAR) for their intellectual guidance, enduring all the odds for this work to be accomplished.

Special appreciation goes to the Regional Universities Forum for Capacity Building in Agriculture (RUFORUM) for the scholarship award which supported me in the course work and livelihood at the university. I wholeheartedly acknowledge the International Development and Research Centre (IDRC) for scholarship and research funding support. The assistance from Carnegie Corporation of New York, USA, who awarded me with supplementary research funding, is highly acknowledged.

The support by LUANAR in much needed technical and administrative guidance as well as some fuel, during the in-country research activities, is highly appreciated and will never be forgotten.

I am humbled to all the Sokoine University of Agriculture staff, who made all the effort to make the accomplishment of my studies possible among whom are the Head of Department Professor S. M. Mpanduji, the programme co-ordinators Prof. A.K.P.R. Tarimo, Dr A. Kaaya and Dr F.C. Kahimba.

My immense thanks are due to the management of Total Landcare for assistance in farming community mobilization and assistance of Mr M. Hola who was instrumental in daily site data collection. I am highly indebted to Dr Henry Njoloma of Green Belt Initiative in Malawi for intensifying the taste of hydrological modelling and introducing and familiarizing me with NAM, a model reflected in my research work, to me.

The moral support of my family during the entire course of the study is much appreciated. You endured my long time absence and subjected some of our meagre resources towards the study demands. God bless you.

DEDICATION

To my late father and late mother, and all fellow resource poor small-scale farmers for enduring debilitating and unpredictable weather calamities and produce food and income for their families.

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LIST OF ACRONYMS AND ABBREVIATIONS

A	Irrigated area
APSIM	Agricultural Production Simulator
CERES	Crop Environment Resource Synthesis
CO_2	Carbon dioxide
CWP	Crop water productivity
CWR	Crop water requirement
CV (%)	Percent coefficient of variation
D	Maximum water depth
DHI	Danish Hydraulic Institute
DMA	Double Mass Analysis
DSS	Decision Support System
DSSAT	Decision Support System for Agro-technology Transfer
DWB	Dam Water Balance
ESA	Eastern and Southern African
ELMS	Environment and Land Management Sector
FAO	Food and Agricultural Organization
DGPS	Differential Global Position System
E_{pan}	Pan evaporation
$E_{reservoir}$	Reservoir evaporation
EV	Evaporated water volume (m^3)
Evapn	Evaporation
FAO	Food and Agricultural Organization
FORTRAN	Formula Translation Programming Language
GEV	General extreme value
GIS	Geographical information system

GOM	Government of Malawi
ha	Hectare
H & S	Harvested and Stored respectively
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
ICARDA	International Center for Agricultural Research in the Dry Areas
ICRISAT	International Centre for Research in semi-Arid Tropics
IDRC	International Development Research Centre
IFAD	International Food and Agricultural Development
ITDG	Intermediate Technology Development Group
IWMI	International Water Management Institute
LL	Lower limit
LSD	Least standard deviation
m^2	Square metres
MAFS	Ministry of Agriculture and Food Security
MIWD	Ministry of Irrigation and Water Development
NAM	*Nedbor Afstromnings* Model
NCEA	National Centre for Engineering in Agriculture
NPKS	Nitrogen Phosphorus Potassium Surphur
OMAFRA	Ontario Ministry of Agriculture, Food and Rural Affairs
PARCHED -THIRST	Predicting Arable Resource Capture in Hostile Environments During the Harvesting of Incident Rainfall in the Semi-arid Tropics
PUTU	Hydrological model by Putu, Santikayasa
Q	Flow rate (mm/day)

RA_{max}	Full water supply reservoir surface area (m^2)
RAM	Readily Available Moisture
Res. Balance	Reservoir balance
RUFORUM	Regional Forum for Capacity Building in Agriculture
S	Stored
SADC	Southern African Development Community
SI	Supplementary Irrigation
SSA	**S**ub-Saharan Africa
UL	Upper Limit
US$	United States of Dollar
VEMAP	Vegetation/Ecosystem Modelling and Analysis Program
MS	Microsoft
V	Volume of water
W	Mean Reservoir surface water depth

CHAPTER ONE

1. INTRODUCTION

Increased competition for land and water is one of the major factors likely to increase vulnerability to food insecurity especially in African and Asian regions (FAO, 2011). In these regions, many countries are facing unprecedented decline in per caput amount of irrigated land from 1% to 2.3% per year from early 1960s to 1975, and to less than 1% from 1990s. The decrease has been due to, among other bottlenecks, high environmental and social costs and poor irrigation performance (Rosegrant and Svendsen, 1993). Use of irrigated agriculture indicators signify declining role of agricultural water management as one of the contributing factors (Valipour, 2015). Agricultural water management impinges effectiveness of water use in relation to water source capacity. Crop yield gaps between potential and actual yields attained commonly prevail in the sub-Saharan Africa (SSA) mainly due poor agricultural water management. The yield gaps exist due to limitations in cultivar characteristics, cropping practices, climatic and soil conditions, and pests as well as disease infections (World Bank, 2010).

Identification of factors that impinge most on crop production is a milestone towards achieving potential crop productivity which is a benchmark for crop production under adequate irrigation water or rainfall conditions (van Ittersum *et al.*, 2013). However, recurring and cumulative damage from drought has worsened dramatically the yield production in many of the world regions (Kamthonkiat, 2008). This is a challenge that needs to be addressed.

In SSA where receding of water with the advent of dry season is higher than in high rainfall areas due to below soil surface inadequacy of moisture as a result of frequent large droughts. Poor farmers in developing countries are the most vulnerable and the least able to adapt to these challenges of water scarcity (FAO, 2011). Harvested and stored runoff water can, hence, be used for irrigation through supplementation during dry spells and as sole water source during the dry season (ITDG, 2015; ICARDA, 2014). For smallholder farmers, reserved open surface water can be used for irrigation through gravity fed delivery system or use of minimal pumping effort or water cans.

Small-scale water harvesting systems, which encompass a broad set of technologies from soil and water conservation systems for infiltration enhancement to micro dams, have an important, and a yet untapped, potential to improve soil and water productivity level and contribute to irrigation assets of farmers (Mloza-Banda, 2003). Results from small scale experiments in the central Malawi Plains, have shown positive relationship between harvested runoff and rainfall, and that runoff water harvesting techniques can contribute to food security through irrigation of beans and maize (Singa and Chirambo, 2008).

The rainy season in the country, runs between late November and April and may be interspaced by dry spells lasting more than one week. Dry spells of more than one week render some farmers to either lose the whole bean crop or sustain drastic crop yield reductions. In the southern drought-prone areas use of simple cost-effective techniques of rainwater harvesting have made farmers store water and use it for irrigation through much of the dry season (ASAP, 2011).

From the foregoing scenario, there is, hence, a need to efficiently harvest and use the scarce rainwater resources, stored in reservoirs through integrated rainwater harvesting and irrigation production systems (Ibraimo and Munguambe, 2007). Research reports indicate that when reservoirs are used for dry season irrigation, water storage should be below the calculated yield of the catchment in a dry year or based on an acceptable average minimal yield over a period of years (FAO, 2010). The reports are, however, all based on single system entity and without establishing appropriate variable combinations of catchment area runoff attributes, open surface reservoir stored water and bean crop water productivity. Development of agro-hydrological models to simulate sustainable rainwater conservation and intensified crop productivity based on reservoir capacity and crop field area to be irrigated is therefore needed.

In European countries, Valipour (2015) provided an estimation of areas equipped for irrigation and desirability of water management previously not researched. The relative estimation was based on water management, crop type, cultivated area, irrigation equipped area, active and total rural population (RP), human development index, Gross Domestic Product, National Rainfall Index (NRI) and Irrigation Water Requirement Indices (IWR). Estimation results showed that to obtain relationships among the indices, each country or region must be treated separately. Index prioritization indicated that difference between NRI and IWR; RP per total population and permanent crops per cultivated area had significant effects on estimation of area equipped for irrigation per total cultivated area.

Research in the United States of America (USA) by Valipour (2013) showed that the effect of geographic condition on climate was more than hydrology. The Surface Water Supply Index (SWSI) was found to be one of the most important hydrologic parameters for study of drought and flood periods in hydrological basins. Use of the

SWSI further revealed that the stream-flow component or the reservoir is the predominant driving force for water use and management at any given time.

Elsewhere, such as Thailand, an Agro-hydrological model called SWAP-RS-GA (Soil Water Atmosphere and Plant-Remote Sensing-Genetic Algorithm) has been developed to simulate values of evapotranspiration, soil moisture and other irrigated crop factors following model validation (Kamthonkiat, 2008). These developments have not been reported in SSA.

From the above mentioned scenarios, modeling work to fully relate rainfall, runoff, water storage and irrigation in the drought prone SSA region is needed if the effects of drought and dry spells are to be averted. This is a crucial step towards development of a reliable decision support system (DSS) for assisting the agricultural staff and farmers harvest and store runoff water, in open surface reservoirs , for irrigation of important cereals and legumes during dry periods (ITDG, 2015).

Legumes are one of the major components of farming systems in smallholder agriculture in SSA. In spite of their importance, productivity of legumes has remained stagnant or even declined over the years because of constraints such as drought, pest and diseases, and limited access to improved variety seeds (ICRISAT, 2011).

One of important legumes in sub-Saharan Africa is the common bean (*Phaseolus vulgaris*, L*)*. It is an important legume for resource poor small-scale farmers. The crop is a vital source of protein for many people both in rural and urban areas, especially those who cannot afford meat and fish protein. Common bean is also a source of income to many small-scale farmers who happen to be the major producers (Monyo and Kananji, 2013).

In recent years, common bean crop production trend has not kept pace with the annual population growth rate (estimated above 2%) in southern and eastern Africa due to a number of biotic, abiotic and socio-economic constraints. Among the abiotic constraints, agricultural drought is the major and common constraint across the region (Katungi, *et al.*, 2009).

Trends show that in Malawi, common bean growing area increased from 145,000 ha in 2001 to 220,000 ha in 2007 (a 50% increase). Increasing domestic demand for common beans is the underlying factor behind this acceleration in area expansion, as primary source of protein since animal meat and fish are expensive (Mtumbuka, et al., 2014). However, literature has also revealed that, in Malawi, like in the rest of SSA, common bean production trend has not kept pace with the domestic and export demands. Human population growth rates were 3.5% from 1970 to 1989, 1.6% from 1990 to 1999 and 2.2 % from 2000 to 2007. The corresponding common bean per capita availability was -0.01, -2.90 and 0.00 kg per person respectively (Ibraimo and Munguambe, 2007). Currently, the population growth is 3% while common bean per capita availability has not improved.

In Uzbekistan, three irrigation schedules (recommended, moderate and severe depletions) and combinations were investigated with respect to crop water use efficiency. It was established that increasing common bean water use efficiency is a promising avenue for crop yield improvement, especially for arid and semi-arid areas where there is little or no prospect for expansion of water resources (Webber *et al.*, 2006). However, the investigations were more focused on comparison between common bean and green gram, and two irrigation strategies (conventional and alternate furrow irrigation) than on crop water productivity based on available harvested rain water. This gap of knowledge about harvested water and crop water productivity needs to be investigated for the SSA region.

The most critical common bean growth stage requiring adequate water is during and immediately after the flowering. At this stage the crop requires moderate effective rainfall of more than 600 mm, yet in drought prone areas the low erratic rainfall is less than 520 mm resulting in low annual crop yields. Despite the tremendous crop water problems common bean growers face in SSA, runoff water harvesting as related to long term water storage for irrigating common beans has not been modeled to provide synchronization of availed water quantity and irrigation command area.

Production of common bean, especially the high yielding tasty dwarf *Kalima* variety, has positive impacts on the socio-economic status of the participating farmers in Malawi. The country is one of the principal producers of beans in the Southern African Development Community (SADC) region with average annual production of about 111,889 tonnes (Monyo and Kananji, 2013). This then necessitated incorporation of some socio-economic analysis of the water harvesting system and irrigation of beans as a component of the study.

Available research recommendations have been based on incomplete hydrological, crop production and socio-economic systems. This is another component that needed to be addressed in the study. Furthermore, the recommendations have been based on direct application of harvested water without long term storage, and establishment of appropriate variable combinations for increased and sustainable productivity of crops, such as common bean (Ngigi, 2009). This is a research gap that needs to be addressed.

Literature, in Malawi and elsewhere, has not indicated availability of combined decision support system in runoff water harvesting and long term open reservoir storage in relation to dry season irrigation. Research recommendations have been based on direct application of harvested water without long term storage, and mostly on crop types other than legumes such as common beans. In other agricultural sectors, such as agronomy, crop protection and soil science, decision support systems have been developed and successfully used in specific problem domain (Larbi, 2011). It is thus hypothesized that a model-based decision support system (DSS) for optimum utilization of open reservoir stored water can help common bean growers to minimize over or under irrigation with respect to reservoir volumes and crop water productivity.

Based on the foregoing aspects, therefore, the study focuses on model and decision support system to provide 'what if' solutions for relationships among runoff, stored water amounts and water productivity using dry season common bean crop water requirement. The study is based on conceptualization, documentation and description, program coding and use of subroutines through incorporation of irrigation and socio-economic subroutines to the *Nedbor Afstromnings* Model (NAM) to develop the Decision Support System. The NAM model structure deals with catchment as one unit with parameters and variables as mean values for the entire catchment. The catchment runoff is comprised of *overland flow*, *interflow* and *groundwater flow* from the upper and the lower aquifer. The model structure conceptually uses a combination of physical structures, full equations and semi-empirical equations (Nguyen *et al*., 2012; Njoloma, 2010).

Development of the DSS followed operational trend by, firstly, utilizing catchment and time constants optimization, precipitation and potential evaporation so that it simulates land water storages, and flows which are routed to the reservoir as outputs. Secondly it utilized evaporation, seepage and livestock water use data to display reservoir water balance for irrigation. Finally, it needed crop water use entry so it could display the required land area to be prepared. The procedure was based on Microsoft (MS) Excel version 1997-2003.

Results are conclusive that rainfall in the drought prone areas, such as Ukwe, is unreliable and poorly distributed over a season, and is also frequented by dry spells. It has been demonstrated reservoir water capacities can be more clearly defined and crop water productivity known once water losses and abstraction rates are identified. Calibration and validation results have shown that the developed model is a reliable agro-hydrological tool to simulate runoff with confidence given climate and catchment factors. Use of the developed DSS can provide stakeholders with information to make decisions in planning field area for farmers based on reservoir capacity or build a reservoir to suffice crop land area to mitigate drought and dry spell impacts.

Literature cited in this chapter is listed in Chapter Five (General Conclusion and Recommendations). This is due to the fact that the two chapters complement each other in augmenting the entire study.

1.2. STUDY OBJECTIVES

From the foregoing findings for Asia, Europe, USA and Africa (especially SSA) based on parameters of rainfall, catchment characteristics, forecasted irrigation area and surface water management, the currently reported research work was conducted to relate the parameters for optimization of crop water productivity. The study, using Ukwe Area in Malawi as a case site representing semi-arid areas, focused on hydrological factors as they impinge on surface runoff water storage, irrigation and socio-economic returns for the farmers. The overall objective was to develop a decision support system for surface rainwater storage and irrigation for improving bean productivity in drought prone areas.

Specific objectives include the following:

i. To determine effects of catchment characteristics, water reservoir capacities and irrigation on bean productivity;

ii. To develop a model for irrigated common bean production based on harvested water from small catchments;

iii. To design and validate a Decision Support System for a given combination of catchment characteristics, reservoir capacity and local climatic conditions.

CHAPTER TWO

EFFECTS OF CATCHMENT CHARACTERISTICS, WATER RESERVOIR CAPACITY AND IRRIGATION ON COMMON BEAN PRODUCTIVITY

ABSTRACT

Crop production in semi-arid sub-Saharan Africa (SSA) is limited by over-reliance on erratic and inadequate rainfall which often results in yield reduction or total crop failure. The effects of frequent droughts and dry spells need to be circumvented by water conservation and irrigation. In many areas water for supplementary irrigation during the dry spells/droughts or for dry season irrigation is inadequate or non-existent. Where rainwater has been harvested research recommendations have been based on direct use of the water without relating it to catchment characteristics, long term storage, and on crop types other than legumes. A study aimed at predicting sizes of seasonal open surface reservoir and crop field in relation to catchment characteristics, runoff rainwater and crop-water productivity for smallholder farming communities was conducted from 2011 to 2013 at Ukwe Area, Malawi. The work premised on assessment of land and agro-hydrological factors as they impinge on runoff water storage, irrigation, crop productivity and socio-economic returns. Findings showed that runoff water harvested, under the Ukwe landscape conditions, is linearly related to seasonal rainfall amount with coefficient of correlation (R) 0.75. Total volume of water harvested was estimated to support about two times the current field area at bean water productivity of 0.71 g/L.

Key words: runoff, irrigation, beans, productivity

2.1. INTRODUCTION

Unlike countries of Northern Africa, West Asia, Central Asia, and large parts of South and East Asia, which are already at the peak of their potential irrigation, sub-Saharan African countries have technically ample scope for expansion of irrigation as long as rain water is conserved for the purpose. The situation is even more so for highland areas such as the Fouta-Djallon and the Ethiopia, which experience high volumes of runoff, but have low levels of water infrastructure (FAO, 2011). Elsewhere, many countries in Asia have expanded their irrigation beyond its potential, while those in South America are the least in exploiting their irrigation potential. In Europe, it has been established that agricultural water management impinges on water use in relation to water source capacity (Valipour, 2015).

Similarly, in Eastern and Southern Africa (ESA), agricultural returns are constrained by unpredictable rainfall, droughts and floods which severely disrupt proper performance of farming systems and food production in several areas (FAO, 2008). Legumes, such as common bean (*Phaseolus vulgaris,* L.*),* are one of the major components of farming systems in smallholder agriculture, and source of income and protein for the poor in Sub-Saharan Africa (SSA). In spite of their importance, productivity of beans has remained stagnant or even declined over the years because of constraints such as drought, pest and diseases, and limited access to improved seed varieties (ICRISAT, 2011). Drought is a major constraint to bean production (Katungi *et al.*, 2009).

Though not verified over the current decade, it is widely viewed that dry season irrigation of common beans to improve the annual common bean supply, currently contributes only less than 10% of the annual crop due to scarcity of irrigation water.

In Central and Southern Africa farmers are forced to use extensive seasonally saturated, grassy depressions locally called *dambos,* as means of increasing bean productivity with the challenge of recurrent droughts and floods, and declining soil fertility. Elsewhere, in Saudi Arabia, under very high temperatures and water scarcity, crop water productivity values of 1g/L have been reported from experiments (Hashim, *et al*., 2012). Research is required for SSA bean growers to establish the prevailing crop water productivity in SSA in order to optimize water use in the face of continuing irrigation water scarcity.

