

Decision Support System for Runoff Water Harvesting and Irrigation

Darwin Dodoma Singa¹, Siza Donald Tumbo¹, Mahoo, Henry Fatael¹, Rwehumbiza, Filbert¹ and Lowole, Maxon²

1. Sokoine University of Agriculture, BP: 3003, Morogoro, Tanzania.

2. Lilongwe University of Agriculture and Natural Resources, Box 219, Lilongwe, Malawi

Abstract

Despite the prevailing versatility of agro-hydrological Decision Support Systems (DSS) in the agricultural sector, a number of associated deficiencies do exist. The deficiencies are due to lack of synchronization of runoff affecting rainfall, catchment factors, reservoir capacity and irrigation field area in the face of recurring droughts and dry spells in several areas of Sub-Saharan Africa (SSA). The study focused on designing and validating a Decision Support System, by adding water reservoir and irrigation sub-routines to an Agro-hydrological Nedbor Afstromnings Model (NAM) to assist in screening best-bet options for either crop field area or reservoir size using a case study of common beans (*Phaseolus vulgaris*, L.) at Ukwe Area in Malawi. Microsoft excel spreadsheet (MS excel) was used to compute cumulative runoff inflows into the dam, seasonal open surface water storage, water losses and withdrawal and reservoir water available for the bean crop. Computer simulation using soil, vegetation and topographical characteristics, and crop water requirements revealed proportion of catchment to irrigation command area of 10:1 with bean water productivity of 0.7g/l (0.7kg/m³), indicating low water demand. The NAM simulated values were in agreement with calculated ones. Post-DSS gross margin analysis indicated that 2.42 times more crop returns were obtained from irrigated than rain-fed bean crops despite additional costs associated with reservoir maintenance and irrigation operations. The DSS is, hence, found potential for users in drought prone Sub-Saharan African countries such as Malawi.

Key words: Irrigation, reservoir, runoff, simulation, storage and synchronization

1. Introduction

Recurring and cumulative crop damage due to drought has reduced the yield of crops in many regions of the world (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 take into account crop growth, environmental diversity and economic considerations to make proper decisions in synchronizing sizes of water reservoirs and fields (Oteng-Darko *et al.*, 2013).

Yalewa *et al.* (2014) in South Africa 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 one another. In Germany, quantification of an improvement of environmental quality and effects of the hydro-morphological measures within different water bodies was followed by an economic value assessment to make decisions on which framework directive was based (Hirschfeld *et al.*, 2005). Literature search has revealed a number of models which can help in designing and validating a DSS instead of developing a completely new one. Despite the existence of agro-hydrological DSSs, Malawi has not embraced their use in catchment analysis due to lack of reliable hydrological parameter framework and poor understanding of their application in water storage and irrigation (Njoloma, 2010). Most of the models are not versatile for establishing appropriate variable combinations of catchment area, hydrological parameters and crop water productivity (Table 1). Some models are also costly in implementation. Furthermore, the current study was aimed at addressing this knowledge gap in synchronizing of water storage capacity and irrigation hydrological parameters for affordable planning of field area or water reservoir sizing under Malawi climatic and catchment conditions.

Table 1: Highlights of potentiality and limitations of some agro-hydrological models for utility in drought prone SSA countries.

Model	Potential use	Limitations
GOSSYM /COMAX expert system	Application of N, irrigation & growth regulators (Boote <i>et al.</i> , 1996; Newman <i>et al.</i> , 2000)	Costly for resource-poor farmers, time & resource demanding in Code adding (modification) to cater for specific aspect deficient
CERES, CROPGRO and CROPSIM model series	Include CROPGRO-dry bean (<i>Phaseolus</i>), ie, the current study test crop	Not versatile in simulation of soil moisture on crops & not combining rainwater harvesting and irrigation
DSSAT	Integrates soil and crop effects, weather and management options allowing users to ask "what if" questions and simulate results (Wani <i>et al.</i> , 2011).	Needs use of CERES, CROPGRO and CROPSIM model series - not versatile on Rain water harvesting, long term reservoir water storage & soil moisture on crops.
APSIM	-Integrates sub-models from fragmented agricultural research efforts - provides means for comparison of	Not yet effective in Rain water harvesting

	models or sub-models -powerful tool for exploring agronomic adaptations	
AQUACROP	-Versatile model -Simulates soil and in-situ water variables	- Deficient in water harvesting –for-irrigation component -hence limited utility in drought prone SSA countries
PARCHED THIRST (PT)	-Simulates crop, soil, land and water management, climatology -Provides for planning and designing of RWH systems (RIU, 2007; Tumbo <i>et al.</i> , 2006)	Not yet for long term water storage
<i>Nedbor Afstromnings Model</i> (NAM)	-Simple & reliable in operation - Versatile and adaptable to sub-Saharan African geo-climatic and crop conditions.	Tested for Southern Africa but not verified and adopted

55

56 The table indicates that models with important hydrological processes, using physical parameters
57 that are readily available or easily measured, and used in water harvesting and irrigation, do not yet
58 have long term water storage and legume irrigation components. Similarly, Larbi (2011) states that
59 some specific problem domain DSSs have not been comprehensive in hydrological, agricultural and
60 socio-economic sectors for use in Southern African drought prone areas.

61

62 The objective of the study was to design and validate a DSS which could provide ‘what if’ solutions
63 emanating from relationships between volumes of stored water, irrigation and crop financial status
64 for strategic and tactical decision making. It focused on assessing the possibility of extending
65 versatile NAM model sub-routines, using simple and limited precipitation, potential
66 evapotranspiration and temperature data to simulate runoff for encompassing the DSS parameters.
67 The NAM model is a deterministic conceptual, lumped type model that links simplified mathematical
68 statements about land characteristics and climate parameters to simulate runoff.

