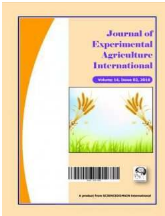

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Decision Support System for Runoff Water Harvesting and Irrigation

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Authors' contributions

This study was conducted with close coordination and collaboration among all the above mentioned authors. Author DDS designed the study, managed the literature search, implemented the field research activities, performed the data analysis and drafted the manuscript. Authors SDT, MHF and RF provided guidance for research proposal, supervised data analyses and made corrections to the first draft and final manuscript. Author LM provided advice on study field designs and reviewed the manuscript. All authors read and approved the final manuscript.

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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

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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 0.7 g/l (0.7 kg/m^3), 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.

Keywords: Irrigation; reservoir; runoff; simulation; storage; synchronization.

ABBREVIATIONS

AQUACROP	*: Crop water productivity model which simulates yield response to water*
APSIM	*: Agricultural Production Simulator*
CERES	*: Crop Environment Resource Synthesis*
Commul	*: Cumulating*
Comptr simutg	*: Computer simulating*
Crop availab	*: Crop available water*
CROPGRO	*: Crop growth model*
CROPSIM	*: Package with functions for dynamic & mechanistic simulation of crop growth and development in response to inputs*
CWP	*: Crop water productivity*
CWR	*: Crop water requirement*
D	*: Maximum water depth*
dgps	*: Differential global positioning system*
DSS	*: Decision Support System*
DSSAT	*: Decision Support System for Agro-technology Transfer*
DWB	*: Dam Water Balance*
DGPS	*: Differential Global Position System*
ec	*: Emulsifiable concentrate*
EV	*: Evaporated water volume (m^3)*
Evapn	*: Evaporation*
$E_{reservoir}$	*: Reservoir evaporation*
GEV	*: General extreme value*
Ha	*: Hectare*
HYDATA	*: Purpose-built, Windows-based database and analysis system for processing hydrometeorological data*
H & S	*: Harvested and stored respectively*
ICRISAT	*: International Crops Research Institute for the Semi-Arid Tropics*
IDRC	*: International Development Research Centre*
IFAD	*: International Food and Agricultural Development*
ITDG	*: Intermediate Technology Development Group*
IWMI	*: International Water Management Institute*
m^2	*: Square metres*
MAFS	*: Ministry of Agriculture and Food Security*
MIWD	*: Ministry of Irrigation and Water Development*
NAM	*: Nedbor Afstromnings Model*
N	*: Nitrogen*
PARCHED –THIRST	*: Predicting Arable Resource Capture in Hostile Environments During the Harvesting of Incident Rainfall in the Semi-arid Tropics*
Pot evap	*: Potential evaporation*
Pot irrigb	*: Potential irrigable area*

Res. Balance	*: Reservoir balance*
RUFORUM	*: Regional Universities Forum for Capacity Building in Agriculture*
SADC	*: Southern African Development Community*
Spg	*: Seepage*
SSA	*: Sub-Saharan Africa*
Temp	*: Temperature*
US$	*: United States Dollar*
VEMAP	*: Vegetation/Ecosystem Modeling and Analysis Program*

1. INTRODUCTION

Recurring and cumulative crop damage due to drought has reduced the yield of crops in many regions of the world [1]. 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 [2].

Yalewa et al. [3] 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 [4]. 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 [5]. 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.

The Table 1 indicates that models with important hydrological processes, using physical parameters that are readily available or easily measured, and used in water harvesting and irrigation, do not yet have long term water storage and legume irrigation components. Similarly, Larbi [6] states that some specific problem domain DSSs have not been comprehensive in hydrological, agricultural and socio-economic sectors for use in Southern African drought prone areas.

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

2. MATERIALS AND METHODS

2.1 Analysis of Runoff, Reservoir Water and Crop Water Requirement

The reservoir inflows were measured using a calibrated gauge installed in the reservoir as practiced by the Ministry of Irrigation and Water Development in Malawi [7]. The volume of water in the reservoir was obtained by measuring the dam average water width and depth using differential global positioning system (dgps). To calculate reservoir volume, the following equation, which has been employed in Zimbabwe and Malawi to estimate small reservoir water volume was used [8]:

$$\boldsymbol{C} = \boldsymbol{DWT/6} \tag{1}$$

where, $\boldsymbol{C}$ is the reservoir water volume (m^3), D is the water depth (m), $\boldsymbol{W}$ 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 $E_{pan}/E_{reservoir}$ ratio for small reservoirs was 0.7. Evaporation from reservoirs was calculated using equation 2:

$$EV = \frac{2}{3}\frac{RA_{max}E}{1000} \tag{2}$$

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) [9]. Quantification of the reservoir water seepage (GW) was achieved using the water balance Equation 3:

$$GW = IV_c + P - E - Q - \Delta C - I \tag{3}$$

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.