The *dambos* have impermeable soil layers and, therefore, are potentially rain runoff recipients with high retention capacities of water, available for residual or irrigated crop water growth. Currently 62,000 ha of *dambo* land in Malawi are under simple traditional irrigation using residual moisture and supplementary irrigation on stream-bank gardens (*dimba*) and wetlands (Bishop-Sambrook, 2007).

In Malawi, where *dambo* residual moisture prolongs, up to June, it solely supports the bean crop growth, but where it rescinds and the *dambo* fields dry up, irrigation takes the crop to maturity. Sole dry season bean crop is grown from August/September to November (after avoiding the crop-harmful winter chill of June to July) irrigating it using water from natural or artificial reservoirs (dams). The size of a *dambo* varies widely from an area of several square km to a narrow wetland of about 100 meters, and fluctuates from year to year or season to season depending on amount of rainfall (Balek, 2011).

It is estimated that the total irrigable area in Malawi ranges between 400,000 and 600,000 ha, with some literature showing irrigation potential of 1,000,000 ha (Waalewijn, 2010).

Out of the total Malawi land area of 2,158,334 ha, 12% (259,000 ha) is occupied by *dambos*. About 70% of the *dambo* area is formed by upland *dambos* and 25% by flood plain *dambos* (Kambewa, 2005). The small farm water reservoirs of different sizes built in the *dambos*, fed by stored soil water sustain most of the small scale irrigation in Malawi, countering recessional water as the dry season progresses (Kadyampakeni *et al*., 2014).

Farm water reservoirs with capacity of less than 100,000 m^3 are classified as small, 100,000 m^3 to 5,000,000 m^3 as medium and over 5,000,000 m^3 as large (McCartney *et al*., 2002).

Average reservoir depths are about 2, 8 and 15 m respectively and surface area to volume ratio 0.88. The water reservoirs in *dambos* are used in more diversified needs, viz; irrigation, livestock drinking and for domestic purposes such as washing and bathing (Veldman, 20120). Water in the small Mphetsankhuli reservoir, involved in this study, is only used for irrigation and livestock drinking.

The driving forces behind establishment of Ukwe *dambo* reservoir and bean production club were food insecurity and poor income generation in the face of recurrent droughts. Farmers, with help of the government managed to build the water reservoir, water delivery pipe to the edge of the field downstream and established a bean growing club 2 decades ago. Physical (waterways and bunds) and biological (woodlots) conservation measures were put in place to prevent catchment and reservoir degradation. All recommended agronomic and crop protection measures were being practiced by common bean growers, but there prevailed lack of technical and scientific knowledge about agro-hydrological interactions by field staff and farmers. The amount of runoff to the reservoir with respect to seasonal rainfall and catchment area was not established.

The procedure to quantify seasonal open surface reservoir and relate it with bean crop yields for optimization of returns from the system has not been devised. During drought years, coupled with increasing population of farmers, the crop runs out of irrigation water (*dambo* desiccation) and during normal or high rainfall seasons, excess water remains in the reservoir due to comparatively smaller bean fields. Application of concepts of catchment, water storage and irrigation parameter variations and their applications has not been technically and socio-economically embraced due to catchment parameter variations and poor understanding of their application in water storage and irrigation (Njoloma, 2009).

The overall objective of the study was, therefore, to determine the effects of catchment characteristics, water reservoir capacities and irrigation on bean productivity. The specific objectives were,

i. To predict seasonal runoff amounts based on rainfall and catchment characteristics
ii. To quantify seasonal variation of open surface reservoir water in relation to runoff from a catchment area
iii. To relate seasonal reservoir water capacity and bean crop water productivity

2.2. MATERIALS AND METHODS

2.1. Study location

Ukwe Area, is located in Lilongwe North-West in Malawi - about 20 km from the Lilongwe city, was used as a study site. The area is about 1150 m above sea level, 13^{o} 46’ S and 33 ^{o} 37’ E to 13^{o} 55’ S and 33^{o} 38’ E, extending 13^{o} 46’ S and 33 ^{o} 31’

E to 13 º 50’ S and 33 º 32’ E, occupying flat *dambo* margins. The area has a small dam, called Kalembe dam, also called *Mphetsankhuli* dam (for its support of production of appetite satisfying food crops) fed by an ephemeral Kalembe stream (Figure 2.1). The stream is seasonal, flowing only in the rainy season (December to April).

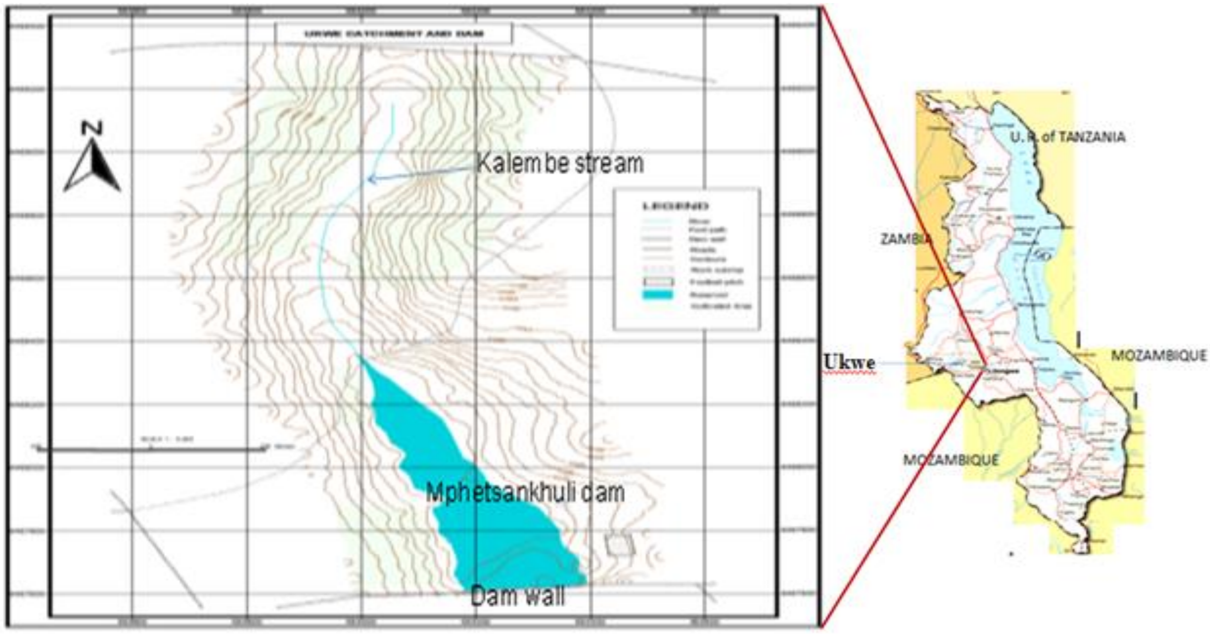

Figure 2.1: Location of Ukwe area in Malawi

The Kalembe stream and Mphetsankhuli dam catchment lies on a gentle slope (2 to 5%) towards the dam with savannah woodland vegetation regenerated shrubs and scattered trees (mostly exotic cassia type). Temperatures range from 18 to 24ºC rising to 29ºC just before the start of rains (October to November). Cultivated fields have organic matter content of 1.75%, pH of 5.5 and soil bulk density of 1.35 g/cm^3. The area is drought-prone and farmers have a bean irrigation club whose activities are being assisted by an agricultural field assistant based at the area.

2.2.2. Instrumentation and data collection

2.2.2.1. Catchment area and rainfall

Catchment area and topographic determinations were carried-out using the Differential Global Position System (DGPS) – Leica model G509. The highly precise equipment, composed of datum set base station and several point mobile rover stations with radio communication facility was found to have a measurement error of less than 3 mm out of 100 m differential. A total catchment area of 103 ha, including the reservoir whose maximum rainy season area is 8 ha was identified. But physical observations showed only 16 ha to be the actual catchment that contributed runoff water to the reservoir, with the rest areal runoff being intercepted by some physical (bunds) and biological conservation (woodlot) measures.

Vegetation influences runoff in line with soils, slope and land use. The dominant vegetation type and intensity were identified using the Food and Agriculture Organization grouping with each vegetative category given a percentage value (FAO, 2014). For Ukwe's Mpetsankhuli dam, the catchment area is proportionally composed of 26% cultivated land, 11% tree bush, 20% heavy grass, 22% scrub or medium grass, 21% settlements. Literature reports indicate that location of weather station grid cell size is based on the assumption that within a region of 25 by 25 kilometers the meteorological data are homogeneous. It is expected that temperature, sunshine, humidity, and wind speed gradually change over distances of 50 to 150 km (MARS, 2014).

Daily rainfall data for 2012/2013 was collected using rain gauges. Nine rain gauges, three in the upper catchment area, three in the middle slope (arable area) and three in the *dambo* area were used. Collected gauge point daily rainfall data were converted to daily mean areal data for use in the study. Thirty year rainfall data were obtained from Chitedze Agricultural Research Station (8 km west of the study site) in the same agro-ecological zone.

Literature gives a number of ways to compute daily mean areal rainfall from daily gauge stations data. Commonly recommended methods include arithmetic mean, Thiessen polygon, isohyetal, grid point, orographic and isopercental methods (Mair and Fares, 2012). Although the simplest procedure to obtain the daily mean areal rainfall for the catchment is

by calculating arithmetic mean, the procedure does not present accuracy and objectivity of the results. For this research, therefore, the Thiessen Polygon Method was chosen to obtain areal rainfall means. The method has advantages of being much more accurate, objective and being based on simple computational procedure. The purpose was to avoid inaccuracy that would occur if data of direct gauge point rainfall means were used to represent the site daily rainfall values – a scenario that would render unreliable spatial mean rainfall data for the catchment area.

High rain gauge density (nine) in the catchment area was done to reduce the error involved in the measurement of the actual rainfall. Njoloma (2009) confirmed that high rain gauge density in a small area catchment results in significant inter-station correlation among gauges reducing errors in computed areal means.

2.2.2.3. Livestock water consumption

Apart from reservoir water use by common bean irrigation farmers the only other water users are the cattle and goat owners. There were 102 heads of cattle and 143 goats depending on the reserved water, each consuming 40 L and 6 L of water per day respectively. Once a week, each head of cattle and each got was 30 L and 10 L respectively, twice a day. The remaining water was subtracted from the provided amount to obtain daily consumed amounts. The daily animal water consumption was found to be in the range reported by Ward (2014), which ranged from 38L/day for dry cows, bred heifers and bulls to 55 L/day for short keep feedlot cattle, 4 to 10 L/day for goats and sheep. Livestock water consumption values were computed by multiplying weekly individual water consumption amount by the number of animals (cattle and goats).

2.2.2.4. Reservoir and water delivery for irrigation

Depth of water in the reservoir was measured using a staff gauge, vertically installed, (using a builder's level) from a boat and height determined by the differential geographical positioning system (DGPS) rover. The reservoir had a 45 by 30 cm concrete outlet (30 cm 'dead base') on the western edge that is regulated to drain water into an iron pipe through the embankment. 'Dead base' was the depth of water retained in the reservoir (dead storage) that could not be accessed since it was below the outlet.

The piping was laid beneath the embankment at the time of its construction and delivers water into the measuring concrete rectangular basin (1.0 m X 0.5 m and 0.5 m deep) at the upper-most edge of the field 80 m downstream. The calibrated basin would be filled with a known volume of water represented by a depth line, for each bean plot as required by the crop with respect to 2.5 or 5.0 or 7.5 cm weekly application. After demonstrations by the field agricultural assistant based at Ukwe area, the farmers would, therefore, easily apply the required amount of water determined by the calibrated water basin depth line.

2.2.2.3.5. Cropping Area

The study was conducted from 2012 to 2013. The fields were located at the uppermost, middle and lowest plots along the downstream western bank of the Kalambe Stream, i.e., C, E and F (Figure 2.2). The three household fields were selected from the total of 7 common bean family fields (A to G). Common dwarf bean (Kalima variety) was used as a test crop. The variety was bred in Columbia, South America, and released in Malawi in 1995 through the Bean/cowpea CRSP programme. It is an important variety for cash, food security, nutrition and gender equity (Rusike *et al*., 2013). It is a large seeded bush type with a seed coat that has red mottles on a cream background.

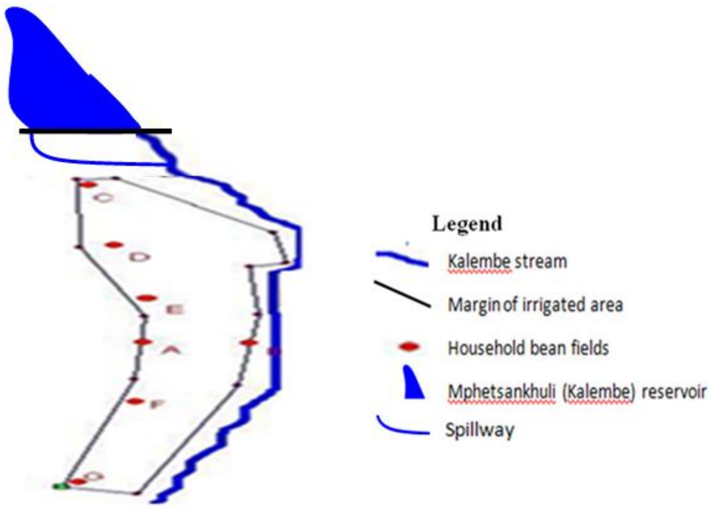

Figure 2.2: Household fields along the seasonal Kalembe Stream

All agronomic and pathological practices to avoid allelopathy, and biocides for the crop's potential growth and protection as recommended by the Ministry of Agriculture and Food Security (MAFS, 2012) were followed. These included planting in 2 rows (one seed per station) at 10 cm apart, on ridges 75 cm apart. The area of the trial field was 459 m^2. The inter-boundary spacing was one metre. NPKS (23: 21: 0 + 4) fertilizer was applied at 100 kg/ha and cypermethelin (20 % immiscible concentrate) insecticide was applied seven weeks after planting.

In this agro-ecological zone, when all the aforementioned agronomic and crop protection recommendations are followed, to achieve optimum yields, bean researchers have made a recommendation of 50 mm as a weekly irrigation water amount, following pre-planting water application of 100 mm to achieve moisture field capacity (MAFS, 2012). Emanating from this recommendation, three water regimes (25 mm, 50 mm and 75 mm) were applied for area bean yield response verification. It was a completely randomized block design with three replications for the water depths. Pre-planting water application was 100 cm.

Bi-weekly crop sampling was carried-out for biomass yield with respect to irrigation regimes. Readily available moisture (RAM) at early growth (less than 3 trifoliate), active vegetative stage (3 to 5 trifoliate) and flowering stages were determined at standard allowable depletion (P) of 50%, using a tensiometer. Two weeding operations were carried out 2 weeks and 6 weeks after planting.

In terms of water management each common bean plot was allocated time (twice) in a week to irrigate their bean plot. The reservoir water was also consumed by 102 heads of cattle and 143 goats. All domestic water is supplied by shallow wells hence reservoir water is not used for domestic chores. Like in other *dambos* sites in Malawi, the participatory decision making is coordinated by the village headman, who is instrumental in mobilizing public support towards more appropriate and effective water uses.

2.2.2.6. Areal rainfall consistency and homogeneity tests

Using the Thiessen Polygon Method the catchment area of Ukwe was subdivided into polygonal sub-areas using rainfall stations as centres. The mean areal rainfall Ř was calculated using Equation 1.

$$\bar{R} = \sum_{i=1}^{n} \frac{R_i a_i}{A} \qquad \text{..} (1)$$

Where *Ř* is mean areal rainfall, R_i is rainfall measurements at each rain gauge station, A is total area of catchment, and a_i is polygon area corresponding to rain gauge station. Since runoff into the reservoir from the catchment area, and the stream, is non-point specific flow from each area contributes to the change in volume of the reservoir.

The daily gauge rainfall data were correlated with the areal rainfall to compute a correlation coefficient, which is a statistical parameter determining the extent of correlation between the two variables. Low level of correlation would depict poor representation of the areal computed rainfall data to the measured rainfall values (Mair and Fares, 2012).

Gauging station from which rainfall data is collected and reported may not always be stationary, homogeneous and consistent over time and space. Unknown errors would occur due to unreported shifting of the location or elevation of a rain gauge, nearby abstracting activity in the area or change of observation procedures or occurrence of bush fires, earthquakes or any other natural occurrence. The data was, therefore, subjected to a Double Mass Analysis (DMA) to investigate such inconsistencies (Njoloma, 2009). Based on DMA, the cumulative rainfall of the study station and of the nearby stations is determined and a curve is drawn. Once a straight line is obtained then the study station data is consistent and reliable. All data lying after the deviation point from the straight line requires correction (Ahmad, 2010). Accumulated values of monthly mean rainfall from the nine gauge stations of Ukwe site were plotted against the areal mean values of the other stations.

Similarly, accumulated values of each of the nine rainfall stations were compared with mean values of the rest of other two stations, viz, Bunda and Kandiya stations, 50 km South and 12 km South-east respectively. The basis for this theory is that rainfall for stations in the Ukwe reservoir catchment, which is in the same climatic region with the other two stations, should be related in a long run. Any inconsistencies would result in unrepresentative trend (not real trend).

2.2.3. Analysis of data

2.2.3.1. Rainfall-Runoff Analysis

Seasonal rainfall was graphically compared to runoff values. Linear regression was used to establish a relationship between rainfall and runoff into the reservoir.

2.2.3.2. Runoff-Reservoir analysis

Since rainfall and evaporation were expressed in mm/day the surface runoff in m^3/s was also converted into mm/day. The reservoir inflows (daily discharges from the catchment area) were measured by calibrated gauge installed in the reservoir (MIWD, 2011). Measured data of daily area discharges into the reservoir were verified by data made available from the Water Department, Surface Water Division of the Ministry of Irrigation and Water Development obtained by using a calibrated gauge in the reservoir from 1959 to 2000.

The amount of runoff water accumulated in the reservoir was estimated using the derivation method from direct measurement (Sawunyama, 2005). The method is based on actual determination of reservoir characteristics in the field involving measurement of throwback, maximum depth and maximum width of reservoir water using an equation, with different values for the two constants, *K1* and *K2*. The general equation is:

$$C = K1K2DWT \quad (2)$$

Where *K1* and *K2* are constants related to the shape of the valley cross-section, *D* is the maximum water depth (difference in elevation between the lowest point in the reservoir bed and the spillway crest level in m), *W* is the width of water surface at the dam spillway crest level (m), *T* is the “throwback” at the spillway crest level (distance from the dam wall along the reservoir axis to the point of the stream inlet (m).

Equation 3 can be simplified by replacing the two constants by 1/6, thus

$$C = DWT/6 \quad (3)$$

where *C* is the reservoir water volume (m^3), *D* is the water depth (m), *W* is the average dam width (m), and *T* is the throwback distance (m) (Hudson, 1998 cited by FAO, 2010). The equation estimates capacity of a reservoir more correctly as it assumes a reservoir to be a pyramid whose base is the water surface, other than being the dam wall. Apart from being recommended for Zimbabwe, the method has also been proven valid and is also used in Malawi (Kambuku, 2010). The method was, therefore, used in this study to predict reservoir volume.