69

70 **2. Materials and Methods**

71 **2.1. Analysis of runoff, Reservoir water and crop water requirement**

72 The reservoir inflows were measured using a calibrated gauge installed in the reservoir as practiced by
73 the Ministry of Irrigation and Water Development in Malawi (MIWD, 2011). The volume of water in
74 the reservoir was obtained by measuring the dam average water width and depth using differential
75 global positioning system (dgps). To calculate reservoir volume, the following equation, which has
76 been employed in Zimbabwe and Malawi to estimate small reservoir water volume was used
77 (Saunyama, 2005):

$$C = DWT/6 \dots\dots\dots (1)$$

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). The volume was then equated to the seasonal field crop water use. Reservoir water balance was based on losses due to seepage, evaporation and livestock consumption. A relationship between evaporation from calibrated standard (Class 'A') open pans 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 sourced from Chitedze National Agricultural Research Station. Calibrated $E_{\text{pan}}/E_{\text{reservoir}}$ ratio for small reservoirs was 0.7. Evaporation from reservoirs was calculated using equation 2:

$$EV = \frac{2 RA_{\text{max}} E}{3 \times 1000} \dots\dots\dots (2)$$

Where EV is the volume of water evaporated (m^3), E is the open pan water evaporation (mm), RA_{max} is surface area of the reservoir at full supply level (m^2) (Kambuku, 2010). Quantification of the reservoir water seepage (GW) was achieved using the water balance Equation 3

$$GW = IV_c + P - E - Q - \Delta C - I \dots\dots\dots (3)$$

Where; ΔC is new water balance, IV_c is previous week water balance, P is precipitation = 0, E is evaporation, and Q is surface runoff = 0 during the dry season.

The reservoir water volume balance (following seasonal losses through evaporation, seepage and abstraction by livestock) divided by total seasonal crop water requirement, over a hectare, provided the maximum land area (ha) the reservoir water could irrigate. The foregoing relationship, in turn, established optimum sizing of either land area or reservoir capacity for maximizing crop productivity based on the runoff generating catchment attributes and climatic conditions.

The procedure involved recording of reservoir water levels on weekly time step in line with the irrigation water abstraction and losses. A local sensitivity of change in reservoir capacity (ΔC) as related to cumulative irrigation withdrawal (ΔI) multiplied by the area irrigated (A) was established. System behaviour and criteria for selecting optimum ΔC and ΔI in relation to seasonal progression (Δt) was hence devised. A finite difference equation based on recommended weekly applied water depths (cm) as depicted by Euler Method (Jones and Luyten, 1998) developed notations of relationship:

$$\Delta t \times \Delta I(A) = \Delta C \dots\dots\dots (4)$$

Applied water at weekly constant of 5 cm (following pre-planting irrigation water of 100 cm) multiplied by the area gave the volume of required water for the field.

2.2 Calibration of the Decision Support System

2.2.1 Case study location, climate and bean crop production

The study site, Ukwe, is located in North-West of Lilongwe in Malawi. The area is about 1150 m above sea level, 13° 46' S and 33° 37' E to 13° 55' S and 33° 38' E, extending to 13° 46' S and 33° 31' E to 13° 50' S and 33° 32' E, occupying flat *dambo* margins. “*Dambo*” is a Bantu term describing an extensive seasonally saturated, grassy low-lying area common in Central and Southern Africa. Being low-lying areas with some impermeable soil layers, *dambos* are runoff recipients with high retention capacities of water, which is available for residual or irrigated crop growth.

Temperatures in Ukwe range from 18 to 24°C rising to 29°C just before the start of rains (October to November). Rainfall in Malawi is of unimodal pattern, starting December and terminating in April. Ninety percent of the rain falls from January to March. The national mean rainfall varies from 760 mm during low rainfall year to 1430 mm during high rainfall year. However, in drought prone areas, including Ukwe, only 400 to 650mm mean annual rainfall is received. To meet seasonal bean crop water requirement, whose minimum is 660 mm farmers use harvested runoff from small catchments (10 - 15 ha) stored in small reservoirs or in some perennial small streams.

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 complete yield loss. At Ukwe, farmers have organized themselves into a club for purposes of growing common dwarf bean (*Kalima* variety) under irrigation during the dry season months (June to November) using water from a small Kalembe reservoir whose catchment area is 16 ha. The weekly irrigation water depth was 50mm, following pre-planting water application of 100 mm. All agronomic and crop protection practices as recommended by the Ministry of Agriculture, Irrigation and Water Development (MAFS, 2012) were followed. These included planting in 2 rows, 10 cm apart (1 seed per station), 15 cm seed station interspacing on ridges 75 cm apart. Type 23: 0 + 4 (NPKS) fertilizer was applied at 100 kg/ha and cypermethlin (20 ec) insecticide was applied 7 weeks after planting.

Biweekly 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%. Two weeding operations were carried out, 2 and 6 weeks after planting. The reservoir water was also

consumed by 102 heads of cattle and 143 goats. All domestic water was supplied by shallow wells hence reservoir water was not used for domestic chores.

2.2.2 Study site data calibration

Rainfall data from Lumbadzi, Kandiya and Bunda, 8 km North-east, 12 km East and 30 km South-west of Ukwé respectively, were used to calibrate the MS excel based DSS output for Ukwé site. 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 quantification of irrigation water abstraction. A local sensitivity of change in reservoir capacity was obtained by multiplying cumulative irrigation withdrawal by the area irrigated. System behaviour and criteria for selecting optimum reservoir capacity and cumulative irrigation withdrawal, as the dry season progressed, was established.