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 [10,11]	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 (*Phaseolus*), 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 [12]	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 models or sub-models -powerful tool for exploring agronomic adaptations	Not yet effective in Rain water harvesting
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 [13,14]	Not yet for long term water storage
Nedbor Afstromnings Model (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

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 [15]. The following relationship of notations was developed:

$$\Delta t \ x \ \Delta I(A) = \ \Delta C \tag{4}$$

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℃ rising to 29℃ 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 650 mm 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 and Food Security (MAFS) were followed [16]. 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: 21: 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 Ukwe respectively, were used to calibrate the MS excel based DSS output for Ukwe 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 Ukwe 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) [5]. 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, Ukwe, Kandiya and Bunda in the drought prone plateau region of Central Malawi (Fig. 1) within the agro-ecological zone of the study area, detailed in Fig. 2.

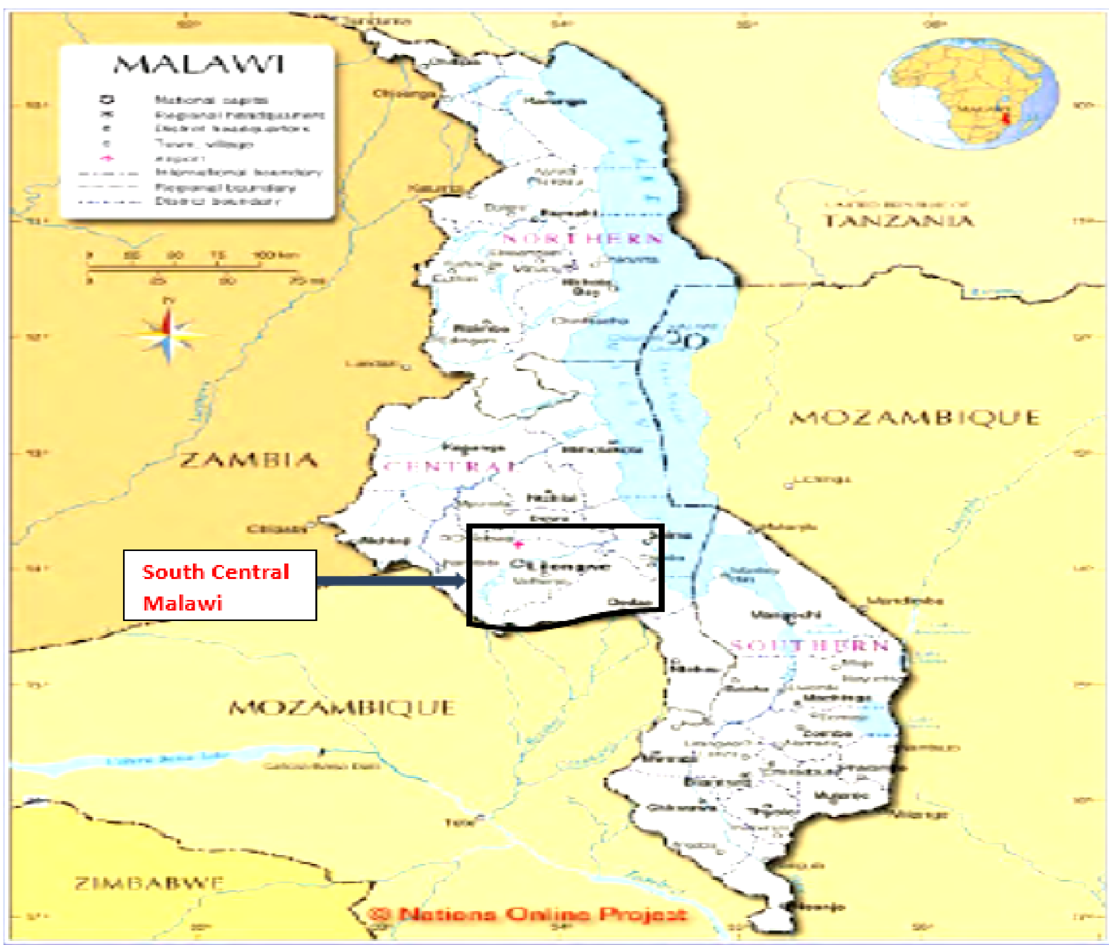

Fig. 1. Map of Malawi showing South Central agro-ecological zone as expounded in Fig. 2
(Source: Malawi Meteorological Services, 2006)