Evaporation from reservoirs was calculated using the Equation

$$EV = \frac{2}{3}\,\frac{RA_{max}}{1000}\,E \qquad (4)$$

Where; EV is the volume of water evaporated (m^3), *E* is the open water evaporation (mm), RA_{max} is surface area of the reservoir at full supply level (m^2) (Kambuku, 2010). A relationship between evaporation from a calibrated standard (Class ‘A’) open pan installed at the site and evaporation from the reservoir was established to verifiably quantify the water loss from the reservoir, as the season progressed. The pans were calibrated with $E_{pan}/E_{reservoir}$ ratio for small reservoirs of 0.7.

2.2.3.3. Reservoir water, crop water requirement

The volume of water in the reservoir was equated to the seasonal field crop water use. This was related to actual and potential water use yields. Reservoir water balance (ΔC) was based on losses due to seepage, evaporation and livestock consumption. The reservoir water volume balance (after losses through evaporation and seepage, and abstraction by livestock, up to crop harvest week) divided by total seasonal crop water requirement over a hectare provided the total area (ha) the reservoir water could irrigate.

The foregoing relationship in turn established optimum sizing of either area or reservoir for maximizing crop productivity based on the runoff generating catchment attributes and climatic conditions. The procedure is supported by the NCEA (2012) after conducting a number of research projects. The reservoir water balance due to irrigation was hence calculated by Equation 5.

$$C = I \times (Ni) \qquad (5)$$

Where; I is application rate (m^3/week) and Ni is the number of applications per week, for weekly applications of 5 cm at different ΔC values. Quantification of the reservoir balance in line with water use was achieved using the water balance Equation 6

$$\Delta C = IVc + P - E - Q - GW - I \ldots\ldots\ldots\ldots (6)$$

Where; ΔC is new water balance, IV_c is current balance from previous week, P is precipitation = 0, E is evaporation, Q is surface runoff = 0 during the dry season, and GW is seepage. GW was computed by Equation 7

$$GW = IV_p - I - E \ldots\ldots\ldots\ldots (7)$$

Where; IV_p is previous week balance, Q and P being zero. All measurements in the equation were in millimeters. The calculated balance for each week was verified by measurements of the reservoir capacity.

2.2.3.4. Crop yield and crop-water productivity

A common method of 'water can' irrigation was used. A relationship between applied water and bean water productivity *(P)* was established as shown in Equation 8

$$P = Y/W \ldots\ldots\ldots\ldots (8)$$

Where; P = Crop water productivity (kg yield/volume of water), Y = grain yield (kg), W = unit of applied water (L). Grain yield was determined as weight per hectare basis at 14% grain moisture content.

2.3. RESULTS AND DISCUSSION

2.3.1. Areal rainfall consistency and homogeneity tests

Following regression between the measured gauge rainfall means and the Thiessen computed means the following linear equation was established, which enabled the prediction of areal rainfall from the data as shown in Equation 9

$$Y = 1.616X - 0.0386 \quad (9)$$

Where; Y is the mean areal rain and X is the observed rainfall.

Rainfall data from Lumbadzi and Kandiya, 8 km North-east and 12 km East of Ukwe respectively were used to verify consistency and homogeneity of rainfall data at Ukwe site using double mass analysis method. Interpretation of the double mass analysis (DMA) is dependent on line shape rather than the usual line equation or regression (R^2) value. The basis for DMA theory is that rainfall for stations at a research site catchment, which is in the same climatic region with two or more other catchments should be related. If there are any inconsistencies, there should be a deviation from the straight line and this is also called a spurious trend not to be mistaken for a real trend (Njoloma, 2009).

There was no inflection points observed from the data plots. Therefore, it is concluded that the data is consistent and homogeneous and could be used for further analyses, such as runoff, with confidence.

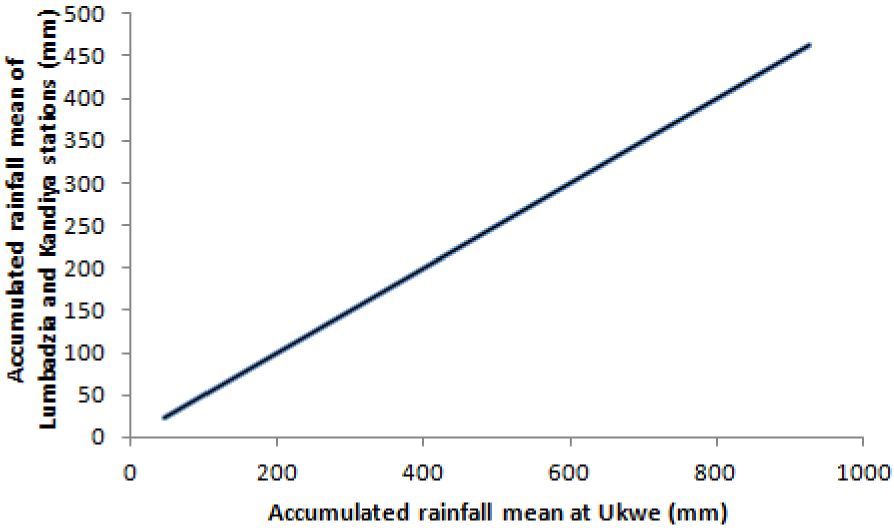

Figure 2.3: Double mass line for accumulated Ukwe mean annual rainfall against the mean of the other two stations

2.3.2. Rainfall-runoff analyses

The unimodal rainfall pattern in Ukwe area commences as heavy storms in December when the soil is dry and highly absorbent resulting to negligible runoff. Runoff relatively peaks up between January and February but again rescinds as the season progresses due to both vegetative cover and reduction in rain amounts. Relative analysis showed runoff trend following the magnitude of rainfall (Figure 2.4). Runoff into the reservoir is non-point; it is distributed into the reservoir by the whole catchment area from diverse points.

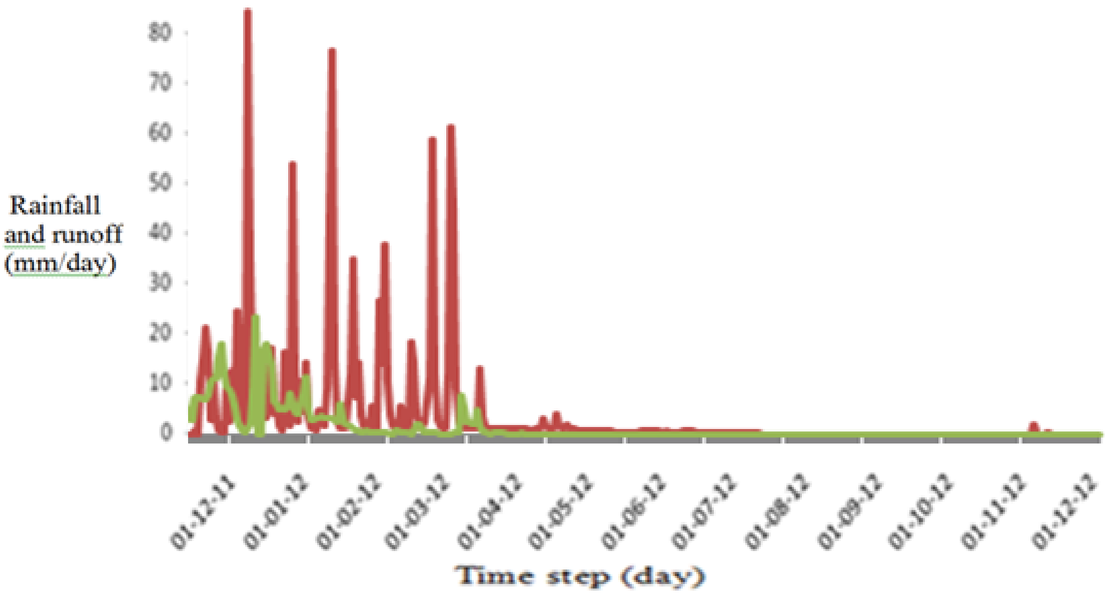

Figure 2.4: Trend analysis of rainfall and runoff

The occurrence of some of the runoff peaks before major rainfall events is due to the fact that in addition to overland flow, catchment runoff also comprised of interflow and groundwater flow from the upper and the lower aquifers.

Regression between runoff and rainfall for Ukwe area, using runoff as a response variant and precipitation as fitted term constant is shown in Table 1. The results indicate the runoff is responsive to rainfall at 0.1 % (tpr = 0.001) confidence level.

Table 1.1: Regression between rainfall and runoff for Ukwe reservoir catchment

Table 1. Regression analysis: Runoff vs Rainfall amount.

Response variate: Qm (Runoff)

Fitted terms: Constant, P (Precipitation)

Estimates of parameters

Parameter	estimate	s.e.	t(363)	t pr.
Constant	0.4081	0.0199	20.55	<.001
P	0.01657	0.00256	6.47	<.001

Relationship : Q =0.165P + 0.408

The following relationship

$$Q = 0.165P + 0.408 \text{ ....} (10)$$

demonstrates that without precipitation (P) in form of rain, annual surface (overland flow, interflow and groundwater flow) feeding the reservoir is only 0.408 mm/day. For every 1 mm rainfall at Ukwe, 0.165 mm runoff is generated. This demonstrates versatility of rain towards reservoir sustenance, and that there is a definite relationship between the frequency of rainfall occurrence and the magnitude of runoff.

Longest annual rainfall for the year 2012 on the catchment was 7 hours (420 mins) duration with intensity up to 140 mm within 10 minutes (14 mm/min) before lowering to 18 mm after hours (Figure 2.5). The soil became saturated, resulting in runoff within 3 minutes lasting 5 hours.

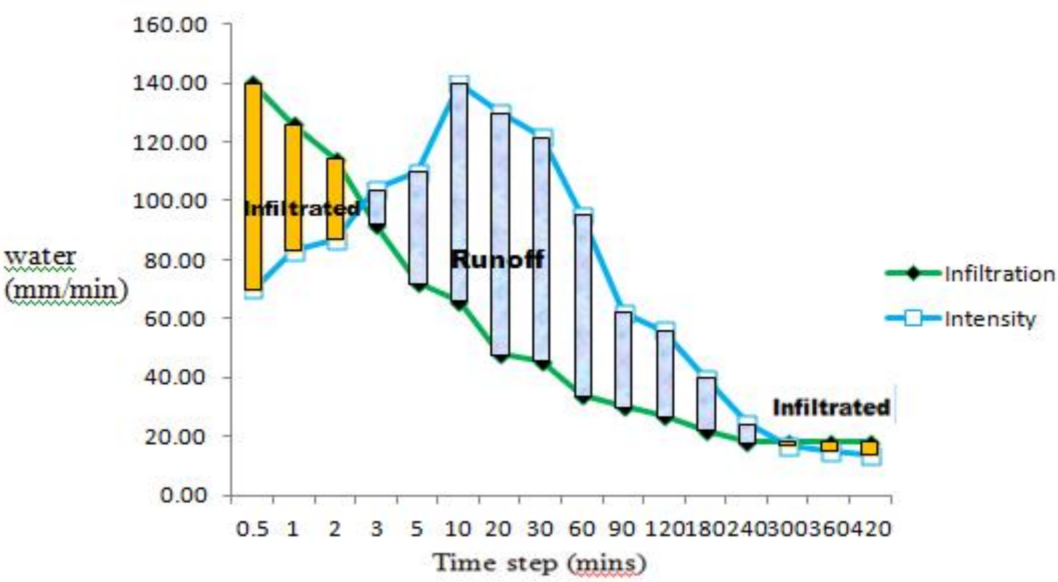

Figure 2.5: Rain intensity, infiltration and runoff at Ukwe

Runoff amount was four times that of infiltrated amount. This highlights the fact that drought prone areas can sometimes be flood prone as well and that under long duration high intensity rainfall, surface runoff start early and tails off late as rainfall intensity rescinds.

2.3.3. Reservoir water

2.3.3.1. Reservoir evaporation and Seepage

Onset of rains in October or November tended to make the reservoir more effluent. During the dry season, evaporation rate from the reservoir was lower from April to August, when temperature is low and wind speed is high, than from September to December when temperature is high and wind speed is low. This indicates that evaporative water loss from the reservoir is more related to temperature than wind speed. Relationship between evaporation from calibrated standard (Class 'A') pan and reservoir confirmed a coefficient (r) of 0.75. The value helped in estimating evaporative losses from the reservoir.

Reservoir water seepage tended to be lower during the months of low rainfall, likely due to low hydraulic potential, demonstrating how influent the reservoir becomes as the dry season progresses. Seepage and evaporation intensities were both responsive to prevailing climatic conditions.

2.3.3.2. Reservoir water availability and crop water use

Plotting of rainfall pattern clearly shows durations of seasonal droughts at the drought prone Ukwe area. The impact of such situations is more pronounced on crops during the growing season, *i.e*. February and April (Figures 2.6).

It is demonstrated that without frequent dry spells and droughts the amount of rain would suffice for bean production which requires at least seasonal rainfall of 600 mm. Historical data has indicated that the seasons are usually frequented by dry spells and/or droughts once in about 4 years. Supplementary irrigation (SI) would be needed during such occurrences.

Dry seasons normally begin end of May and lasts up to November. Harvested and stored (H & S) water from this period can be used both for supplementary irrigation during droughts and dry spells, and for sole irrigation duration the dry season. Such irrigation operations would bridge the gap between produce supply and demand created by the ever increasing population.

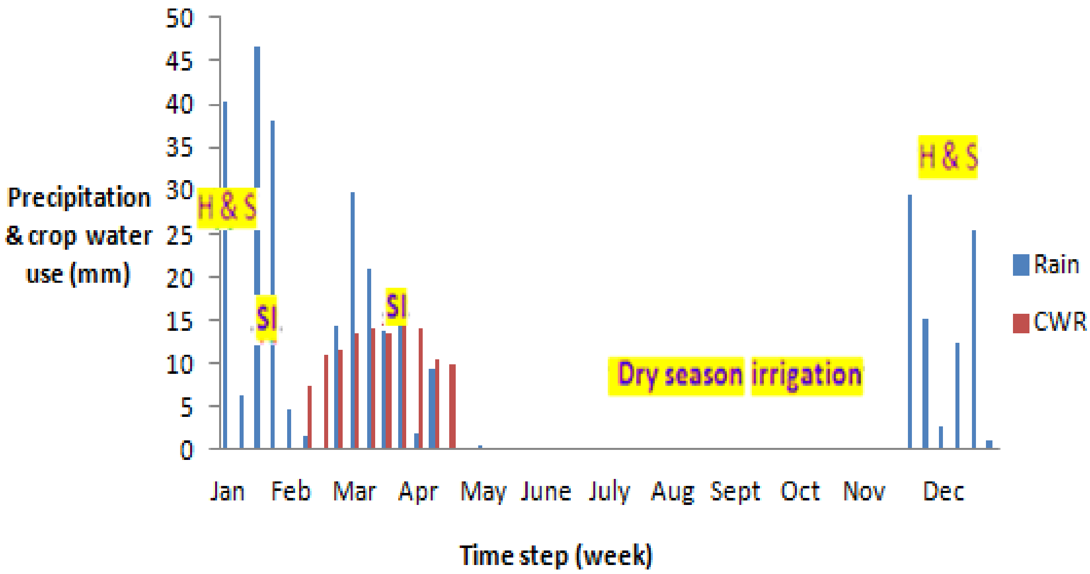

Figure 2.6: Seasonal crop water requirement and rainwater availability

In addition to water losses through evaporation and seepage, uses for livestock during the hot dry season (August to November) based on the number and daily consumption by each animal also needs to be taken into account in order to compute the balance for irrigation (Ward, 2014). The highest water withdrawal from the reservoir is by the bean crop irrigators. The combined annual water losses, through evaporation and seepage and withdrawals by livestock and irrigation, from the reservoir are depicted in Figure 2.7.

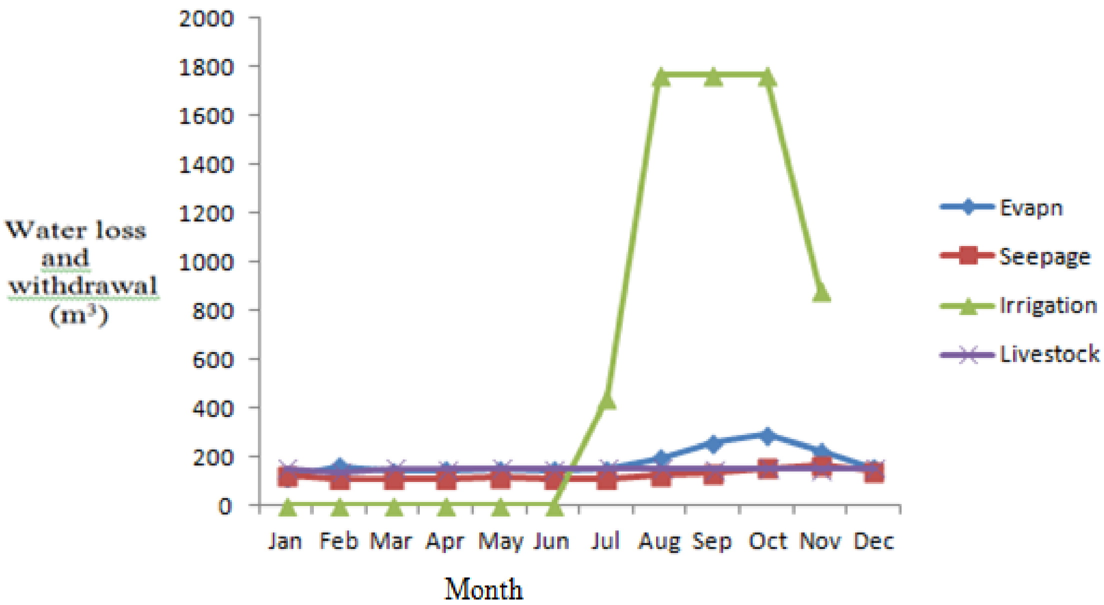

Figure 2.7: Water loss and use from Mphetsankhuli reservoir, Ukwe, 2013

This is critical for reservoir sizing during dam construction or crop field sizing at the onset of irrigation season as it dictates weekly reservoir balance as the irrigation season progresses (Figure 2.8). Irrigation of beans which commences end of July is the main consumer of water at Ukwe. Sharp reduction of available water in the reservoir is experienced from that month. The volume is reduced from 1200 to a minimum of 2000 in November when irrigation stops and the bimodal rainy season is expected to start.