2.3 Input data for Decision Support System

2.3.1 Input Data to develop a decision support system

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 for the system to be operational. Collection of data is simple because 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, located in the same agro-ecological zone as Ukwé area, is a strong data quality control institution with package of a purpose-built, Windows-based database and analysis system for processing the hydro-meteorological data (HYDATA software)(Njoloma, 2010). Rainfall data collection, coordination and storage, in Malawi, is the responsibility of Meteorological and Climate Change Department. For this study, data for DSS validation were sourced from four stations, Lumbadzi, Ukwé, Kandiya and Bunda in the drought prone plateau region of Central Malawi (Figure 1) within the agro-ecological zone of the study area, detailed in Figure 2.

2.3.2 Rainfall data screening

The design of the DSS followed test for data consistency and homogeneity. The accumulated mean rainfall data from Ukwe, as it contributed to runoff, was tested against accumulated means from Bunda, Kandiya and Lumbadzi using Double Mass curve method to test reliability of data (Ali, 2011). Mass analysis showed a spurious relationship indicating data inconsistency and non-homogeneity (Figure 3). It would, hence, not be reliable, therefore, to use the Ukwe data for development of the DSS unless the source of anomaly is established to be a station other than Ukwe.

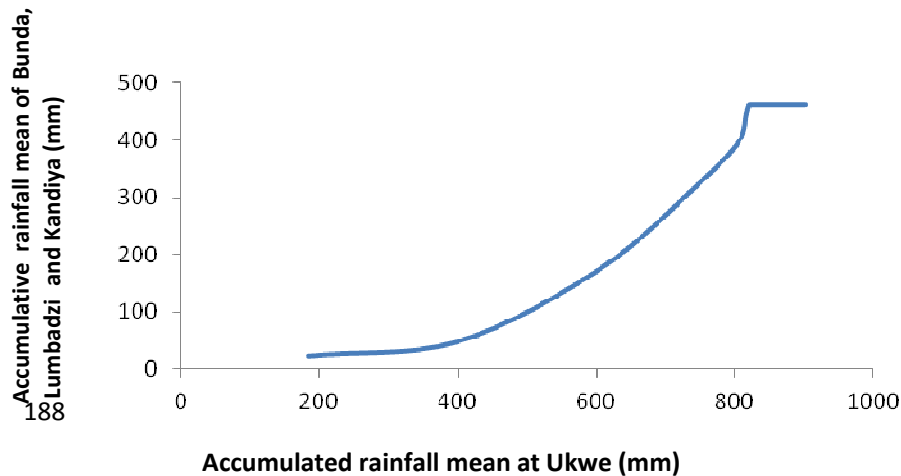


Figure 3: Rainfall double mass analysis of all the stations including Bunda

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. In fact, Bunda site is far removed (50 km) from the rest and is between two mountains, hence it was suspected to have some rainfall variations during some seasons. Generally, 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. A straight line relationship revealing absence of spurious trends was obtained (Figure 4). It is worthy

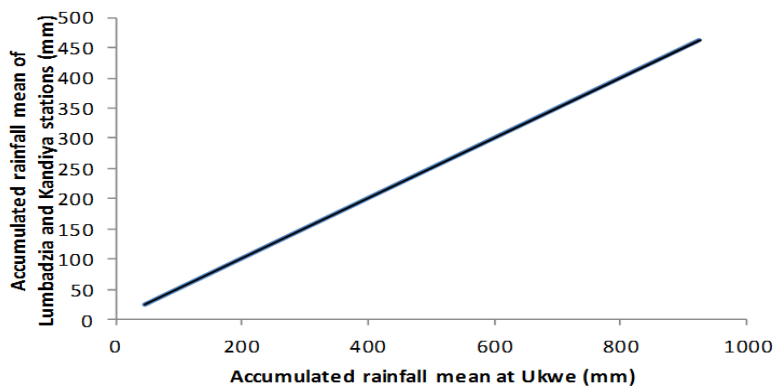


Figure 4: Rainfall double mass analysis of all stations excluding Bunda

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 Ukwé rainfall data were valid for runoff and water storage analysis, hence were used for the DSS development.

2.4 Decision Support System Development

2.4.1 Development procedure of the Decision Support System

Development of the DSS required three main input data sets. Initially 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 needs data of evaporation and seepage, livestock number, and domestic water use (if any) before it displays reservoir water balance for irrigation. Finally, it requires crop water use entry for it to display the required crop land area.

4.1.1 Catchment characteristics

Impacts of the catchment characteristics on runoff and reservoir capacity as simulated by the modified NAM DSS excel spreadsheet, were quantified by parameterization as shown in Table 2.

Table 2: Model Parameter constants as commands 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 Ukwé site
Overland flow runoff coefficient: extent to which excess rainfall runs off as overland flow and the quantity that infiltrates.	CQOF	0 – 1. Since Ukwé 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	CK1	> 0

through a linear reservoir

Stream flow: flow is routed through a linear reservoir.	CK2	> 0
Upper groundwater flow	CKBFU	> 0
Lower groundwater flow	CKBFL	> 0

*Original 'parameter categorization' and 'name abbreviation' from Njoloma, 2010

2.4.1.2 Decision support system function optimization

Several different values were tested to obtain the best value for the storage in the lower zone reservoir (L), because the zone has high 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 (Table 3) were estimated based on the knowledge of the used catchment area and the reservoir.

Simulated data trends were compared with actual field observed data. Model catchment parameters and time constants were then adjusted to get the appropriate representation of the catchment and flow values.

Table 3: Initial parameters and water routing constants in the spreadsheet for calibration

Fixed catchment parameters		Time constants	
Lmax	160.000	CK1	0.5
Umax	15.000	CK2	0.5
Cmelt	0.000	CKBFU	10.0
CQOF	0.300	CKBFL	180.0
CQIF	0.700		
CBFL	0.900		
CLIF	0.700		
CLOF	0.300		
CLG	0.400		

Adjustments of catchment parameters and time constants, for NAM operation, with respect to climatic values, to predict catchment runoff for comparative optimization of measured and computed reservoir water volume were carried-out using computer *solver*. The procedure focused on the DSS performance based on data entry mechanism, model parameters and time constants for

water routing using MS excel spreadsheet computation. Results of optimized parameters and constants are shown in Table 4.