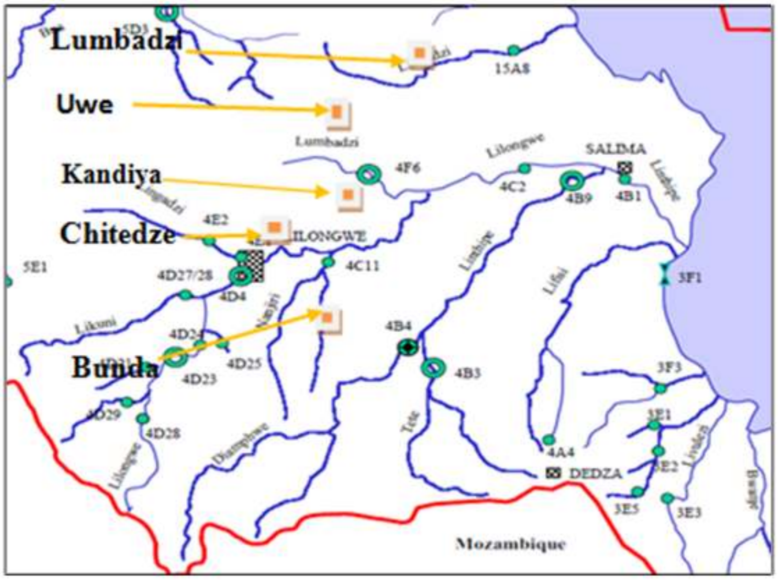

Fig. 2. South-Central Malawi, showing South Central agro- ecological zone weather stations of (Ukwe, Lumbadzi, Chitedze and Bunda)

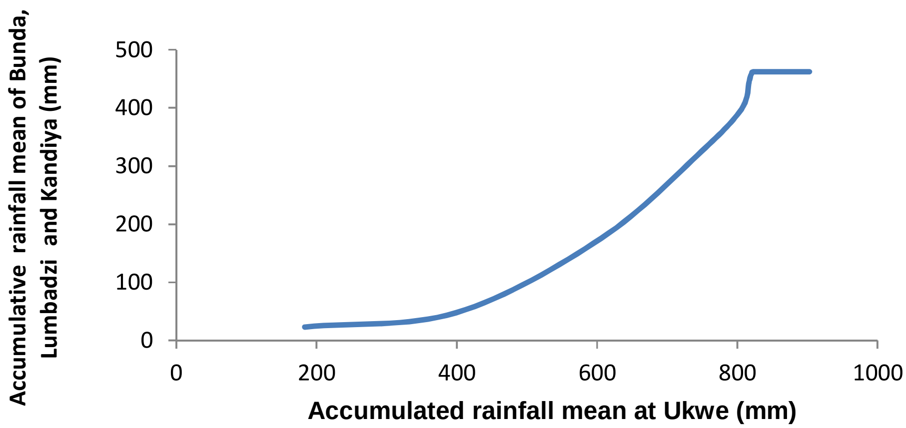

Fig. 3. Rainfall double mass analysis of all the stations including Bunda

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 [17]. Mass analysis showed a spurious relationship indicating data inconsistency and non-homogeneity (Fig. 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.

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 [18]. Double mass analysis test was hence run, excluding this Bunda site. A straight line relationship revealing absence of spurious trends was obtained (Fig. 4). 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 Ukwe 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.

2.4.2 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.

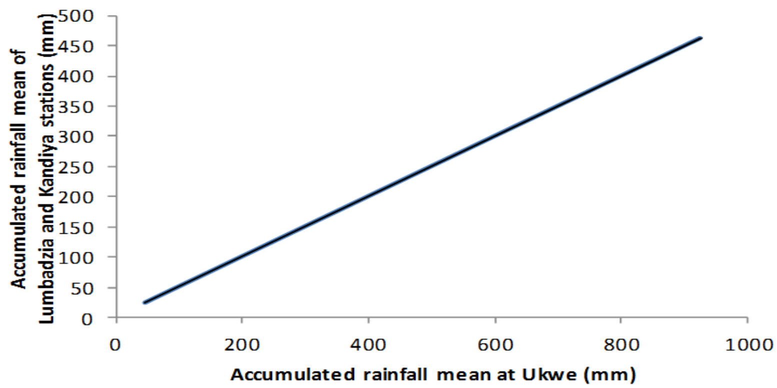

Fig. 4. Rainfal double mass analysis of all stations excluding Bunda

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 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

**Original 'parameter categorization' and 'name abbreviation' from source [5]*

2.4.2.1 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		

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		

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.

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.

$$CDIn = \sum(QR2_{i-1} * \frac{1}{CK2} + (QR1 + BFU1 + BFLi * \frac{1}{CK2})) \tag{5}$$

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:

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

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

$$DWB = \Big(9978 + \sum \Big(QR22_{i-1} * \frac{1}{CK2} + QR1{+}BFU1{*}1CK2 \qquad (7)$$

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 8:

$$SFU = \sum\Big((0.034)\frac{Ep_m^{1.09}}{AD^{0.09}}\Big) \qquad (8)$$

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

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

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.