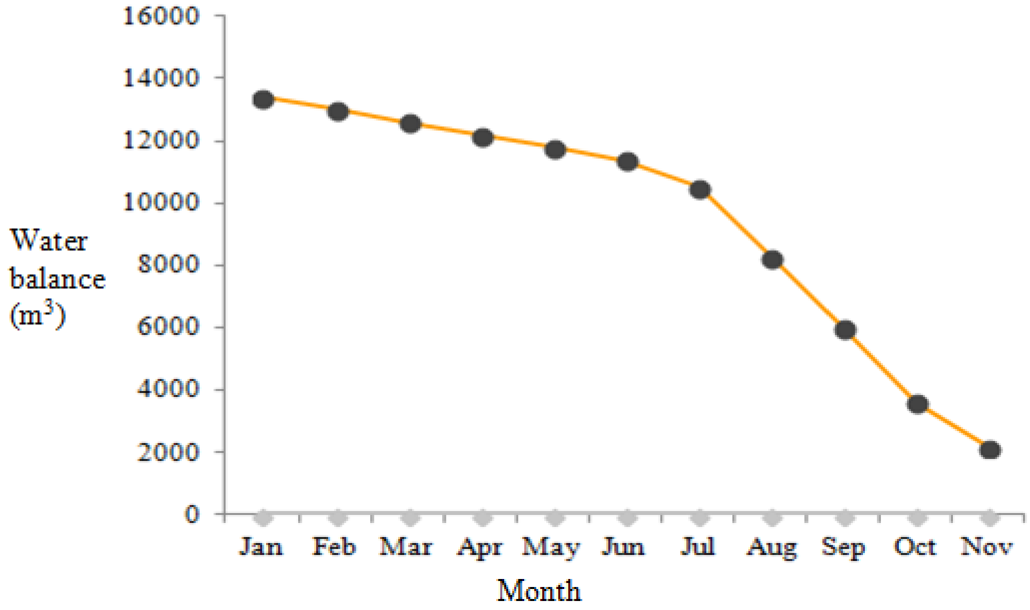

Figure 2.8: Monthly water balance

The dam water change was the weekly water amount that remained in the dam after deep ground losses and evapotranspiration. The results indicate that with adequate knowledge of water abstraction rates, the threshold water abstraction levels can be more clearly defined and unsustainable water use from the reservoir avoided.

2.3.3.3. Crop yields and water productivity

The highest common bean biomass, pod and grain yields were obtained from the 5 cm seconded by 75 mm weekly irrigation regimes (Figure 2.9). Mean pod and grain yields from 50mm per week irrigation of beans (2510 kgha^{-1}) was higher than 1410 kgha^{-1} and 1470 kgha^{-1} under 25 and 75mm/week irrigation depth respectively. This verifies the irrigation recommendation of 50mm/week by the Ministry of Irrigation and Water development based on the calculated crop water requirement (MIWD, 2011).

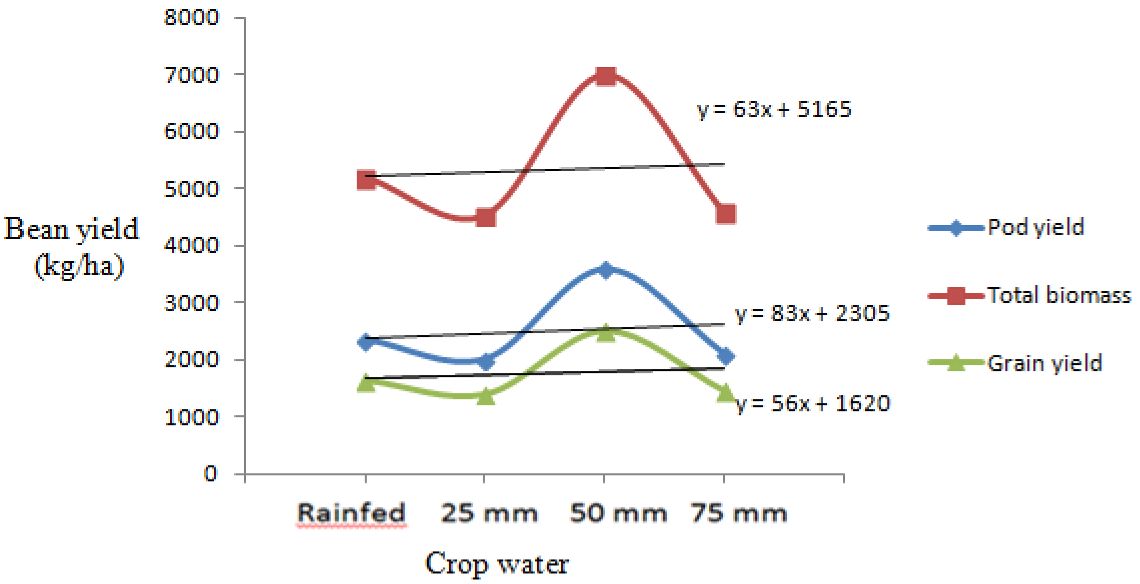

Figure 2.9: Bean crop performance under rainfed and 3 irrigation regimes

Mean pod length obtained from 5 mm water application were 13.20. Similar results were reported by El-Tohamy, *et al.*, (2013), for instance, pod length of beans grown under field capacity (50 mm in this case) were 12.17 cm.

2.4. CONCLUSIONS

The study has demonstrated that runoff hydrograph responses follow the magnitude of rainfall events but as the rainy season progressed the runoff rate is reduced by increasing catchment vegetative cover. The oscillating trends between the two factors augment show frequency of rainfall occurrence following those of runoff. Higher rain intensity than infiltration rate illustrates that drought prone areas are sometimes flood prone as well.

During long duration rainfall, with high intensity, surface runoff starts early and tails off late as rainfall intensity rescinds. A number of hydrological researchers also found strong relationship that exists between frequency and intensity of rainfall on one hand and magnitude of runoff on the other (Elsebaie, 2012). Dry weeks within the rainy season signify that rainfall at drought prone area of Ukwe is unreliable and poorly distributed over a season. The study results augment report by Sivanappan (2009) that in Eastern and Southern Africa rainfall failure occurs is usually below 50% of the average annual rainfall.

Evaporative pressure from the reservoir is more influenced by rise in temperature than increase in wind speed. The proportion of water available for the crop, with respect to evaporative losses, is hence more during cool season than during the hot dry season. The reservoir water seepage tends to be lower during the months of low rainfall, likely due to low hydraulic potential, a demonstration of how influent the reservoir becomes as the dry season progresses.

Water use for livestock similarly picks up during the hot dry season (August to November). The highest water withdrawal from the reservoir is by the bean crop irrigators. Comparative analysis of weekly rainfall amounts and crop water requirements have indicated the need of harvesting and storing rain water for supplementary irrigation during droughts, dry spells, as well as for dry season irrigation. The results indicate that with adequate knowledge of water abstraction rates, the threshold water abstraction levels can be more clearly defined and unsustainable water use from the reservoir avoided.

Crop yield response to irrigation depths indicate how critical it is for reservoir sizing during construction, or crop field sizing at the onset of irrigation season, as it dictates weekly reservoir balance as the irrigation season progresses. Yield differences themselves need to be supported by socio-economic analysis for them to be meaningful to farmers.

Generally, the research results indicate that, through field measurements and computation verifications, it is possible to determine water reservoir capacities, irrigation water requirement and bean water productivity. While cconsistency of the study results over time and places can be verified when a number of traditional field experiments are conducted, the procedure would, however, be time and resource demanding. The problem would be addressed by employment of suitable models.

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CHAPTER THREE

DEVELOPMENT OF AN AGRO-HYDROLOGICAL MODEL FOR IRRIGATED BEAN PRODUCTION BASED ON HARVESTED WATER

ABSTRACT

Agro-hydrological modelling is the combining of mathematical representation of the processes of precipitation, long term water storage and irrigated crop productivity. Literature does not indicate availability of such models suitable for Sub-Saharan Africa (SSA). The study was, hence, conducted to develop a model for strategic and tactical decision making by bean growers based on agro-hydrological factors impinging on surface runoff water storage, irrigation, crop productivity and socio-economic returns. Based on model versatility *Nedbor Afstromnings* Model (NAM) was found most appropriate for sub-Saharan African geo-climatic and crop conditions. Model addendum involved incorporation of a component for water storage, crop water use and crop productivity. Data analysis by Gumbel Distribution There is about 70% predictability difference between 10 and 100 year estimated probability of runoff maginitude. With optimization of catchment parameters and runoff routing constants the model effectively simulated runoff with computed value magnitudes largely matching the measured values, from minimum of 0.5 m^3/day in drought year to the highest 16 m^3/day in the highest rainfall one. The added sub-routine components for reservoir water losses and uses enables the model to compute seasonal water balance. Similarly, the modified NAM is now able to effectively simulate crop water productivity using the added crop water use and yield sub-routines.

Key words: hydrological modeling, crop, model component, socio-economic environment, optimization

3.1. INTRODUCTION

3.1.1. Background

An agro-hydrological model is a computer simulation programme that processes properties, distribution, and effects of water on the earth's surface, in the soil and in the atmosphere in relation to agricultural production. Components of agro-hydrological models include runoff generation and routing, soil water balance and crop water use in response to weather parameters (rainfall, temperature, wind speed, relative humidity and sunshine). While agricultural experimentation mainly focuses on fixed strategies, crop models provide quantitative and qualitative grounds for response farming. Many countries in the SSA are yet to avail a model that can effectively cater for combination of precipitation, long term water storage, crop productivity and socio-economic environment for the farmers.

Agro-hydrological models have so far been developed based on different data source and used to make some specific concrete agricultural recommendations in many areas of the SSA for over five decades. In South Africa, for example, PUTU wheat growth model was used from 1992 to 1993 to determine optimal wheat sowing strategies based on 50 years of historical weather data (Singels and de Jager, 2013). Similarly, Thornton *et al.,* (2008) reported work done using the CERES-Maize model, calibrated for local field conditions in Malawi, to determine the optimum planting window and density for a number of current cereal and legume varieties.

In Tanzania, the PARCH model was developed further, to investigate aspects of rainwater harvesting, resulting in the PARCHED-THIRST model (RIU, 2007). It can be used in simulating crop, soil, land and water management, climatology, and planning and designing of rainwater harvesting systems (Tumbo *e t al.,* 2006). The current version 2.4 combines the simulation of crop, soil, land and water management, climatology, and planning and designing of rainwater harvesting systems hydrology with growth and yield of cereal crops, namely sorghum, rice, maize, millet and rice (SUA, 2006). The model was successful in measuring collection of runoff as sheet flow from a catchment area into an adjacent cropped area but without storage and versatile legume crop irrigation sub-routines.

Despite tremendous versatility of agro-hydrological models in the agricultural sector, a number of associated deficiencies also prevail. The best model for a particular agro-ecological zone will depend on the intended use and prevailing environment. For example, in Columbia, the DSSAT-BEANGRO model was utilized on rain-fed and irrigated dry bean (*Phaseolus vulgaris,* L.) to investigate whether scope of applicability of site-specific models could be extended to regional planning and productivity analysis.

The results indicated that a considerable soil and weather variability existed within three used study sites hence applicability of site-specific models could only be extended to regional planning and productivity analysis by combining their capabilities with a Geographic Information System (GIS) (Lal *et al*., 2013).

Models are adopted only when they are cost effective and user friendly as a result of sufficient interactive communication between researchers, extension staff, and farmers. Malawi has not embraced use of some hydrological and catchment parameter variations and there is poor understanding of their application in water storage and irrigation (Njoloma, 2010).

It is, therefore, difficult for farmers to benefit in agricultural tactical and strategic decision making through use of some promising models. Agricultural tactical decisions refer to choices made once per season, such as date to start irrigation, whereas agricultural strategic decisions imply plans for what will be affected over several seasons, such as irrigation water source and equipment.

Farmers will make their management planning based on what they perceive as information relevant to the prospects for the forthcoming crop season or seasons. A good example is the scenario where farmers may expand the irrigable land area based on expected additional irrigation facilities and increased dam water volume resulting from the forecasted high rainfall. Strategic crop forecasts require application of crop models to either prevailing or forecast climate data. Practically, historical daily weather data, weather data from weather generators are used the future weather mean and variance is represented by the historical or generated data (Hollinger, 2012).

An example of tactical management procedure is measuring the current soil moisture, and depending on seasonal climate forecasts, timing of increases or decreases of growing season soil moisture is predicted. This will enable the farmer to adjust the crop planting date to take advantage of favourable soil moisture during critical crop growth stages (Hollinger, 2012). This indicates that in the absence of use of a hydrological model in identifying and quantifying the stored water variability for precise tactical decision making, crude procedures are used in irrigation.

3.1.2. Review of agro-hydrological models

Literature review was conducted, so as to either develop a completely new agro-hydrological model or make additions to a non-prohibitive existing model, for establishing appropriate variable combinations of catchment area runoff attributes, open surface water reservoir and crop water productivity.

Due to the fact that there is a definite relationship between the magnitude of extreme hydrological events and their frequency of occurrence it is necessary to analyse the relationship through probability distribution. In agro-hydrology, Gumbel distribution has been used with success to describe the populations of many hydrological events since then. It has hence been possible to provide analysis of such variables as monthly and annual maximum values of daily rainfall and river discharge volumes or catchment runoff, as well as description of droughts (Burke *et al.*, 2010) in relation to crops such as common beans.

In Zimbabwe, the Gumbel Distribution had been used to predict river flood magnitudes. The analysis clearly revealed the good capability of the Gumbel distribution function for the prediction. No significant differences were found between the predicted and measured flow magnitudes of River Nyanyazi. The model was hence recommended as a reliable method to predict the flow occurrences (Mujere, 2011).

The common bean crop requires moderate effective rainfall of more than 600 mm during and immediately after the flowering stage. But in drought prone areas the low erratic rainfall averages only 525 mm resulting in low annual crop yields. Despite the tremendous crop water problems bean growers face in SSA, runoff water harvesting as related to long term water storage for irrigating common beans in the region has not been modeled. A suitable model development is hence needed to assist the farmers, with the help of agricultural field staff, in strategic and tactical decision making.

One of the models which show potentiality for use in the agricultural sector is APSIM. It is a modelling framework which is able to integrate sub-models derived in fragmented agricultural research efforts. It also provides means for comparison of models or sub-models on a common platform using an "inclusion - exclusion" functionality approach to the design. It is a powerful tool for exploring agronomic adaptations. However, its adaptation for rainwater harvesting in SSA needs analysis of peak rainwater flow frequency distribution analysis (APSIM, 2010).

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A number of researchers such as Zhu *et al*. (2012) reported limitation of most crop/soil models as being one-dimensional (vertical direction), i.e., focusing on the vertical fluxes such as evapotranspiration, infiltration, and recharge from the unsaturated zone neglecting the lateral fluxes common in subsistence farming sloping land. Another limitation of most models is negligence of preferential flow of water down cracks, again a common occurrence in tropical soils suitable for crops such as beans.

Igbadun (2006) states that if an existing model is found deficient in any aspect it is time and resource demanding to modify or add a code to cater for that specific aspect. The *Nedbor Afstromnings Model* (NAM) was developed at the Danish Hydraulic Institute (DHI) as part of MIKE 11 software package for simulating flows, sediment transport and water quality in estuaries, rivers and irrigation systems

(Njoloma, 2010). The model is currently in use in simulating runoff and dam water volume in Zimbabwe and Malawi (Njoloma, 2010).

Among many countries, the model was also used to measure potential impacts of climate change on flood flow in Nhue-Day River basin, Vietnam (Nguyen *et al*., 2012) and development of a flood forecasting system for the Jamuneswari River catchment of the northwestern part of Bangladesh (Rahman *et al.*, 2012).

Literature has revealed that the model is a deterministic, conceptual, lumped type of model with moderate input data requirements. It links mathematical statements describing, in a simplified excel spreadsheet quantitative form, the behavior of the land phase of the hydrological cycle in rural catchments. The model structure deals with catchment as one unit with parameters and variables as mean values for the entire catchment and operates on simplified Excel Spreadsheet version for simulating precipitation-runoff (Njoloma, 2010).

In addition to simplicity and reliability in operation the model uses simple and few data of precipitation, potential evapotranspiration and temperature to simulate runoff. Based on model versatility and adaptability to sub-Saharan African geo-climatic and crop conditions, none of the models reviewed above, apart from NAM, has been found functional for both harvested open surface water storage, and possibility of addendum for irrigation, of crops such as common beans, and socio-economic sub-routines. Modification of NAM was, hence, found more applicable to achieve the objectives of this study.

3.2. MATERIALS AND METHOD

3.2.1. Water Storage and Irrigation model component using NAM as the basis

Building of the model component to cater for water storage and irrigation used rainfall, temperature, humidity, radiation and potential evaporation data to simulate runoff, water storage and crop water productivity. The procedure followed the structure depicted in Figure 3.1, using an excel spreadsheet version 2007. The only annual source of water into the reservoir is seasonal rainfall whose interception is vegetation, ground depressions and the uppermost part of the ground (*Umax*). Secondly, it is stored in the lower zone as soil moisture in the root zone (*Lmax*).

The model structure deals with catchment as one unit with parameters and variables as mean values for the entire catchment. The catchment runoff is comprised of *overland flow*, *interflow* and *groundwater flow* from the *upper* and the *lower aquifer*. Being a conceptual model, NAM structure conceptually uses a combination of physical structures and semi-empirical equations (Njoloma, 2010).

The study site, Ukwe, having no snow storage, model parameter Ss being zero, water is only stored on the surface through moisture intercepted on the vegetation and ground depressions, and in the uppermost cultivated part of the ground (*Umax*). Secondly, it is stored in the lower zone as soil moisture in the root zone (*Lmax*).

Figure 3.1 shows the structure of the spreadsheet version of the NAM model with addendum of reservoir evaporation (Ea), seepage, livestock water use (L/tock), crop field water use and crop water productivity (cwp), and socio-economic components (s-econ).