Table 4: Ukwe DSS adjusted catchment parameters and time constants

Fixed catchment parameters		Time constants	
Lmax	115.000	CK1	0.5
Umax	10.000	CK2	0.4
Cmelt	0.000	CKBFU	0.4
CQOF	0.300	CKBFL	90.0
CQIF	0.025		
CBFL	0.200		
CLIF	0.000		
CLOF	0.600		

By use of the *solver* function the starting parameter values were optimised until the maximum value of the objective function, coefficient of efficiency (RE), was obtained. The optimized model catchment parameters and routing constants were then used in the design and validation of the DSS. The final development of the DSS involved incorporation of factors of water storage and crop water use and productivity. The following equations were formulated and used to compute reservoir volume, its seasonal balances and irrigation water components of the added DSS component. This was done by use of parameter constants, depicted in Tables 2, and DSS adjusted catchment parameters and time constants depicted in Table 4. The equations were implemented in the spreadsheet in form of implementation commands in the following sequence:

Total flows into the dam ($CDIn$), used the Equation 5 as accumulation maximum water content in the surface storage, U_{max} , values.

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

(5)

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 6:

$$WDI = (0.034) \frac{Ep_m^{1.09}}{AD^{0.09}} \dots\dots\dots (6)$$

Dam Bal = Water volume remaining in the dam after cumulative weekly abstraction and losses. The model component used Equation 7:

$$DWB = \left(9978 + \sum \left(QR2_{i-1} * \frac{1}{CK2} + (QR1 + BFU1) * \frac{1}{CK2} \right) \right) \dots\dots\dots (7)$$

The constant 9978, being the amount of water available in the reservoir in m³ 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 8:

$$SFU = \sum \left((0.034) \frac{EP_m^{1.09}}{AD^{0.09}} \right) \dots\dots\dots (8)$$

DWB = Dam water balance is the difference between accumulated water in the dam and accumulated field water as shown in Equation 9.

$$DWB = \sum \left(QR2_{i-1} * \frac{1}{CK2} + QR1 + BFU1 + BFL1 \right) * \frac{1}{CK2} - (0.034) \frac{EP_m^{1.09}}{AD^{0.09}} - (0.034) \frac{EP_m^{1.09}}{AD^{0.09}} \dots\dots\dots (9)$$

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.

2.5 Validation of the Decision Support System

Factors of water routing (modified function of total flows), storage and crop water use and productivity were incorporated to the NAM based operation using an excel spreadsheet version 2007. Table 5 shows the spreadsheet data input, merged computer simulation (simulatn) columns, cumulative (cummul) dam inflows and dam water balance (dwb). At this point the DSS operator inputs data of pot evaporation (Pot evap), seepage and abstractions by livestock and persons.

Table 5: Decision support system operational design spreadsheet

Date	Computer			Water losses		Water withdrawals			Computer	Crop		Potential
	Simulation	Cummul	DWB	Pot	Seepage	Goat	Cattle	Persons	simulatn	available	Appld	irrigable
	→	dam		evap					→	water	water	Area
		inflows	(m ³)	mm	(m ³)	(m ³)	(m ³)	(m ³)		(m ³)	(cm)	(ha)

2.6 Financial analysis of bean irrigation at Ukwe

Once the DSS is employed to determine appropriate relationships among runoff, reservoir capacity and crop land area with respect to seasonal rainfall and catchment characteristics for water harvesting, financial analysis needs to be conducted to determine comparative benefits between rain-fed and irrigated crop production. A decision can then be made as to whether to employ the DSS. The financial data required for the study case analysis included labour use, production costs, amount of water applied to each treatment and grain yields.

Comparative gross margin analysis and break-even analysis were conducted on rain-fed and reservoir based irrigated bean crops. The gross margin analysis was conducted to indicate profit margin for a farming family, while break-even analysis was done to demonstrate minimum yield a farming family needed to achieve to recover money spent on the bean production. Break-even price is described as the minimum output price beyond which the farmer is likely to make profit (Kadyampakeni *et al.*, 2010).

3. Results and Discussion

3.1 Simulation spreadsheet for the Decision Support System Operation

The process of adjusting catchment parameters and time constants, indicated in Tables 4 above, was meant to assess the ability of calibrated parameters to produce observed run off values. It was revealed that the initial parameters and constants were in line with those reported by Njoloma (2010) after conducting research in the same catchment and climatic zone. Using long historical runoff data sourced from the Ministry of Irrigation and Water Development (MIWD) the computed runoff underestimates values of the peak when compared to the measured runoff in all the years (Figure 5).