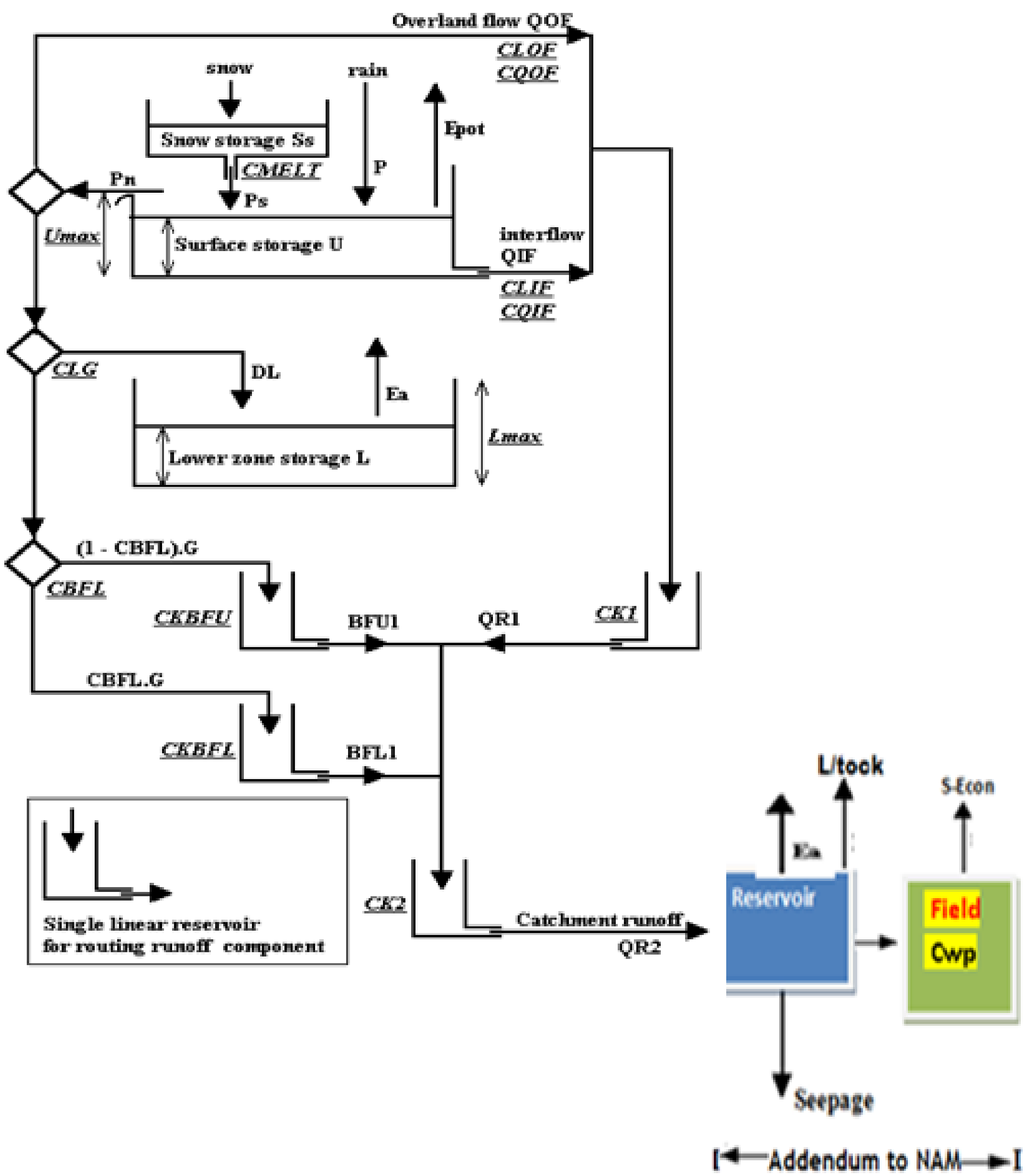

Figure 3.1: Structure of the spreadsheet version of the NAM model (Njoloma, 2010) with sub-routine for reservoir and irrigation components

Model parameters and constants used for analysis of data from Ukwe site are shown in Table 3.1. These were subjected to trial-and-error parameter adjustment to achieve goodness of fit of the calibrated model between simulated and observed hydrographs.

Table 3. 1: Model Parameterization as used for Ukwe data analysis*

Parameter	Name	Constants
Lower zone storage capacity: maximum water storage in the root zone	Lmax	> 0
Upper zone storage capacity: maximum water content in the surface storage.	Umax	> 0 First estimate Umax=0.1Lmax.
Snow melt coefficient	Cmelt	0 for Ukwe site
Overland flow runoff coefficient: extent to which excess rainfall runs off as overland flow and the quantity that infiltrates.	CQOF	0 – 1. Since Ukwe catchment is small, small values with low, permeable soils are as expected.
Interflow runoff coefficient: proportion of the surface storage that runs off through horizontal leakage.	CQIF	0 – 1. For catchment with a flat topography the value is very close to zero.
Threshold value interflow:	CLIF	0 – 1
Threshold value overland flow	CLOF	0 – 1
Time Constants for Routing		
Overland and interflow: both flows together are routed through a linear reservoir	CK1	> 0
Stream flow: flow is routed through a linear reservoir.	CK2	> 0
Upper groundwater flow	CKBFU	> 0
Lower groundwater flow	CKBFL	> 0

*Modified from Njoloma, 2010

Model modification involved incorporation of factors of water storage and crop water use and productivity. In addition to the original model formulation equations in the Appendix 1, the following equations were formulated and used to compute reservoir volume and its seasonal balances, and irrigation water components of the added model component. The equations were implemented in the spreadsheet in form of implementation commands in the following sequence:

CDIn = Total flows into the dam, used the Equation 1 as accumulation U_{max} values.

$$CDIn = \sum(QR2_{i-1} * \frac{1}{CK2} + (QR1 + BFU1 + BFL1) * \frac{1}{CK2}))......................... (1)$$

Where QR2 = Total stream flow, applying model equation, QR1 = Outflow resulting from the overland flow together with the interflow. Outflow at Ukwe from the month of June is zero, BFU1 = Upper storage component of the groundwater flow and BFL1 = Lower storage component of the groundwater flow.

WDI = Weekly depth of water application (Constant schedule of 5 cm per week following pre-application, using soil water depletion (*AD*) and potential evaporation (*Ep*) in mm. The model component used the Equation 2:

$$WDI = (0.034)\frac{Ep_m^{1.09}}{AD^{0.09}} .... (2)$$

Dam Bal = Water volume remaining in the dam after cumulative weekly abstraction and losses. The model component used Equation 3:

$$\text{Dam Bal} = \mathbf{(9978} + \sum(QR2_{i-1} * \frac{1}{CK2} + (QR1 + BFU1 + BFL1) * \frac{1}{CK2}))\mathbf{)} - (0.034)\frac{Ep_m^{1.09}}{AD^{0.09}} \mathbf{.......} (3)$$

The constant 9978, being the amount of water available in the reservoir in m^3 at the onset of irrigation season, is used as the initial amount of reservoir.

SFU = Seasonal field water use for irrigation being cumulative weekly water use as shown in Equation 4:

$$SFU = \sum((0.034)\frac{Ep_m^{1.09}}{AD^{0.09}}).. (4)$$

DWB = Dam water balance is the difference between accumulated water in the dam and accumulated field water as shown in Equation 5.

$$DWB = \sum(QR2_{i-1} * \frac{1}{CK2} + (QR1 + BFU1 + BFL1) * \frac{1}{CK2}))- (0.034)\frac{Ep_m^{1.09}}{AD^{0.09}} (0.034)\frac{Ep_m^{1.09}}{AD^{0.09}} ....(5)$$

The reservoir water volume balance (after losses through evaporation and seepage, and abstraction by livestock and humans, up to crop harvest week) divided by total seasonal crop water requirement over a hectare provided the total area (ha) the reservoir water volume could irrigate.

3.2.2. NAM Modelling spreadsheet logical commands for hydrological and irrigation system at Ukwe area

Nedbor Afstromnings Model (NAM) operates on excel spreadsheet commands. The user opts for an input file that contains a range of catchment parameters and routing constants as indicated in Table 3.1. The optimization of the catchment parameters and runoff time constantans result into model simulated objective function which is the difference between the observed and model simulated runoff or reservoir water capacity.

The aim is to obtain zero or negligible difference between the measured and the model simulated values. Utilized in an excel spreadsheet version 2007, the procedure followed the sequence depicted in foregoing equations 1 to 5 proceeding implementation of programme commands.

3.2.3. Rainfall and runoff input data source

The model development for the sub-Saharan semi-arid areas, with Ukwe as a case study site, focused at simulating rainfall–runoff for water storage and irrigation processes in a rural catchment by making modification to the NAM. NAM operates by continuously accounting for the moisture content based on three different and mutually interrelated physical climatic elements of the catchment, *i.e.*, precipitation, potential evapotranspiration and temperature. The study uses NAM in simplified

Excel Spreadsheet version for simulating precipitation-runoff, and with addendum of irrigation and financial analysis components.

Aggregating rainfall data into monthly totals and means reduces the degree of spatial variability; a lot of intensity information that can be critical to runoff generation processes is lost. This scenario would complicate the modelling process if a short time step is to be used for short time step simulations and forecasts, as is the case in this work (Njoloma, 2010). Therefore, daily rainfall data was used in the NAM simulation and development of reservoir and irrigation model components.

Daily data was collected using spot rain gauges distributed in the catchment area. Long time rainfall data is normally scarce in SSA, let alone Malawi. Reliable 20 year rainfall data was sourced from Chitedze National Agricultural Research Station, 8 km from the study site. The available runoff data for the area is from 1959 to 2000 obtained from the Water Division of the Water Resources Department, Ministry of Irrigation and Water Development. Out of the historical runoff data only 16 year data (1960 to 1975) had minimum missing scores hence was used as historical data for frequency distribution analyses and rainfall-runoff analyses. Such uses included peak flows to depict average probability level or average return periods of a given runoff.

Simulations of runoff and reservoir water capacity were done using spreadsheet computations based on the NAM model commands. Similarly the modified model was used to relate seasonal reservoir water amounts to crop water requirements to simulate crop water productivity.

3.2.4. Frequency distribution and expected runoff return analysis

Runoff is vital not only as a major factor contributing to the reservoir water quantity but also as a process paramount to the simulation of the model processes. Extreme runoffs, as they influence reservoir capacity hence subsequent irrigation water volume, need to be assessed. Frequency distribution was used to relate the magnitude of extreme rainfall/runoff events with their number of occurrences such that their chance of occurrence with time could be predicted successfully.

The runoff values of annual extreme peaks from each of the 16-year (1960 to 1975) daily data sets were isolated and subjected to extreme value analysis. The data sets were fitted to a Gumbel distribution. Reliability of the runoff data was hence assessed against the Lower Confidence Limit (LCL) and the Upper Confidence Limit (UCL). The analysis was carried out using the following distribution parameters:

Non-exceedence probability: $F_i = (i - \alpha)/(n + 1 - 2\alpha)$; $\alpha = 0.44$ (the Gringorten Formula for plotting annual extreme runoff peaks)...............................(19)

Plotting position: $y_i = -ln\ (-ln\ F_i)$.. (20)

Scale parameter, a: $\sigma^2 = \pi^2 a^2/6$... (21)

Location, c: $\mu = c + 0.5772a$... (23)

Estimate: $X = ay + c$.. (24)

Variance of estimate: $Var\ (X) = a^2\ (1.17+0.196y+1.099y^2)/n$..................... (25)

95% Confidence limits of estimate: $CL\ (X) = X +/- t_{97.5,n-1}\ SE_x$................. (26)

$SE_x = (var\ X)^{0.5}$... (26)

Where F_i is normal probability density occurrence of runoff function for year i (1-p), i is year of interest, α is the distribution shape parameter ($\alpha > 0$), n is total number of years used for prediction analysis, ln is natural log, σ is standard deviation defining scale of distribution, c is location parameter with Euler constant ($\approx$0.5772), μ is mean of distribution (scale parameter), and X is extreme rate of runoff (mm/day) for each year.

3.2.5. Model calibration

3.2.5.1. Calibration of input using precipitation and runoff parameters

Catchment and reservoir components were calibrated using field measured values against the model computed values in graphic displays. The procedure encompassed rainfall pattern, rainfall-runoff relationships and historical data runoff simulations. Computed reservoir water balance (ΔC), due to water losses and use (irrigation and livestock), and the changes in irrigation water amounts ($\Delta I(A)$) as the season progressed (Δt) were calibrated by actual water balance measurements to assess the model for the simulated relationship.

Simulated data trends were compared with actual field observed data. Where model performance was deficient, adjustments were made to correct either its formulation or data entry mechanism or model parameters or time constants for water routing, based on Excel spreadsheet computation (Table 3.2).

Table 3.2.Initial parameters and water routing constants in the spreadsheet for calibration

Catchment Parameter	
Lmax	*160*
Umax	*15*
Cmelt	*0*
CQOF	*0.3*
CQIF	*0.025*
CBFL	*0.9*
CLIF	*0.7*
CLOF	*0.3*
CLG	*0.4*
WDI	*50*

Routing time constant	
CK1	0.5
CK2	0.5
CKBFU	10
CKBFL	180

3.2.5.2. Calibration of the model output using rainfall and runoff data

Using SOLVER function, the starting parameter values were optimised until the maximum value of the objective function that was the Coefficient of efficiency (RE) was obtained. Parameters QR1, BFU1, BFL1 and QR2 were also subjected to the same optimisation procedure. This was done by the process of 'trial and error' by inputting the rainfall data obtained from the study and observing the computed runoff trend in comparison to the measured values was found effort demanding and not precise. This was verified by solver programme. The objective function used was the Coefficient of Efficiency, which measures the degree of association between the observed and simulated values. Its value can be below zero but not more than one. The closer the value is to one the better the degree of fitting.

Since the snow component in the region (Ukwe inclusive) was zero as the temperature data was greater than zero, the initial and final value for the storage in the snow reservoir Ss in the model was taken as zero. Similarly, the initial value for the storage of the surface water reservoir U was taken as zero as the year progressed from dry to wet seasons – Malawi having unimodal rainfall pattern.

Several different values were tested to obtain the best initial value for the storage in the lower zone reservoir (L) due to its sensitivity in the optimization process. The initial values given for QR1, BFU1, BFL1 and QR2, were also defined. The starting parameter values (QR1, BFU1, BFL1 and QR2) for all the parameters in Table 3.2 were estimated by the researcher based on the knowledge of the catchment area and the reservoir.

3.2.5.3. Model calibration for simulation of irrigation

The model calibration was based on parameter and time constants with respect to climatic values to predict catchment runoff for a given rain storm on daily basis. The reservoir water levels were recorded on weekly time step basis in line with the irrigation water abstraction. A local sensitivity of change in reservoir capacity (ΔC) was obtained from cumulative irrigation withdrawal (ΔI) multiplied by the area irrigated (A). System behaviour and criteria for selecting optimum ΔC and ΔI in relation to seasonal progression (Δt) was established, viz:

$$\boldsymbol{\Delta t \times \Delta I(A) = \Delta C.}$$

3.2.6. Model validation

Validation is the authentication of performance for a calibrated model using a different set of data and sites. In addition to Ukwe *dambo* area, three other *dambos* in the same agro-ecological zone were studied viz; Kandiya (12 km South), Bunda (60 km South-west) and Lumbadzi, (11 km East). Validation was performed by comparing the simulated and measured runoff data at the three sites.

Double Mass Analysis (DMA) for accumulated rainfall mean for Ukwe site against the rainfall means of other stations was carried-out to assess data consistency and homogeneity. DMA is one of the recommended methods for a particular station data screening for reliability and consistency. It compares data of the single station with that of a pattern composed of the data from other stations in the area (Ali, 2011).

The Double Mass theory relies on the fact that a plot of the two cumulative quantities during the same period exhibits a straight line so long as the proportionality between the two remains consistent hence the line slope represents the proportionality (Ali, 2011). Results of DMA, therefore, helped to determine if data could be used for further analyses, such as runoff, with confidence.

3.2.7. Model simulation of dam water balance and crop water productivity

The model was used to simulate dam water balance based on evaporation, seepage, livestock and irrigation water use, and possible crop land area employing, NAM excel spreadsheet commands. The input data included weekly dam water average width and depth, and throw-back, seepage, evaporation, livestock (cattle and goats) water consumption and irrigation water.

Gross margins and break-even analysis, as a measure of crop returns were also computed. During calibration and validation excel spreadsheet was employed for data processing. Realization of need for tactical decision making apparatus for farming with respect to runoff water storage and irrigation hence understanding of hydrological parameters and agricultural aspects, model concept formulation is conducted.

3. 3. RESULTS AND DISCUSSION

3.3.1. Frequency distribution analysis and estimated runoff return

Using spreadsheet, the required quantile was computed from the fitted cumulative distribution function. Detailed results of Gumbel parameter functions are shown in Table 3.3. The Gumbel computed extreme runoff (X gum) into the reservoir is 5.04 with upper limit (UCL) of 5.73 and lower limit (LCL) of 4.35 at very high confidence probability of 0.97 (≈ 1).

Table 3.3: Results of Gumbel parameter functions

Rank (m)	Xext	P=(m-.44)/(N+0.12)	Y=-ln(-ln(1-p))	X gum=Y*a+c	UCL	LCL	Simulated extreme flows 1960 to 1975	
1	4.216	0.0347	3.34	4.21	4.72	3.69	-0.009	4.216
2	3.724	0.0968	2.28	3.51	3.88	3.14	- 0.2159	3.724
3	3.42	0.1588	1.75	3.16	3.46	2.86	- 0.2623	3.543
4	2.912	0.2208	1.39	2.92	3.17	2.66	0.0032	2.912
5	2.855	0.2829	1.10	2.73	2.95	2.50	- 0.1295	2.855
6	2.614	0.3449	0.86	2.57	2.77	2.37	- 0.0476	2.614
7	2.310	0.4069	0.65	2.43	2.61	2.25	0.1168	2.310
8	2.182	0.4690	0.46	2.30	2.47	2.13	0.118	2.182
9	2.084	0.5310	0.28	2.18	2.34	2.03	0.0975	2.084
10	1.984	0.5931	0.11	2.07	2.22	1.92	0.084	1.984
11	1.906	0.6551	-0.06	1.96	2.10	1.81	0.0503	1.906
12	1.889	0.7171	-0.23	1.84	1.99	1.69	- 0.0456	1.889
13	1.682	0.7792	-0.41	1.73	1.88	1.57	0.0431	1.682
14	1.470	0.8412	-0.61	1.59	1.76	1.43	0.1245	1.650
15	1.467	0.9032	-0.85	1.44	1.62	1.25	- 0.1555	1.467
16	1.352	0.9653	-1.21	1.20	1.41	0.98	1.2102	1.352
Xavg=	2.38	UCL=X gam+1,96*0,78*((1,17+0,196*Y+1,099*Y^2)^0,5)*Std/(90^						
Std=	0.85	LCL=X gam-1,96*0,78*((1,17+0,196*Y+1,099*Y^2)^0,5)*Std/(90^0,5)						
a=	0.66		a=0,7796968*Std					
c=	2.00		C=Xavg-0,5772* a					
		0.01	4.60	5.038552	5.726	4.351		

The resulting data set in Table 3.3 of extreme annual values, were then fitted to a Gumbel distribution as shown in Figure 3.2. Gumbel measures the reliability and of data once the line fits well, between the upper confidence limit (UCF) and Lower Confidence Limit (LCL). The figure depicts that the data fit well, within the two limits, and with strong regression relationship (R ≈ 1) between discharge and reduced variance. The data are reliable for use in runoff analysis, with confidence, for Ukwe study site. There is no disparity between observed and computed runoff results.