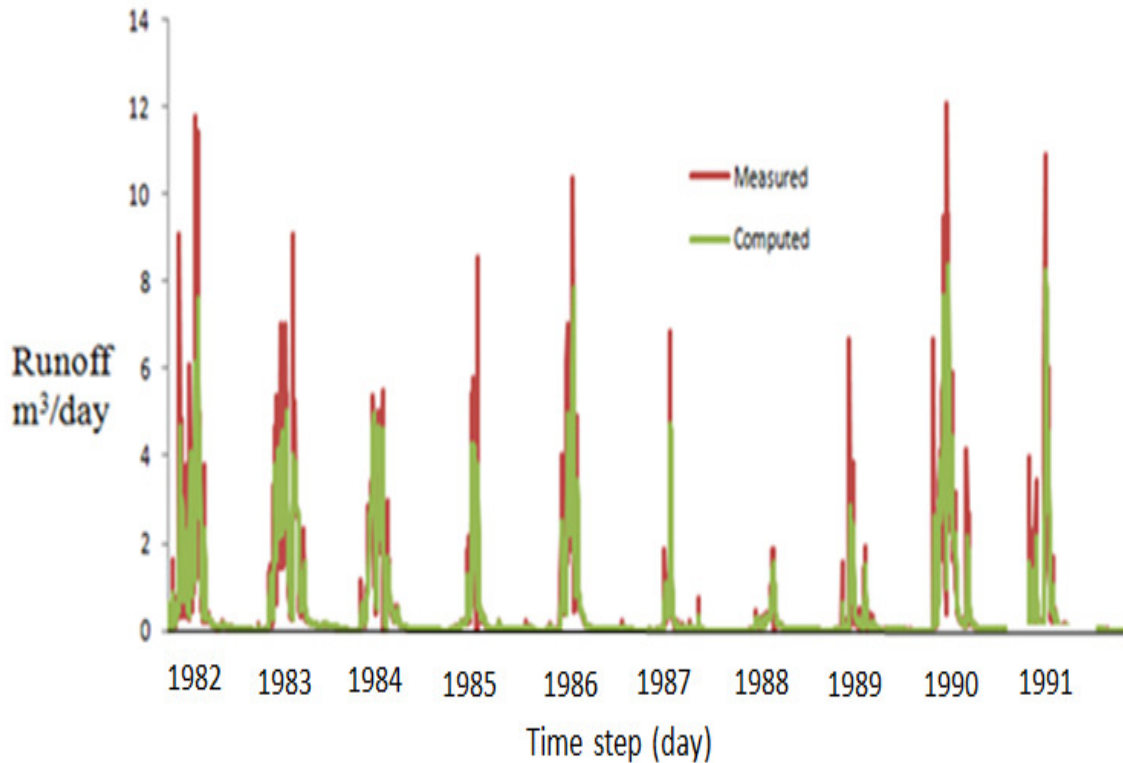


Figure 5: Measured and simulated hydrographs based on original parameters and constants

Therefore, it was necessary to adjust parameters and routing constants until the computed value magnitudes largely match the measured hydrograph values, from minimum of $0.5 \text{ m}^3/\text{day}$ in drought year of 1988 to as much as $16 \text{ m}^3/\text{day}$ in the highest rainfall week in 1987 (Figure 6).

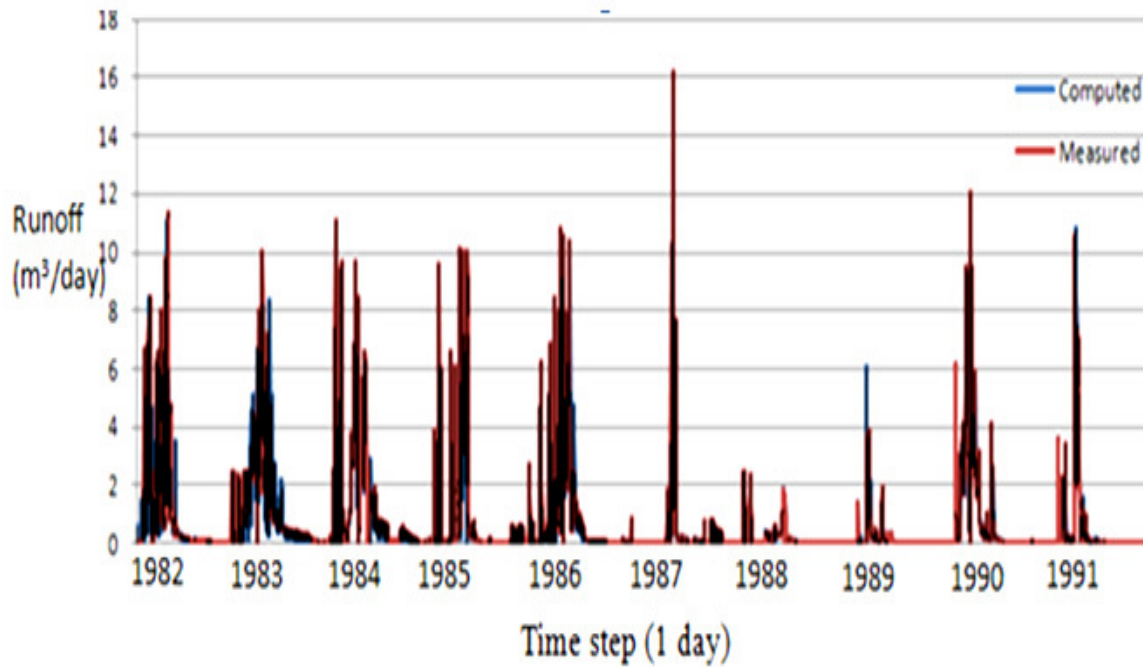


Figure 6: Hydrographs of simulation using adjusted catchment parameters and time constants

The model then tended to provide peaks and depressions in tandem with measured trend. The objective of this work relies on the coincidence of time step peaks between measured and computed hydrographs. Coinciding of the peaks of measured and computed runoff, at the same time step, demonstrates simulation reliability in the DSS prediction of runoff hence validating its ability to simulate runoffs given the prevailing climatic and catchment conditions. Detailed values can be made clearer with stretching the table for enlargement. Results confirm that using catchment constants and data of precipitation, potential evapotranspiration and temperature simulation of runoff is achieved. Dam Water Balance (DWB) and potential irrigable area following input of water withdrawals and losses (inputs and variables) in the detailed operational spreadsheet workbook are highlighted in Table 6.

Table 6: Computer simulation for the decision support system

Obj. Fun. 432.4		USE OF NAM MODEL IN SIMULATION																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																													
-----------------	--	--------------------------------	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--

(irrigable) area, using the spreadsheet commands, the DSS is also able to simulate expected yield value and crop water productivity (prdcty).