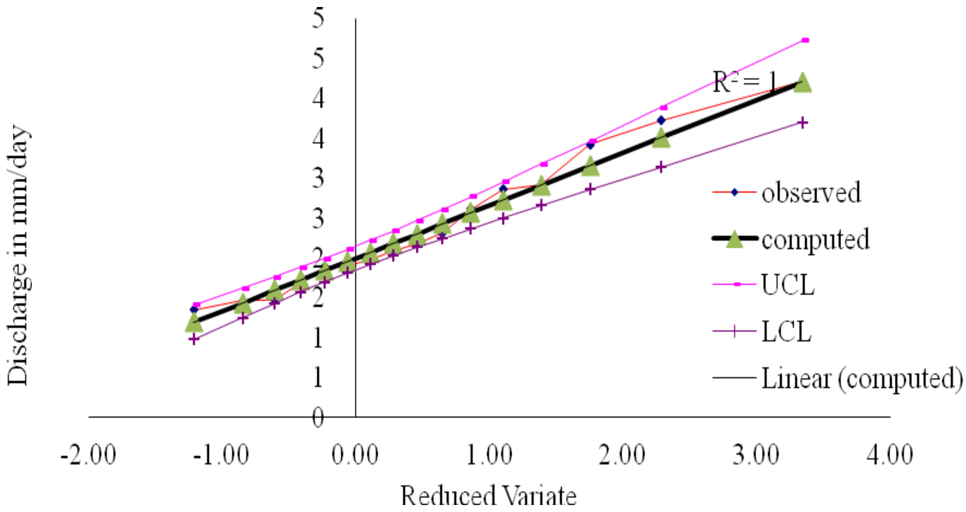

Figure 3.2: Gumbel distribution using isolated annual extreme runoff peaks (1960 to 1975)

Gumbel prediction model is a powerful tool to predict return of extreme rainfall storms over a long period of time, even up to 1000 years given minimum historical data of at least 10 years. A large sample, say over 20, of extreme runoff data is preferred Gumbel distribution fitting (FAO, 2010). The used sixteen year data fitting estimates the prediction of the 100-year discharge by 70%. Use of this data size for prediction analysis is supported by Yahaya *et al*., (2012) who found that the Gringorten plotting formula had still been viable using small data sample size. Small data sample sizes *n* is between10 and 20 while medium sizes is for *n* between 50 and 60, and large sample sizes for *n* between 80 and 100. This still enables validation exercise in the face of scanty data, as long as the data is non-spurious (Yahaya et al., 2012). Due to inadequacy of data in SSA it is widely reported that any data over 10 years still provides an insight of prediction. Stephens (2010), states that if more information is known, return period of 1 in 10 years can be used as a computational guideline.

By employing Gumbel's distribution parameters the magnitude of 100-year daily runoff was then estimated, as shown in Table 3.4. The magnitude of the 10, 20, 50 and 100 year runoffs that would contribute to the reservoir water capacity, estimated by the Gumbel distribution parameters are presented. There is about 70% runoff difference between 10 year and 100 year estimated return period given sustenance of prevailing catchment characteristics and climatic conditions.

Observations over the 2 year research duration have shown prevalence of cultural conservation measures (bunds and ridges) to be more effective in controlling overland runoff and promoting below-surface runoff than biological (forestation) conservation practices. The former measures tend to reduce reservoir siltation and sustain reservoir water capacity more than the latter practice.

Table 3.4: Maximum expected runoff estimated from Gumbel Distribution (different return periods)

Return Period (years)	y	a	c	Estimated Xest mm/day
1000	6.91	1.35	3.57	12.87
100	4.60	1.35	3.57	9.76
50	3.90	1.35	3.57	8.82
20	2.97	1.35	3.57	7.57
10	2.25	1.35	3.57	6.60

3.3.2. Model Calibration of inputs - simulation for precipitation and runoff

The model was calibrated using two rainfall sets, *viz,* observed and computed areal rainfall means using the iteration parameters. Runoff outcomes from the two data sets were compared as shown in Figure 3.3. Results gave matching trend between the two data sets. However, runoffs from areal rainfall values are slightly higher than the measured ones.

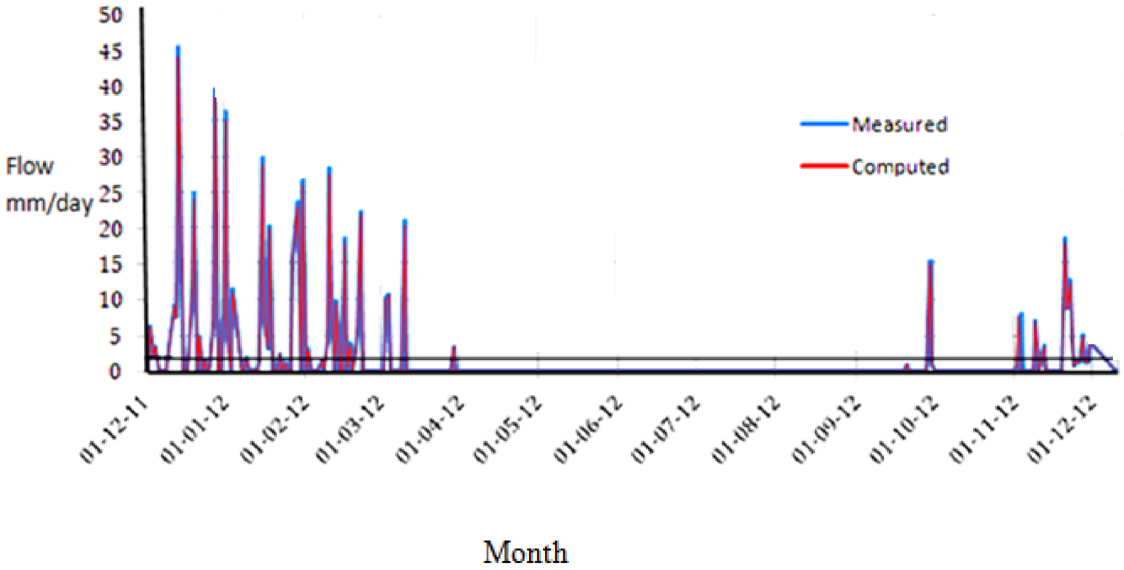

Figure 3.3: Annual measured and simulated hydrographs for calibration

By maintaining the trend hydrograph limb rise and fall for each month, it is demonstrated that the model is reliable in simulating the runoffs in response to rainfall in line with the observed values. Simulation of runoff, *per se*, has generally revealed that there is no annual trend disparity revealed between the observed and computed runoff results. This demonstrates that the model was able to simulate runoff effectively.

The hydrographs oscillations in daily time step shows the position of peaks of observed runoffs coinciding with the computed runoffs, but for some steps the ascending and descending limbs of the peak hydrographs slightly differ in magnitude (Figure 3.4). While measured limb demonstrates frequent oscillations, computed results show smooth curve of decline after the rainy season.

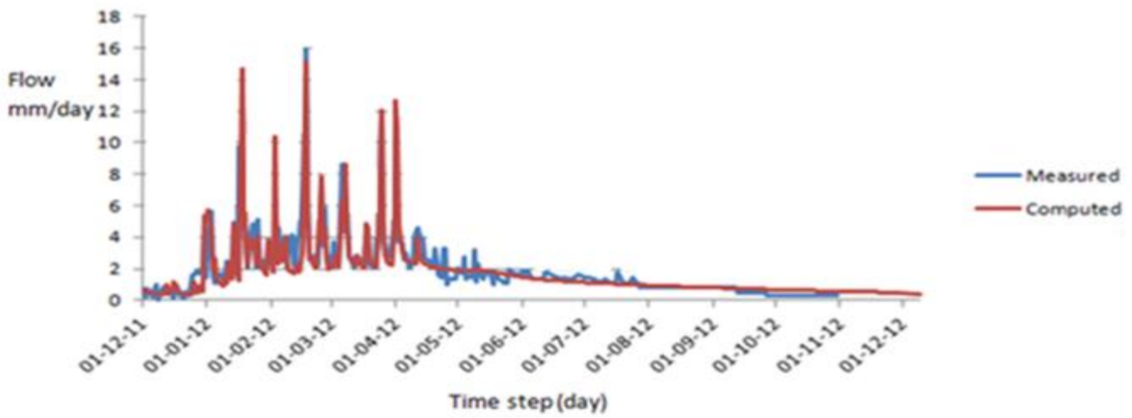

Figure 3.4: Trend analysis between computed and measured runoffs

Calibration using long term (10-year) data series is shown in Figure 3.5. The model tended to provide peaks and depressions in tandem with measured trend. The shapes of the rising and recession limbs of both the measured and computed annual hydrograph take similar shape showing the ability of the model to simulate runoff.

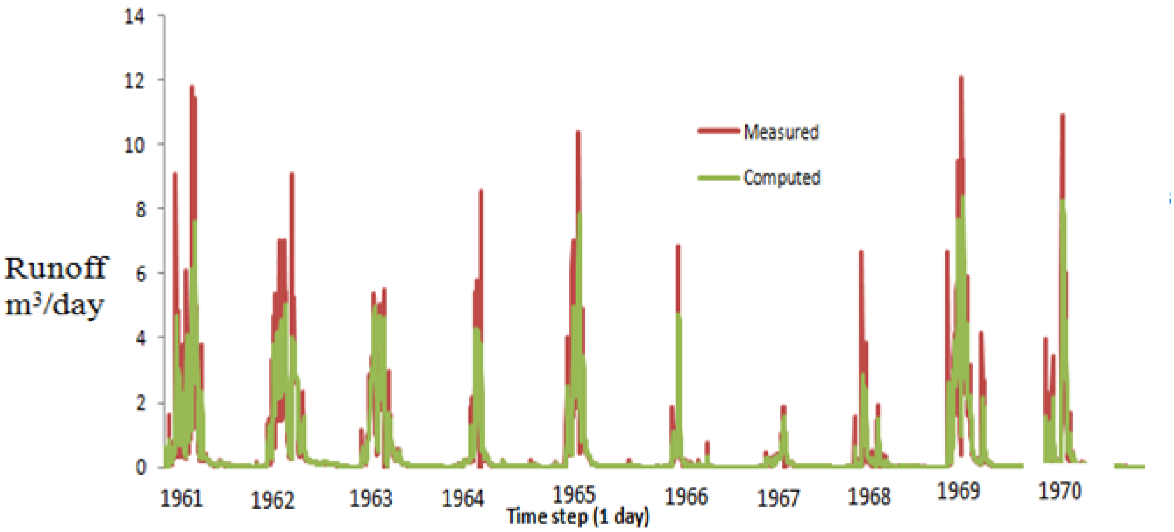

Figure 3.5: Measured and simulated hydrographs based on original parameters and constants (1961 to 1970)

However, the hydrographs demonstrate that the model simulated lower peak flows than the measured ones over the years of calibration.

3.3.3. Model validation

Before the model validation process, rainfall data, the cause of runoff, was tested for reliability and homogeneity using Double Mass Analysis, which preserves the mean and not the standard deviation of the time series, unless a proportional error has been made. The accumulated runoff mean data from Ukwe was plotted against accumulated data means of the Kandiya, Bunda stations and Lumbadzi, 12 km South-east, 50 km South and 8 km North-east of Ukwe respectively. A plotted straight line was achieved, Figure 3.6, revealing absence of spurious trends. This shows that there was no human or station error or any other natural problems with the data source (Ali, 2011). This indicates that the data was valid for runoff and water storage simulations. This indicated that the disparity between the observed and computed results were not due to data errors.

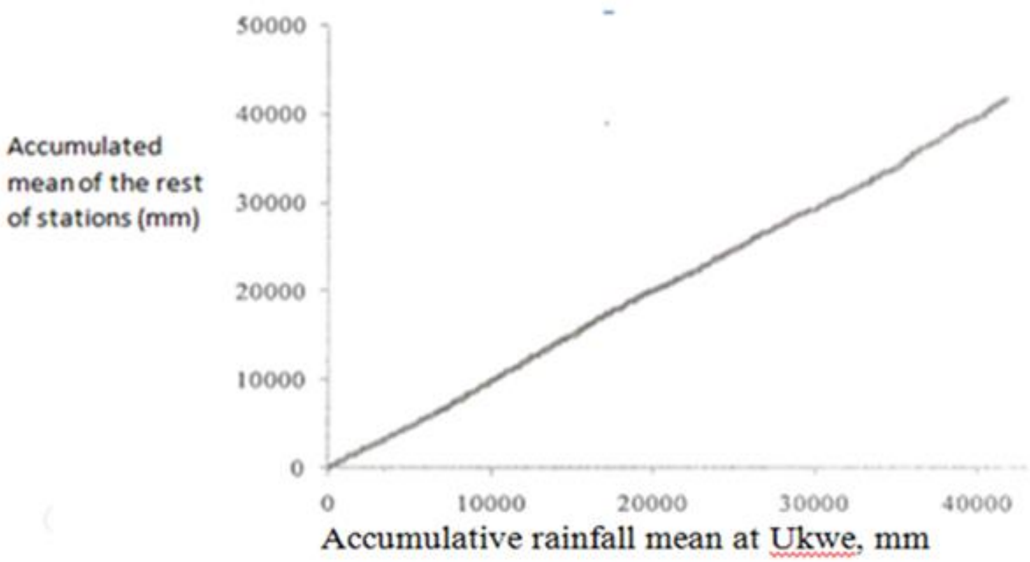

Figure 3.6: Double mass line for accumulated mean of Ukwe site against the mean for the rest of the stations (Bunda, Lumbadzi and Kandiya), 2012

Another set of historical (1972 to 1981) data set was used to verify the results. The same trend, as in Figure 3.5 was achieved, where the simulated hydrograph limbs are in oscillation with the measured ones, but the latter are in higher magnitudes, Figure 3.7.

The runoff data model validation on these different historical data sets (1972 to 1981) visually shows small simulated differences between the measured and computed trends. However, there is a clear indication that, using the existing catchment parameters and flow

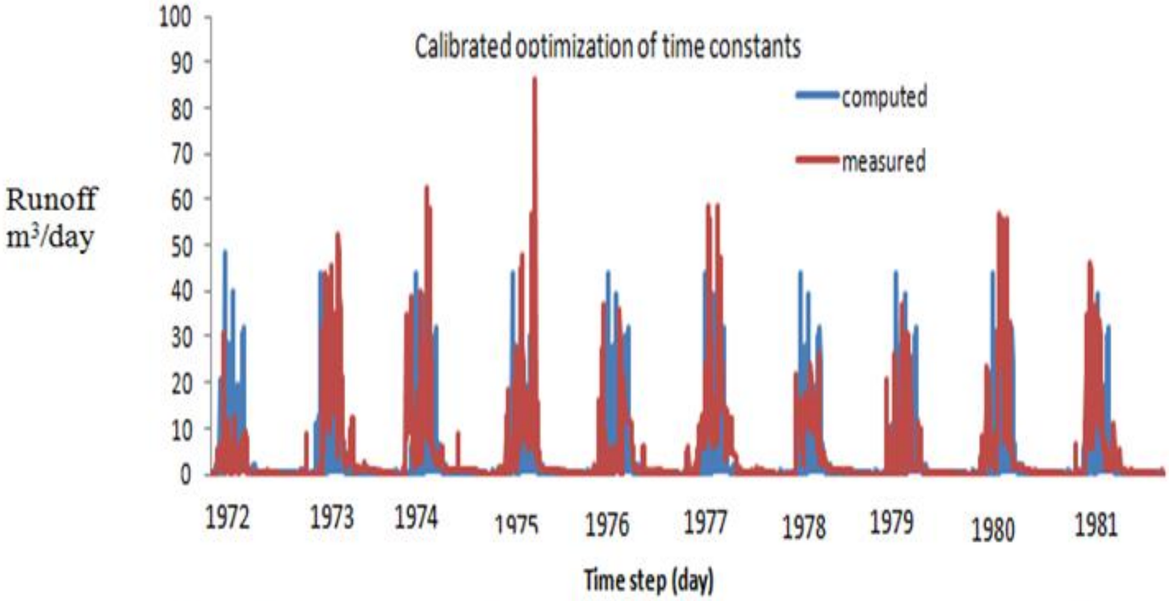

Figure 3.7: Measured and simulated hydrographs for the calibrated parameters (1972 to 1981)

constants, that the model underestimates the flows in all the years except in 1972 and 1978. Model catchment parameters and time constants were then adjusted to get the appropriate representation of the catchment and flow values. The new parameters are shown in Table 3.5.

Table 3.5: Adjusted catchment parameters and runoff routing constants

Catchment parameters		Time constants for routing	
Lmax	*115*		
Umax	*10*	CK1	*0.5*
Cmelt	*0*	CK2	*0.4*
CQOF	*0.3*	CKBFU	*0.4*
CQIF	*0.025*	CKBFL	*90*
CBFL	*0.2*		
CLIF	*0*		
CLOF	*0.6*		
CLG	*0.2*		

After parameter and routing constant adjustments results shown in Figure 3.8 were achieved. It is demonstrated that the computed value magnitudes largely match the measured values, from minimum of 0.5 m^3/day in drought year of 1988 to the highest 16 m^3/day in the highest rainfall week in 1987. This then validates the model as a reliable tool to simulate runoffs given the climatic and catchment conditions.

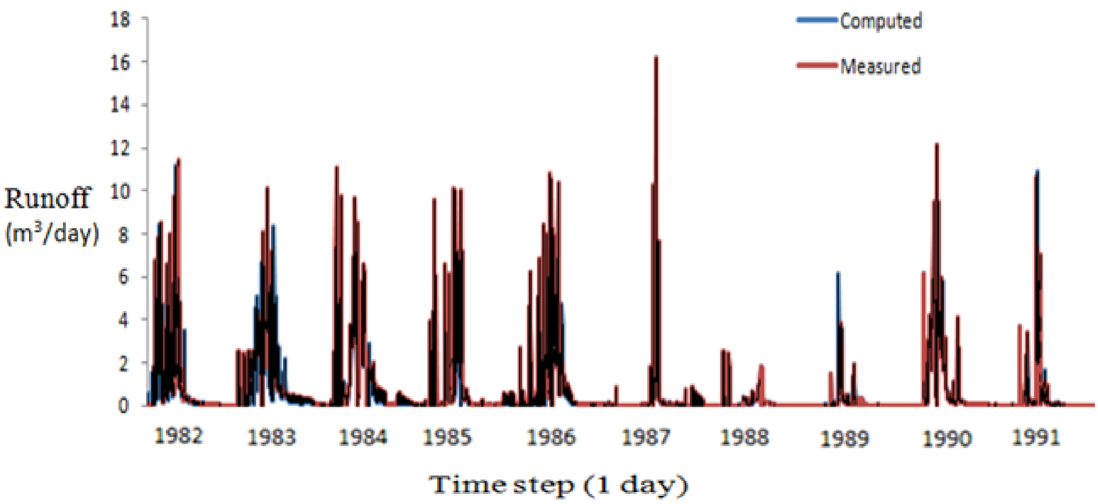

Figure 3.8: Computed and measured hydrographs matched

3.3.4. Calibration of the model for reservoir volume and crop-water production

Results in Table 3.6 indicate that the model is able to simulate seasonal reservoir water balance and irrigation command (irrigable) area after input of water loss and crop water use data, using the spreadsheet commands. With addition of yield value, it is able to simulate crop water productivity (Table 3.6).