Table 7: Operational spreadsheet workbook simulation highlight for computer simulated and available reservoir water and potential field area

Date 1	Factors 2	Comp Simuln 3	4	5	Water losses 6		Water withdrawals 7			Computer Simuln 8	9	10	11
Plantg Dec. ↓ Time step (day) ↓ End Season	Climate Land	→	Cumml dam inflows (m ³ /dy)	DWB (m ³)	Pot evap mm	Spg (m ³)	Goat (m ³)	Cattle (m ³)	Human (m ³)	→	Crop Availab Water (m ³)	Applied Water (cm)	Potel Irrigb Area (ha)
Results highlight													
Dec. 31	Temp & Pot evap	→	10796	10087	1.69	5.7	27.5	122	0	→	9931	7990	16.9

Most of the run off harvested and stored in the reservoir (98%) was available for irrigation, signifying proportional negligible losses through evaporation, seepage and livestock uses. Out of the available dam water balance, 80% was indeed used for irrigation showing complete dependence of the bean crop growers on the stored water during the dry season. Use of DSS to simulate the first crop water removal, dam water balance, and crop water productivity gave results shown in Table 8.

Table 8: NAM addendum spreadsheet based water loss, irrigation and water balance

Crop Growth (wks)	Measured dam vol. m ³	Evapor m ³	Seepage m ³	Field use m ³ /ha	Removal m ³ /ha	Simulated				
						Balance (m ³)	Irrigable crop Area (ha)	Yield (kg/ha)	Prdcty g/L	Bean/Water
Pre-planting	9978	6	11	500	517					
1 to 2	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	6000	6094	3884	1.71	1400.0	0.71	

The DSS simulated synchronized land area of 1.71 ha (with reservoir water) is almost the equal to the calculated area of 1.70 ha based on the research recommended bean crop irrigation depth of 5 cm per week, if static application rate is followed. Using the realized (observed) yield production of 1398 kg/ha (almost 1400 kg/ha reported by MIWD, 2011 and FAO 2010) calculated seasonal bean

water productivity was 0.7 g/L. Elsewhere values of 0.6 kg/m³ (0.6 g/L) have been reported in drought-prone areas (Hashim *et al.*, 2012). Computation of crop water productivity gave the value of 0.7g/L, lower than values of 1g/L reported from experiments under non-drought conditions (Hashim *et al.*, 2012). In drought prone areas reduction in yields of common beans is due to low moisture levels during flowering and pod filling of common dwarf beans. Asfaw *et al.*, (2012) also attributed drought as a major problem for common bean yield loss experienced by rain-fed growers at Kasinthula, another drought prone area located in the southern part of Malawi. The yield loss, due to drought stress under farmers' field conditions, was associated with reduced photosynthate acquisition, accumulation and remobilization, which are primary mechanisms for yield gain (Mwale *et al.*, 2012). During the study year of 2012, the total rainfall was less than 660 mm. The common bean requires more than this rainfall amount to realize its potential yield in the area.

The relative consistency of the findings validates the DSS for utilization to establish reservoir capacity and/or corresponding crop land area. Using the MS Excel operation, the developed DSS reliably relates runoff rainwater harvesting, its seasonal open surface storage and irrigation to crop water productivity. 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.

3.2 Comparative financial analysis of irrigated and rain-fed bean production

Gross margin and break-even analysis was conducted on the grain yield of rain-fed and reservoir water irrigated beans, as a determinant of relevance of the DSS to the community harvesting rainwater for bean crop production. Variable cost data included production, processing (drying, threshing, treatment) and transportation costs, while fixed costs included contribution towards annual reservoir maintenance (Table 4). Output was in terms of grain yield. Mean grain yield was 42% lower with the rain-fed environment than with the irrigation environment. Similarly at drought prone Kasinthula area, Southern Malawi, mean grain yield in the same year of 2012 was 62% lower in the water stress environment than in the non-stress environments based on drought intensity index calculated from the mean yield of all common bean genotypes (Asfaw *et al.*, 2012).

The gross margins were higher with irrigation (2.42 times) than with rain-fed bean production despite additional costs associated with 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, 2013).

Table 9: Gross margin and break-even analysis for rain-fed and irrigated beans

Details	Unit	<u>Without irrigation</u>			<u>With irrigation</u>		
		Quantity Kg	Unit price MK	Total cost MK	Quantity kg	Unit price MK	Total cost MK
Output value	kg	801.2	150	120 000	1 400	165	231 000
FIXED COSTS							
Reservoir contribution	Annual fee	-	-	-	-	-	5 000
Irrigation	Mandays	-	-	-	346	157	54 352
Sub total							59 352
VARIABLE COSTS							
<u>INPUTS</u>							
Seed	Kgs	75	250	18 750	75	250	18 750
Insecticides	Litres	10	1 500	15 000	10	1 500	15 000
Fungicide	Kgs	25	1 000	25 000	25	1 000	25 000
Sub-total (inputs)				58 750			58 750
<u>LABOUR</u>							
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	6 000
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 for labour	Mandays			26 800			28 600
<u>OTHER COSTS</u>							
Sacks	50 kg						
	bag	12	80	960	30	80	2 400
Transport	Bags	12	100	1 200	30	120	3 600
Sub total				2 160			6 000
Total Cost				87 710			152 702
Gross Margin (A-B)	MK/ha			32 290			78 298
A. Break-even Yield	MK/ha			585			925

B. Break-even Price	MK/ha	110	109
---------------------	-------	-----	-----

Gross margins were higher with irrigated crop than rain-fed crop and break-even price lower for irrigated crop than with the rain-fed crop, showing that the bean producers made more profit from irrigated bean crop in the drought prone Ukwe area. Serna et al. (2000) reported that common beans yields are drastically reduced when dry spells and erratic rainfall occur in a growing season, especially during the reproductive stages such as flowering and pod filling which critically require adequate water. It is, therefore, not surprising that the irrigated crop returns surpassed the rain-fed crop. The study has augmented reports about the benefits of irrigation in comparison to rain-fed farming in the challenging face of frequent droughts and dry spells.

4. Conclusion and recommendation

According to the verification result, the parameters calibrated by the DSS simulate the observed runoff. The DSS is capable to simulate harvested reservoir water volume, potential irrigable area and crop water productivity. Two dry season crop production cycles, at crop water productivity of 0.7 g/L, as the case at Ukwe Area, would require small holder potential crop command field area of 1.7 ha, *ie.*, 10% of the irrigable area. The structure and spreadsheet entries of the DSS have been designed and validated. 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 meet the recommended crop water requirement. Financial analysis has indicated clear benefits for farmers producing the common beans using stored runoff water.

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 and mitigate drought and dry spell impacts. The DSS provides stakeholders such as 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 to plan for dry season crop field sizing. At agricultural academic institutions in SSA, the DSS can be included in curricula modules and research projects. Evaluation and monitoring by the academic and Ministry of Agriculture and Food Security's irrigation Department may form the foundation for a follow-up on the use of the DSS. This would be done at national level in agro-hydrological zones.

It is recommended that the DSS be further validated on different crops, and be conducted in other agro-ecological zones, for wide-scale utilization. In addition to spreadsheet data entry operational

structure, a computer interface be developed for interactive data entry. Input of fixed catchment parameters, time constants, predicted precipitation, potential evaporation and temperature will achieve runoff values and seasonal reservoir volume. Input of seepage and evaporation data should display reservoir water balance and get crop water application interface and related irrigable field area to be prepared. The procedure would be an option to the presented excels spread sheet data entry used in this study.

5. Acknowledgement

Special appreciation goes to the Regional Universities Forum for Capacity Building (RUFORUM), the International Development and Research Centre (IDRC) and Carnegie Corporation of New York, USA for research funding support. The technical and administrative guidance as well as fuel assistance by the Lilongwe University of Agriculture and Natural Resources is highly appreciated. The authors deeply acknowledge all the Sokoine University of Agriculture (Tanzania) and Total Land Care (Malawi) staff who made contributions towards the successful accomplishment of the study.

6. References

- Ali H. 2011. Double Mass Curve, Precipitation Presentation, Technology and Business Publication, London, United Kingdom. <http://www.slideshare.net/hamza07/precipitation-presentation>. Accessed: Feb. 11, 2015.
- Asfaw A, Blair MW and Struik PC. 2012. Multienvironment Quantitative Trait Loci Analysis for Photosynthate Acquisition, Accumulation, and Remobilization Traits in Common Bean Under Drought Stress, G3: Genes, Genomes, Genetics Mission, New York, 2(5): 579–595.
- Boote KJ, Jones JW and Pickering NB. 1996. Potential uses and limitations of crop models. Agron. J. 88(5):704-716
- FAO. 2010. Manual on Small Earth Dams, A Guide to Siting, Design and Construction, Paper number 64, Rome.
- FAO. 1991. Manual for Design and Construction of Water Harvesting Schemes for Plant Production. Rome
- Hashim MAA, Shiam A, Al-Dosari A, Asl-Gaad KA, Patil VC, Tola EHM, Rangaswamy M and Samdany MS. 2012. Determination of Water Requirement and Crop Water Productivity of Crops Grown in the Makkah Region of Saud Arabia, Australian Journal of Basic and Applied Sciences, 6(9): 196 – 206

- Hirschfeld J, Dehnhardt A and Dietrich. Socioeconomic analysis within an interdisciplinary spatial decision support system for an integrated management of the Werra River Basin, *Limnological Ecology and Management of Inland Waters*, Magdeburg; 2005. 35(3) 234–244.
- Jones JW and Luyten JC. Simulation of Biological Processes. In *Agricultural Systems Modeling and Simulation*. Peart, R.M. and Curry, R.B, editors. Marcel Dekker Inc. Univ. of Florida, Gainesville, 2:19-62, ISBN: 0-824-0041-4; 1998.
- Kadyampakeni D, Longwe A, Mangisoni JH, Mloza-Banda HR., Singa DD, Ferguson A and Snapp S. A Comparative Assessment of Benefits of Irrigation and Water Management Practices on Bean Production in Chingale, Zomba, Southern Malawi, *Bunda Journal of Agriculture, Environmental Science and Technology*; 2010. University of Malawi, Malawi, 4, 1 -8. ISSN 1726-3220.
- Kadyampakeni DM, Mloza-Banda HR, Singa DD, Mangisoni JH, Ferguson A, and Snapp S. Agronomic and socio-economic analysis of water management techniques for dry season cultivation of common bean in Malawi; 2013. *Irrig Sci* (2013) 31:537–544, DOI 10.1007/s00271-012-0333-5
- Kambuku D. Conjunctive use of small earth dams and boreholes for sustainable rural livelihood in a semi-arid area: Case of Lilongwe West Rural Groundwater Project area, Malawi; 2010
- Kamthonkiat D. Near Real-time Decision Support System for Drought Monitoring and Impact Assessment on Rice in Ubon Ratchathani, Northeastern Thailand, Department of Geography, Faculty of Liberal Arts, Thammasat University Klong Luang, Pathumthani 1212, Thailand. www.asprs.org/wp-content/uploads/2013/08/Kamthonkiat.pdf Accessed: December 27, 2015.
- Larbi PA. Development of a Model to Predict Spray Deposition in Air-carrier Sprayer Applications, 2011; A PhD Dissertation, University of Florida.
- Ministry of Irrigation and Water Development (MIWD). 2011. Annual Report of Daily Runoff for Lingadzi at S111, 40502, 1959 to 2000, Water Department, Surface Water Division, Lilongwe, Malawi. Pp 2 – 6.
- Monitoring Agricultural Resources (MARS). Spatial interpolation of daily meteorological data. Theoretical evaluation of available techniques, European Commission Joint Research Centre, EU Common Agricultural Policy (CAP). 2014. DLO 53 (1) 43.