Table 3.6: NAM addendum spreadsheet based water loss, irrigation and water balance

						Season 1			Bean
Crop Growth (wks)	Measured dam Vol. m^3	Evapor m^3	Seepage m^3	Cummulative Field use m^3/ha	Total Removal m^3/ha	Water Balance (m3)	Dam Irrigable crop Area (h	Simulate Yield (kg/ha)	Water Prdcty g/L
Pre-planting	9978	6	11	500	517				
1 to 4	9015	9	16	1500	1525				
5 to 9	4646	10	19	2000	2029				
6 to 10	2541	8	15	2000	2023				
TOTAL	0	33	61.0	6000	6094	3884	1.7	1400.0	0.7

At the realized yield production of 1400 kg/ha the seasonal bean water productivity is 0.7 g/L is achieved. This is equivalent to value of 0.6 kg/m^3 (0.6 g/L) reported by FAO (2013). Calculated crop water use was 0.71 g/L which is the same as model computed value.

3.4. CONCLUSION

Gumbel distribution analysis indicates that the data fitting estimates the prediction of the 100-year discharge by 70%. Results of NAM simulation have shown observed and measured runoff hydrographs showing same timely trends. However, calibration of the model performance has shown that the model slightly underestimates runoff in comparison with measured runoffs.

Assessment of runoff data used in calibration using Double mass analysis revealed absence of spurious trends indicating lack of human or station error or any other natural problems with the data source. Optimization of parameters and time constants resulted in the model producing computed hydrographs in the same magnitude as observed ones. The results, therefore, demonstrate that the measured and simulated outcomes are in unison. The model has provided reliable simulation hence is verified for utilization to predict runoffs with confidence given climate and catchment factors.

Validation of the model also resulted in goodness-of-fit between the measured and computed hydrograph trends demonstrating that the model slightly underestimates the flows for the catchment in most of the years. Parameter optimized result simulation, for long time data series from different sites, demonstrated hydrographs of measured runoff and computed ones being in conformity. This reveals efficiency of the validated model to simulate real situation. The model is, therefore, a reliable agro-hydrological tool for making informed prediction relating to runoff, open rainwater storage and irrigation crop water productivity.

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CHAPTER FOUR

DESIGN AND VALIDATION OF A DECISION SUPPORT SYSTEM FOR A GIVEN COMBINATION OF CATCHMENT, RESERVOIR AND CLIMATIC CONDITIONS

ABSTRACT

Recurring droughts and dry spells severely disrupt food production and financial attainability in several areas of Sub-Saharan Africa (SSA). The problem is exacerbated by poor or lack of planning for storing rainwater and sizing of irrigation fields in the face of rainfall from existing catchment areas. Versatile agro-hydrological Decision Support Systems (DSSs) are, hence, needed by farmers for effective synchronization of rainwater reservoir capacity and irrigation field area. The study, therefore, focused on designing and validating DSS to assist in screening best-bet options for crop field area or reservoir sizes using a case study of common beans (*Phaseolus vulgaris, L.)* and Ukwe Area in Malawi. To design and validate the DSS water reservoir and irrigation components were added to an Agro-hydrological *Nedbor Afstromnings* Model (NAM). Simulation of parameter optimized results revealed efficiency of the validated DSS to simulate real situation by reliably relating runoff rainwater harvesting, its seasonal open surface storage and irrigable crop land area. Simulated crop water productivity of 0.7 g/L and potential crop command field area of 1.5 ha were achieved. The simulated synchronization values were in agreement with calculated values. The DSS is recommendable to potential users.

Key words: decision support systems, designing, validation, NAM, efficiency and simulation

4.1. INTRODUCTION

Recurring and cumulative damage from drought has reduced the yield of crops in many regions (Kamthonkiat, 2008). The negative impacts of droughts and dry spells on crop production in sub-Saharan Africa (SSA) strongly call for supplementary or sole irrigation which needs proper sizing of water reservoir with respect to cropped area or vice-versa. Computerized decision support systems allow users to combine technical knowledge of models that combine crop growth, environmental diversity and economic considerations to make proper implementation decisions (Oteng-Darko *et al*., 2013). Therefore, with use of agro-hydrological Decision Support System it is possible to make reliable decisions for synchronization of water reservoirs and field sizes.

Limitation to implementation of agricultural recommendations is contributed by the failure to take into account socio-economic aspects. Yalewa, *et al.,* (2014) conducted research on Dynamic Feedback between Land Use and Hydrology in South Africa and reported that ecosystem services assessment requires an integrated approach, as it is influenced by elements such as climate, hydrology and socio-economics, which in turn influence each other.

In Germany, a contingent valuation method was applied in order to determine people's willingness to pay for an improvement of environmental quality and effects of the hydro-morphological measures within the different water bodies along the River Werra and its tributaries. This was followed by an economic value has been assessed by transferring the adjusted results of the Elbe study. Cost and benefit analysis as additional analysis to evaluate the acceptance and social dimension of the potential planning measure before a decision support system for integration and evaluation of hydrology, ecology, sanitary engineering, social sciences for Water Framework Directive (Hirschfeld *et al*., 2005).

Despite the existence of agro-hydrological DSSs, SSA countries, such as Malawi, have not embraced their use in catchment analyses due to hydrological parameter variations and poor understanding of their application in water storage and irrigation (Njoloma, 2010).

Some decisions in crop production have been made out of use of agro-hydrological models which have fallen short of one aspect or another as a tool for concrete decision making. For example, AQUACROP effectively simulates soil and in-situ water variables but does not have the water harvesting-for-irrigation component, hence has limited utility in drought prone SSA.

Versatile DSSs, like the one emanating from PARCHED-THIRST model, represent important hydrological processes using physical parameters that are readily available or can be easily measured or estimated (RIU, 2007). The THIRST model component was developed in Tanzania to encompass aspects of rainwater harvesting in terms of collecting runoff from a catchment into an adjacent cropped area (Tumbo *et al*., 2006). Currently the model is a land mark in water harvesting and irrigation (RIU, 2007). It combines the simulation of hydrology with growth and yield of cereal crops. However, it does not yet have long term water storage and legume irrigation components.

In other agricultural sectors, DSSs have been developed and successfully used in specific problem domain without being comprehensive in hydrological, agricultural and socio-economic sectors (Larbi, 2011). A system such as the DSS for Agro-technology Transfer (DSSAT) is a software package which integrates the effects of soil, crop phenotype, weather and management options allowing users to ask "what if" questions and simulate results (Wani *et al*., 2011). The system uses other models such as Vegetation/Ecosystem Modelling and Analysis Program (VEMAP), CERES, CROPGRO and CROPSIM model series. However, the above mentioned models do not simulate long term storage of rainwater and soil moisture on crops.

The study, therefore, focused on design and validation of a DSS to provide 'what if' solutions emanating from relationships between amount of stored water and crop area for strategic and tactical decision making. An extended NAM model (to encompass DSS parameters) was utilized on dry season beans as a study crop.

4.2. MATERIALS AND METHODS

4.2.1. Socio-economic analysis of bean irrigation at Ukwe

Economic data measured included labour use, production costs, amount of water applied to each treatment and grain yields. Comparative gross margins and break-even analyses were conducted on rain-fed and reservoir based irrigated bean crops. The analysis was conducted to indicate profit margin for a farming family, while break-even analysis was conducted to demonstrate a minimum yield a farming family needed to achieve in order to recover money spent on the bean production. Break-even price gives the minimum output price beyond which the farmer is likely to make profit (Kadyampakeni *et al*., 2010).

4.2.2. Study framework

Design of the Decision Support System followed the framework depicted in Figure 4.1.

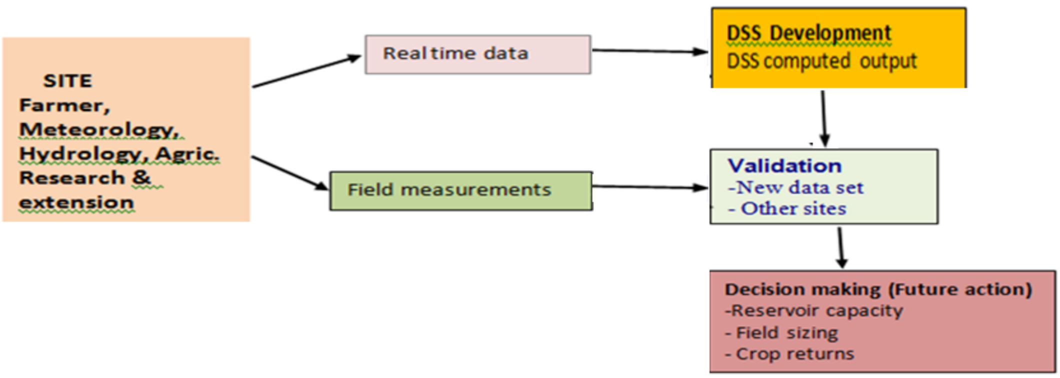

Figure 4.1: Study framework

4.2.3. Input Data

The formulated NAM based DSS is a system requiring limited data input. Three input data files, namely meteorological station data file (potential evapotranspiration, temperature and precipitation), Hydrological Department data file (reservoir evaporation and seepage) and agricultural extensionist/farmer data file (head of cattle, goats/sheep, number of persons using the water, irrigation water depth,) are needed. Collection of data is simple as the meteorological and hydrological data stations in SSA are spread in a number of the agro-ecological zones where weather predictions are made on daily basis. The DSS operation is based on Excel software operation.

In Malawi, the Hydrology Section in the Water Division of the Water Resources Department (Ministry of Irrigation and Water Development), located in the same agro-ecological zone of Ukwe area, is a strong data quality control institution with package of HYDATA software, a powerful tool for hydrological data storage, analysis and routine processing (Njoloma, 2010). Rainfall data collection, coordination and storage, in Malawi, is the responsibility of Meteorological and Climate Change Department (Ministry of Transport and Communication) which also trains personnel manning gauging stations on daily basis. For this study, data for DSS validation were sourced from four stations in the drought prone plateau region of Central Malawi, within the agro-ecological zone of the study area (Figure 4.2).

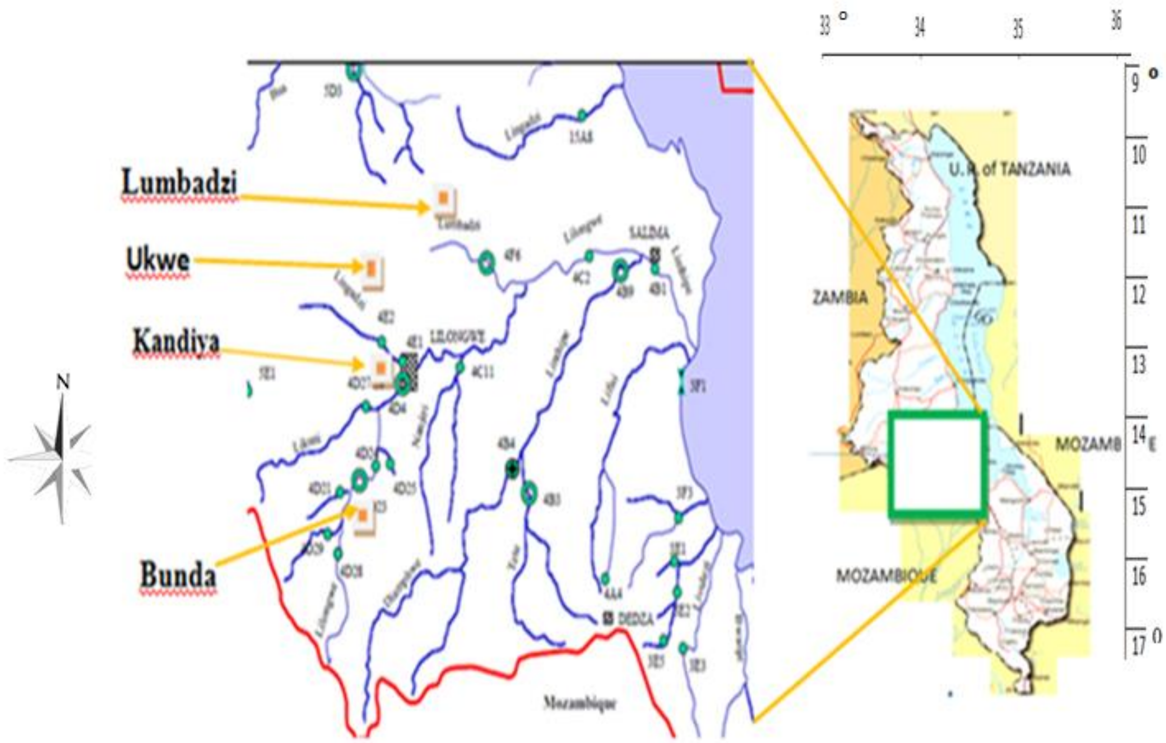

Figure 4.2: Lower Central Malawi agro- ecological zone weather stations

4.2.4. Rainfall data screening and operation of the DSS

Rainfall is a vital component of the runoff water harvesting, storage and irrigation. Therefore, initially, the design of the DSS followed test for data consistency and homogeneity, *i.e.* if data be used for DSS design and validation with confidence. The accumulated mean rainfall data from Ukwe, as it contributed to runoff, was tested against accumulated means from Bunda, Kandiya and Lumbadzi (50 km South, 12 km South-east and 8 km North-east respectively) which are sites in the same agro-ecological and agro-hydrological zone, using Double Mass curve method (Ali, 2011).

4.2.5. Decision Support System Development Procedure

Development of the DSS followed the trend of operation of the system. Initially the system operation requires three main input data sets. Firstly, it requires catchment parameters and time constants, precipitation and potential evaporation so that it can simulate land water storages, and flows which are routed to the reservoir as output. Secondly, it requires data of evaporation and seepage, livestock number (and domestic water use, if any) before it displays reservoir water balance for irrigation. Thirdly, it needs crop water use entry for it to display the required land area to be prepared. The Microsoft (MS) Excel version 1997-2003 NAM based procedure followed the structure depicted in Figure 4.3.

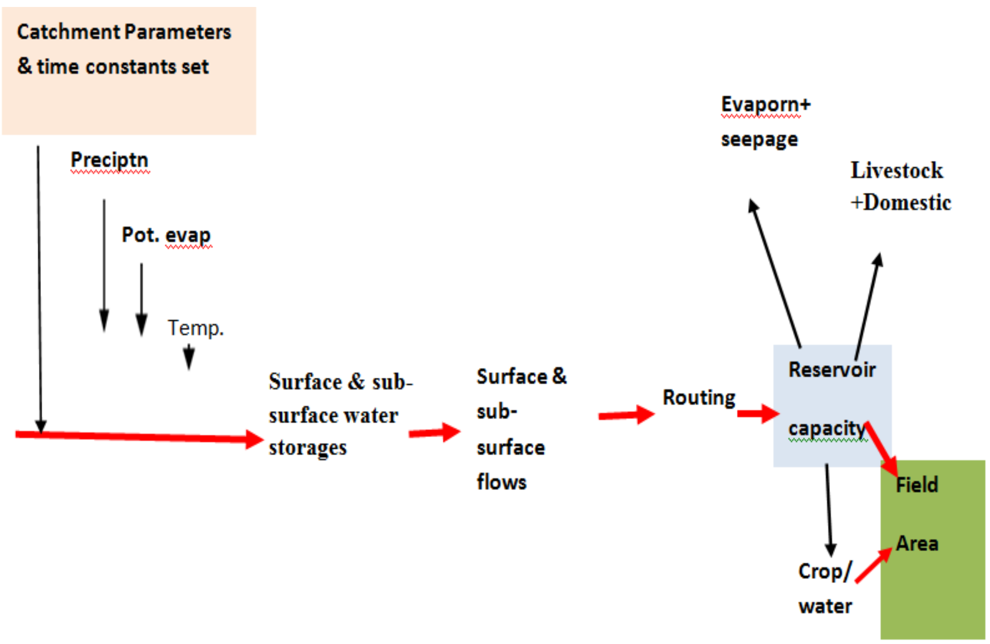

Figure 4.3: DSS flowchart as per excel based NAM spreadsheet programmed commands

4.2.6. Catchment characteristic factors

Impacts of the catchment characteristics on runoff and reservoir capacity, as simulated by the modified NAM DSS excel spreadsheet, are quantified by parameterization. The optimized model catchment parameters and routing constants computed in Chapter three, during the model development, were used in the design and validation of the DSS (Tables 4.1 and 4.2).

Table 4.1: Model Parameter constants in the spreadsheet

Parameter	Name	Constants
Lower zone storage capacity: maximum water storage in the root zone	Lmax	> 0
Upper zone storage capacity: maximum water content in the surface storage.	Umax	> 0 First estimate Umax=0.1Lmax.
Snow melt coefficient	Cmelt	0 for Ukwe site
Overland flow runoff coefficient: extent to which excess rainfall runs off as overland flow and the quantity that i*nfiltrates*.	CQOF	0 – 1. Since Ukwe catchment is small, small values with low, permeable soils are as expected.
Interflow runoff coefficient: proportion of the surface storage that runs off through horizontal leakage.	CQIF	0 – 1. For catchment with a flat topography the value is very close to zero.
Threshold value interflow:	CLIF	0 – 1
Threshold value overland flow	CLOF	0 – 1
Time Constants for Routing		
Overland and interflow: both flows together are routed through a linear reservoir	CK1	> 0
Stream flow: flow is routed through a linear reservoir.	CK2	> 0
Upper groundwater flow	CKBFU	> 0
Lower groundwater flow	CKBFL	> 0

Table 4.2: Ukwe DSS adjusted catchment parameters and time constants

Fixed catchment parameters		Time constants for routing	
Lmax	*115*	CK1	*0.5*
Umax	*10*	CK2	*0.4*
Cmelt	*0*	CKBFU	*0.4*
CQOF	*0.3*	CKBFL	*90*
CQIF	*0.025*		
CBFL	*0.2*		
CLIF	*0*		
CLOF	*0.6*		
CLG	*0.2*		

4.2.7. Decision Support System Validation

Factors of water routing (modified function of total flows), storage and crop water use and productivity have been incorporated to the NAM based operation using an excel spreadsheet version 2007. Table 4.3 shows the spreadsheet data input, merged computer simulation (simuln) columns, cumulative (cummul) dam inflows and dam water balance (dwb). At this point the DSS operator inputs data of pot evaporation (PotEvap), seepage and abstractions by livestock and persons.

Table 4.3: Decision support system operational spreadsheet

Date	Rainfall (mm)	Pot. Evap. (mm)	Temp °C	Computer Simulatn →	Cummul Dam Inflows	DWB m^3	Pot.Evap	Seepage	Cattle	Goat	Persons	Computer Simuln →	Available Water	Appld Water	**Potential Irrigable Area (ha)**

4.3. RESULTS AND DISCUSSION

4.3.1. Rainfall data screening for design of the Decision Support System

The accumulated rainfall means from Ukwe were plotted against accumulated data means of Bunda, Kandiya, and Lumbadzi, 50 km South, 12 km South-east and 8 km North-east respectively, to test reliability of data. Results of the double mass analysis shown in Figure 4.4 indicate that Ukwe rainfall data as tested against the other three weather station data produces spurious relationship showing data inconsistency and non-homogeneity. It would not be reliable, therefore, to use the data for the validation of the DSS unless the source of anomaly is established to be a station other than Ukwe.

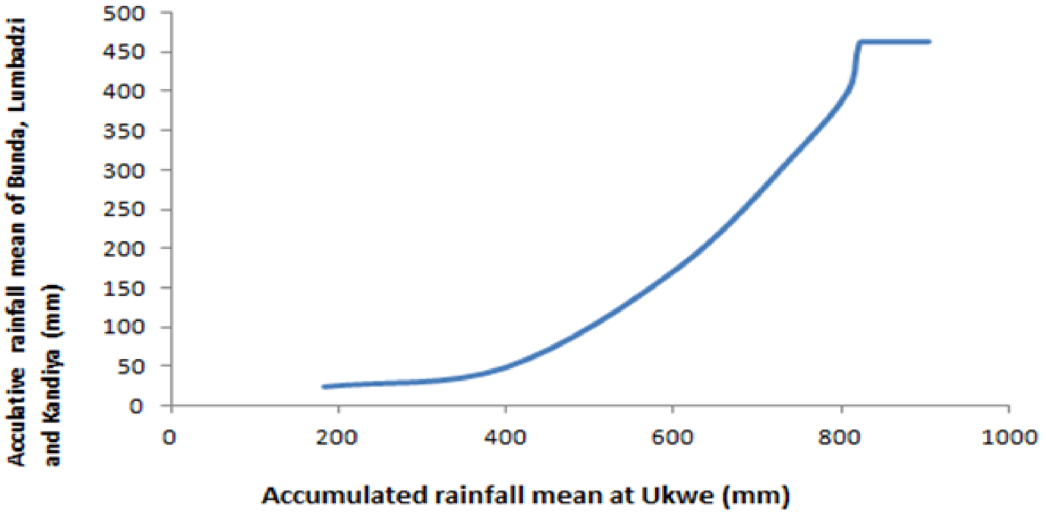

Figure 4.4: Rainfall double mass analysis of all the stations including Bunda

Although Bunda, Kandiya and Lumbadzi are in the same agro-ecological and agro-hydrological zones, the daily rainfall data from each site was eliminated during each analysis to trace source of the anomaly. Errors were discovered in the Bunda data. Infact, Bunda site is far removed (55 km) from the rest and is between two mountains, hence it is suspected to have some rainfall variations during some seasons. Weather conditions are reported to gradually change over distances of 50 to 150 km (MARS, 2014). Double mass analysis test was hence run, excluding this Bunda site. The results, as shown in Figure 4.5, indicate straight line relationship revealing absence of spurious trends. It is worthy pointing-out that Double Mass analysis interpretation is dependent on data line shape rather than use of coefficient of determination (R^2). The analysis, therefore, demonstrated that the rainfall data were valid for runoff and water storage, hence used for the DSS validation.

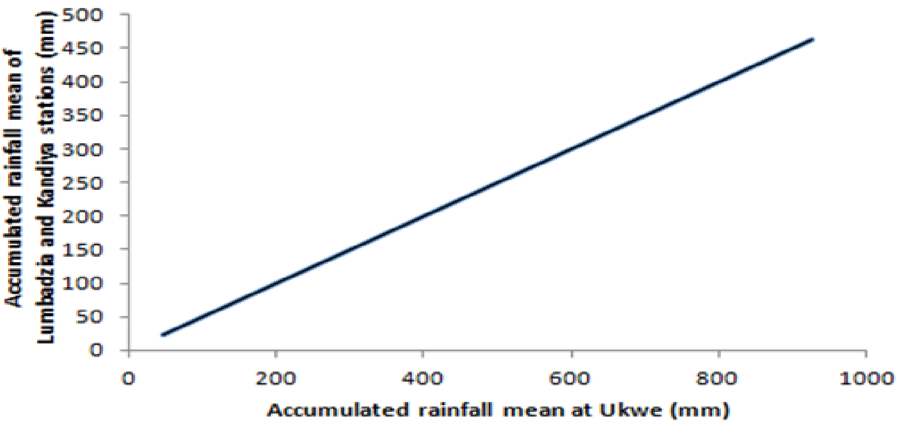

Figure 4.5: Rainfall double mass analysis of all stations excluding Bunda

4.3.2. Socio-economic analysis

4.3.2.1. Gross margin and break-even analyses

Gross margin and break-even analyses were conducted on the grain yield of rain-fed and reservoir water irrigated beans. Variable cost data included production, processing (drying, threshing, treatment) and transportation costs, while fixed costs included contribution towards annual reservoir maintenance (Table 4.4). Output was in terms of grain yields.

The gross margins were higher under irrigation (2.42 times) than under rain-fed bean production despite additional costs of contribution towards reservoir maintenance and irrigation operations. Controlled water application during high dry season temperature, with less pest incidences, tends to make irrigated beans yield higher than rain-fed crop (Kadyampakeni, 2004).

Table 2.2: Gross margin and break-even analysis for rainfed and irrigated beans

		Without Irrigation			With irrigation (50 mm)		
DETAILS	Unit	Quantity	Unit Price	Total cost	Quantity	Unit Price	Total cost
		Kg	MK	MK	kg	MK	MK
Output value	Kg	801.2	150	120,000	1,400	165	231,000
FIXED COSTS							
Reservoir	Annual fee	-	-	-	-	-	5,000
Irrigation	Man days	-	-	-	346	157	54,352
Sub total							59,352
VARIABLE COSTS							
INPUTS							
Seed	Kg	75	250	18,750	75	250	18,750
Insecticides	Litres	10	1,500	15,000	10	1,500	15,000
Fungicide	Kg	25	1,000	25,000	25	1,000	25,000
Sub Total (inputs)				58,750			58,750
LABOUR							
Land preparation	Mandays	42	200	8,400	42	200	8,400
Planting	Mandays	15	200	3,000	15	200	3,000
Supply	Mandays	3	200	600	3	200	600
Weeding/banking	Mandays	23	200	4,600	23	200	4,600
Harvesting/drying /threshing	Mandays	36	200	7,200	40	200	8,000
Drying/packing/loading	Mandays	15	200	3,000	20	200	4,000
Subtotal Labour	Mandays			26,800			28,600
OTHER COSTS							
Sacks	50 kg bags	12	80	960	30	80	2,400
Transport	Bags	12	100	1200	30	120	3,600
Subtotal				2,160			6,000
Total Costs				87,710			152,702
Gross Margin (A-B)	Mk/ha			32,290			78,298
Break-even Yield	kg/ha			585			925
Break-even price to pay variable cost	Mk/kg			110			109

Break-even yield was lower than the achieved yield, showing that the bean producers gained from the enterprise and made a profit. Computation of crop water productivity gave the value of 0.7g/L, lower than values of 1g/L reported from experiments elsewhere (Hashim, *et al*., 2012). The study has shown the benefits of irrigation in comparison to rain-fed farming in the challenging face of frequent droughts and dry spells.

4.3.2.2. Willingness to invest in irrigation

Farmers were interviewed to know their willingness to pay for runoff water harvesting and irrigation (Table 2.3). The cost calculated by the dam committee, which an irrigation household was paying for water preservation, is MK5 000 (US$16.67).

Table 2.3: Willingness to pay for runoff water harvesting and bean irrigation

Maximum willingness to pay		Percent
MK	US $	
<5 000	< 16.67	48.20
5 000 - 10 000	16.67 - 33.34	25.30
10 000 - 15 000	33.34 - 50.01	18.10
>15 000	>50.01	8.40
	Total	100.00

Forty eight percent of farmers would like to pay less than the equivalent US$16.67. With the need to reforest the catchment area and dam peripheral, only less than 26% of the total number of households would be willing to pay. They rest of the farmers (74 %) would rather do the work themselves as self-help operations. The expectation was that somebody else, either the non-governmental organization or the government, should assist them in paying for such operations. The unwillingness of the small-holder farmers to invest in irrigation infrastructure was similarly reported by Kadyampakeni *et al*., (2010).

4.3.3. Decision Support System Spreadsheet Simulation

Operational spreadsheet workbook inputs, with hidden computer simulation command columns (computer simuln) are shown in Table 4.4. The results of validation based on 2011-2012 data (with hidden command rows and columns for December 2, 2011 to December 31, 2012) displaying Dam Water Balance (DWB) and potential irrigable area are highlighted in the table.

Table 4.4: Operational spreadsheet workbook simulation highlight for computer simulated and available reservoir water (m^3), and potential field area

Date	Rainfall (mm)	Pot. Evap. (mm)	Temp °C	Computer Simulatn →	Cummul Dam Inflows	DWB m^3	Pot Evap	Seepage	Cattle	Goat	Persons	Computer Simuln →	Available Water	Appld Water	Potential Irrigable Area (ha)		
Planting ↓ Time step (day)																	
END SEASON	2.8	1.1	1.68	24	0.478	10795.6	709	10087	1.69	5.7	122	25.7	0	9931.1	9	0	
																0.71	
															10335	7990	1.5

The DSS simulated synchronization of reservoir water and land area (1.5 ha) is equivalent to the calculated area (1.6 ha) based on the research recommended bean crop irrigation depth of 5 cm per week, if static application rate is followed (Mloza-Banda, *et al*., 2010). This validates the DSS for utilization to establish reservoir capacity and/or corresponding crop land area.

4.4. CONCLUSIONS AND RECOMMENDATIONS

4.4.1. Conclusions

Socio-economic analyses have indicated clear benefits for the farmers producing the common beans using stored runoff. Once the socio-economic benefits of water storage and irrigation are revealed, it is then feasible to endeavour into the development of a

decision support determination of required crop field area in relation to the reservoir water capacity or vice-versa.

The conceptual framework, structure and spreadsheet entries of the DSS have been designed and validated using Ukwe Area data on common beans (*Phaseolus vulgaris*, L.). Two dry season crop production cycles, at crop water productivity of 0.7 g/L, as the case at Ukwe Area, would require potential crop command field area of 1.5 ha.

The DSS requires few parameters and input data to simulate accumulated reservoir capacity and its appropriated crop field size to be irrigated. The DSS has comparative advantage to others, developed for rainwater harvesting for irrigation, because apart from using simple data entry it is versatile in simulating runoff, long term surface water storage capacity and synchronized crop land area farmers need to prepare to meet the recommended crop water requirement. Stakeholders can use the DSS developed information to support their decision in planning field area for farmers based on reservoir capacity or build a reservoir to suffice crop land area to mitigate drought and dry spell impacts.

4.4.2. Recommendations

The DSS has been developed and validated in only one agro-ecological zone, representing drought prone areas of SSA and on common bean crop only. It is recommended that it be further validated on different crops and other agro-ecological zones for wide-scale utilization.

It is also recommended that, in addition to spreadsheet data entry operational structure, a computer interface be developed. The user can perform progressive some interactive data entry starting with fixed catchment parameters and time constants as the DSS data base memory to evoke prominent catchments used for water harvesting. Then a window should display a request for predicted precipitation entry, once entered, it be followed by potential evaporation value then temperature to achieve seasonal reservoir volume display.

The user will be asked to enter *seepage*, then *evaporation*. Once the evaporation value is entered, a new *reservoir balance* is shown. The user will then enter *continue* and the interface will ask for crop *water application*. Once a figure is entered the computer interface will display the *field area* to be prepared. The procedure would be an option to the presented excels spread sheet data entry.

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CHAPTER FIVE

5.1. GENERAL CONCLUSION AND RECOMMENDATIONS

Although rainfall seasons in sub-Saharan Africa would, generally, provide adequate seasonal bean water requirement, droughts and dry spells result in inadequate seasonal water to meet the crop water requirements. Dry seasons are not adequately utilized for irrigated crop production due to deficiencies in water availability as rainwater is not adequately harvested and stored for the purpose. The study, therefore, focused on synchronization of runoff rainwater storage capacity and crop productivity.

Results have demonstrated that a change in the size of reservoir or field will provide the related optimum sizing of the other for maximizing crop productivity based on runoff generating catchment attributes and climatic conditions. It has been demonstrated that yield from irrigation using harvested and stored water surpasses that obtained from rain-fed farming. It recommends paradigm change from major dependence on rain-fed agriculture programmes, *per se,* to runoff water harvesting, storage and irrigation programmes to avert negative consequences associated with the inadequate and erratic annual rainfall manifested in dry spell or droughts.

The study has revealed high positive correlation between measured and computed runoffs during modified NAM calibration although the model slightly under-estimates runoff. However, with adjustments of model parameters and time constants it efficiently simulates measured runoff. In general, the calibrated and validated model effectively simulated rainfall-runoff relationship and crop response to stored runoff irrigation. Utilization of optimized (adjusted) parameters and time constants into the Decision Support System gave high versatility for use to predict required sizes of a reservoir and/or crop production area based on climatic and reservoir evaporation and seepage factors. Using the MS Excel operation, the developed DSS reliably relates runoff rainwater harvesting, its seasonal open surface storage and irrigation to crop water productivity.

Data from the Department of Climate Change and Meteorology will be useful for farmers to make decisions in order to optimize their crop yields. At national level, the Early Warning Section of the Ministry of Agriculture and Food Security anticipates using the DSS, given climate forecasts, to predict crop yield. Assistance will be sought from national, regional and international funding institutions for the aforementioned activities and training fora involving water and irrigation specialists, agronomists, extension specialists and instructors.

The DSS provides farmers and agricultural research and extension workers a simplified procedure for determination of reservoir water capacities, given climatic forecasts, catchment characteristics and crop water requirement, in order to plan for dry season crop field sizing. Agricultural extension workers will be able to deduce useful information they need to advise farmers on how large the reservoir should be and how much land area to prepare given the aforementioned rainfall forecasts. At agricultural academic institutions in SSA the DSS can be included in curricula modules and research projects.

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6. APPENDIX 1

6.1. NAM calculation sequence

- Logical commands for corresponding spreadsheet formulae*

i. Set Catchment parameters and time constants

U = Storage of the surface water reservoir = 0 for Ukwe reservoir - No water in the upper storage at the beginning of rainy season

$$\begin{aligned} &if \quad Temp_{i-1} > 0 \quad \Rightarrow \quad U_i = U_{i-1} + P_{i-1} - Ep_{i-1} - QIF_{i-1} - Pn_{i-1} + Ps_{i-1} \\ &if \quad Temp_{i-1} < 0 \quad \Rightarrow \quad U_i = U_{i-1} - Ep_{i-1} - QIF_{i-1} - Pn_{i-1} \end{aligned} \quad \text{...............(27)}$$

ii. Add potential evaporation for the area (pot evap)

$U_t = U_t - E_a$

iii. Ss = Snow storage in reservoir – Temperature values for SSA, are above

Hence, value = 0 for Ukwe Area

$$\begin{aligned} &if \quad Temp_{i-1} < 0 \quad \Rightarrow \quad Ss_i = Ss_{i-1} + P_{i-1} \\ &if \quad Temp_{i-1} > 0 \quad \Rightarrow \quad Ss_i = Ss_{i-1} - P_{i-1} \end{aligned} \quad \text{...(28)}$$

iv. L = Storage in the lower zone reservoir
- value more sensitive to the optimization process.

$$L_i = L_{i-1} + DL_{i-1} - Ea_{i-1} \quad \text{..(29)}$$

v. Enter : *L/Lmax*

vi. Ps = Snow contribution to the system. In the case of the research site (Ukwe) all values are zero as there is no snow

vii. p = Calculated potential evapotranspiration as minimum value between:

$$\begin{aligned} &U + Ps + P \\ &\quad \text{and} \\ &\quad Epot \end{aligned} \quad \text{..(30)}$$

viii. QIF = Interflow contribution. The spreadsheet model shows the following command

$$U + Ps - Ep + P \qquad \text{...} (31)$$

and

$$\begin{array}{lll} if \quad \dfrac{L}{L\max} > CLIF & \Rightarrow & \dfrac{CQIF * U * (\dfrac{L}{L\max} - CLIF)}{1 - CLIF} \\ if \quad \dfrac{L}{L\max} < CLIF & \Rightarrow & 0 \end{array} \qquad \text{..............................}(32)$$

ix. Pn = Excess water indicating scenario of maximum surface storage, maximum value between:

$$\begin{array}{lll} if \quad T > 0 & \Rightarrow & U + P + Ps - Ep - QIF - U\max \\ if \quad T < 0 & \Rightarrow & U - QIF - Ep - U\max \end{array}$$

$$and$$

$$0 \qquad \text{...}(33)$$

x. QOF = Overland flow, minimum value between:

$$Pn$$

and

$$\begin{array}{lll} if \quad \dfrac{L}{L\max} > CLOF & \Rightarrow & \dfrac{Pn * CQOF * \left(\dfrac{L}{L\max} - CLOF\right)}{1 - CLOF} \\ if \quad \dfrac{L}{L\max} < CLOF & \Rightarrow & 0 \end{array} \qquad \text{..........}(34)$$

xi. Ea = Actual Evapotranspiration, taking the minimum value between:

$$Epot * \frac{L}{L\max}$$

and

$$Epot - Ep$$

xii. G = Groundwater flow

$$if \quad \frac{L}{L\max} > CLG \quad \Rightarrow \quad \frac{(Pn - QOF) * \left(\frac{L}{L\max} - CLG\right)}{1 - CLG}$$

$$if \quad \frac{L}{L\max} < CLG \quad \Rightarrow \quad 0$$

....(35)

xiii. *DL* = Portion of the amount of infiltration which increases the moisture content L, maximum value between

$$Pn - QOF - G$$

and

$$0$$

ivx. *QR1* = Outflow resulting from the overland flow together with the interflow

Outflow at Ukwe from the month of June is zero.

$$BFL1_i = BFL1_{i-1} * \left(\frac{1}{CKBFL}\right) + \left(G * CBFL * \left(1 - \frac{1}{CKBFL}\right)\right) \text{.......(37)}$$

$$QR1_i = QR1_{i-1} * \left(\frac{1}{CK1}\right) + (QOF + QIF) * \left(1 - \frac{1}{CK1}\right)$$

…...............................(36)

vx. *BFU1* = Upper storage component of the groundwater flow.

BFL1 = Lower storage component of the groundwater flow

xiv. QR2 = Total stream flow

$$QR2_i = QR2_{i-1} * \left(\frac{1}{CK2}\right) + (QR1 + BFU1 + BFL1) * \left(1 - \frac{1}{CK2}\right)$$

……….........(38)

xv. Objective function = Measured (*Qm*) minus spread sheet estimated stream flow (*QR2*)

$$OF = (Qm - QR2)^2 \qquad \text{.. (39)}$$

* Source: Njoloma, 2010.