504

505 Mwale VM, Bokosi JM, Masangano C and Kabambe VH. Performance of climber common bean
 506 (*Phaseolus vulgaris* L.) lines under research designed farmer in Malawi. African Journal of
 507 Biotechnology 7(16); 2008. Available: <http://dx.doi.org/10.1534/g3.112.002303>. Accessed: July 10,
 508 2016

509 Newman S, Lynch T and Plummer A. Success and failure of decision support systems: Learning as we
 510 go. Journal of Animal Science, Society of Animal Science, Queensland 4702. Australia; 2000.
 511 Available: <https://www.animalsciencepublications.org/publications/jas/tocs/77/E-Suppl>Journal of
 512 Animal Science 2000 77:1-15, doi:10.2527/jas2000.77E-Suppl1e. Accessed: April 10, 2015

513

514 Njoloma HM. Synchronizing Irrigation Development with Hydrology of the Local Catchment Areas by
 515 Use of Rainfall-Runoff Modeling in Lilongwe in Malawi, PhD Thesis, Tottori, Japan. 2010.

516

517 Oteng-Darko P, Yeboah S, Addy SNT, Amponsah S and Danquah OE. Crop modeling: A tool for
 518 agricultural research – A review, E3 Journal of Agricultural Research and Development. 2013; 2(1).
 519 001-006.

520 Research into Use (RIU). Rainfall modelling can predict future yields NRSP13, New technologies, new
 521 processes, new policies: tried-and-tested and Ready-to-use resource from DFID-funded research,
 522 Research into Use Programme; 2007. Ayiestora, Kent, UK

523

524 Saunyama T. Estimation of Small Reservoir Storage Capacities in Limpopo River Basin Using
 525 Geographical Information Systems (GIS) and Remotely Sensed Surface Areas: A Case of Mzingwane
 526 Catchmen; 2005. Dept of Civil Engineering, Faculty of Engineering, Univ. of Zimbabwe. 10 – 12.

527

528 Tumbo SD, Mpulila T, Mzirai OB, Mahoo HF, Rwehumbiza FB, Semoka JMR and Hatibu N. Maize Yield
 529 Simulation Under Rain-fed and Rainwater Harvesting Systems using Parched-Thirst Model,
 530 Harvesting Systems Using PARCHED-THIRST Model, Soil Water Management Research Group,
 531 Sokoine University of Agriculture, Morogoro, Tanzania. pp1. 2006. Available: <https://www.academia.edu/1104952/Maize>. Accessed: December 4, 2015.

532

533 Wani SP, Rockstrom J and Sahrawat KL. Integrated Watershed Management in Rainfed Agriculture.
 534 2011. Taylor and Francis Group, NW, Florida, USA. CRC (In Press).
 535 <https://books.google.co.tz/books?isbn=1466512822>. Accessed: January 18, 2016.

536

537 Yalewa SG, Pilz T, Schweitzer C, Liersch S, van der Kwast J, Mul ML, van Griensven A and van der
 538 Zaag P. Dynamic Feedback between Land Use and Hydrology for Ecosystem Services Assessment,
 539 International Environmental Modelling and Software Society (iEMSs); 2014. 7th Intl. Congress on
 540 Environmental Modelling and Software, San Diego, CA, USA.

541

542 **7. List of acronyms and abbreviations**

543	AQUACROP	Crop water productivity model which simulates yield response to water
544	APSIM	Agricultural Production Simulator
545	CERES	Crop Environment Resource Synthesis
546	Commul	Cumulating
547	Crop availab	Crop available water
548	CROPGRO	Crop growth model
549	CROPSIM	Package with functions for dynamic & mechanistic simulation of crop
550		growth and development in response to inputs
551	CWP	Crop water productivity
552	CWR	Crop water requirement
553	D	Maximum water depth
554	dgps	differential global positioning system
555	DSS	Decision Support System
556	DSSAT	Decision Support System for Agro-technology Transfer
557	DWB	Dam Water Balance
558	DGPS	Differential Global Position System
559	ec	emulsifiable concentrate
560	EV	Evaporated water volume (m ³)
561	Evapn	Evaporation
562	E _{reservoir}	Reservoir evaporation
563	GEV	General extreme value
564	Ha	hectare
565	HYDATA	Purpose-built, Windows-based database and analysis system for processing
566		hydrometeorological data
567	H & S	Harvested and stored respectively
568	ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
569	IDRC	International Development Research Centre
570	IFAD	International Food and Agricultural Development

571	ITDG	Intermediate Technology Development Group
572	IWMI	International Water Management Institute
573	m ²	Square metres
574	MAFS	Ministry of Agriculture and Food Security
575	MIWD	Ministry of Irrigation and Water Development
576	NAM	<i>Nedbor Afstromnings</i> Model
577	N	Nitrogen
578	PARCHED -THIRST	Predicting Arable Resource Capture in Hostile Environments
579		During the Harvesting of Incident Rainfall in the Semi-arid
580		Tropics
581	Pot evap	Potential evaporation
582	Pot irrigb	Potential irrigable area
583	Res. Balance	Reservoir balance
584	RUFORUM	Regional Universities Forum for Capacity Building in Agriculture
585	SADC	Southern African Development Community
586	Spg	Seepage
587	SSA	S ub-Saharan Africa
588	Temp	Temperature
589	US\$	United States Dollar
590	VEMAP	Vegetation/Ecosystem Modeling and Analysis Program