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 [19].

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 Table 4, 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 [5] 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 (Fig. 5).

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 m^3/day in drought year of 1988 to as much as 16 m^3/day in the highest rainfall week in 1987 (Fig. 6).

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 (pot irrig area) area following input of water withdrawals and losses (inputs and variables) in the detailed operational spreadsheet workbook are highlighted in Table 6.

Validation for December 2, 2011 to December 31, 2012 dam simulation results are illustrated in Table 7 (with hidden command rows and command columns for clarity). Achieved weekly depth of water application and reservoir balance synchronization of irrigation command area and reservoir capacity are also demonstrated. In addition to seasonal reservoir water balance, irrigation command (irrigable) area, using the spreadsheet commands, the DSS is also able to simulate expected yield value and crop water productivity (prdcty).

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.

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, in the area, of 1398 kg/ha (almost 1400 kg/ha) reported by the Department of Irrigation in Malawi and supported by FAO [20], calculated seasonal bean water productivity was 0.7 g/L. Elsewhere values of 0.6 kg/m^3 (0.6 g/L) have been reported in drought-prone areas [21]. 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 [21]. 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. [22] 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 [23]. 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 [22].

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 [24].

Table 5. Decision support system operational design spreadsheet

Date	Computer Simulatn →	Cummul dam inflows	DWB (m^3)	**Water losses**		**Water withdrawals**			Computer Simulatn →	Crop available water (m^3)	Appld water (cm)	Pot Irrig area (ha)
				Pot Evap (mm)	Seepage (m^3)	Goat (m^3)	Cattle (m^3)	Persons (m^3)				

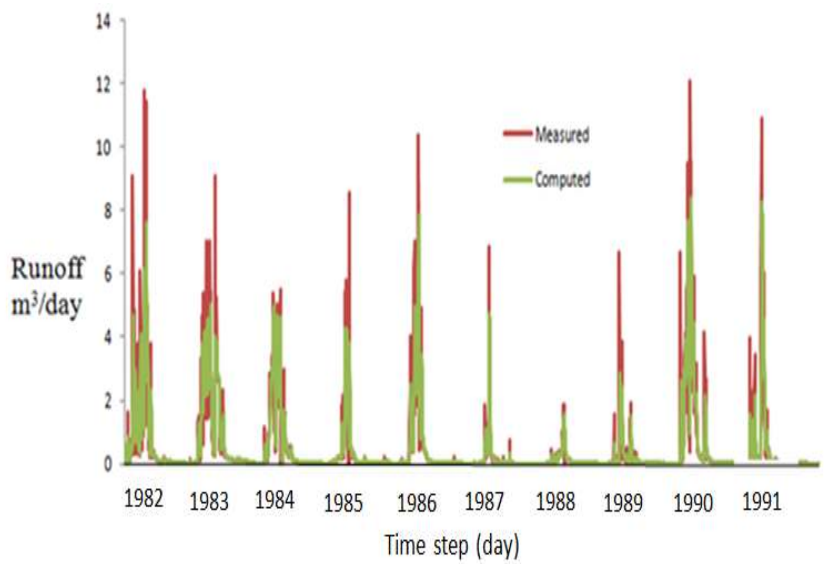

Fig. 5. Measured and simulated hydrographs based on original parameters and constants

Table 6. Computer simulation for the decision support system

	DATA				USE OF NAM MODEL IN SIMULATION																		Irrign	component		
					Storages				Runoff								ROUTING									
Date	Measured Stream Flow (QM) (m^3/day)	Rainfall (mm)	Pot. evap. (mm)	Temp (°C)	Ss	U	L	L/Lma	Ps	Ep	QIF	Pn	QOF	Ea	G	DL	QR1	BFU1	BFL1	QR2	Objective function	Cummul Dam Inflows	Appld Water	Dam Bal	SFU (m^3/ha)	DWB (m3)
01-12-11	0.001	0	1.68	24.9	*0*	*0*	*110*	0.69	0	0	0	0	0	0.42	0	0	*0.3*	*0.3*	*0.3*	*0.6*	0.24108	*0.6*	0	9978.6	0	9978.6
02-12-11	0.005	0	1.69	25.7	0	0	109.58	0.68	0	0	0	0	0	0.42	0	0	0.04	0.271	0.298	0.61	0.35401	0.6596	0	9978.7	0	9978.66
03-12-11	0.004	0	1.62	26.4	0	0	109.16	0.68	0	0	0	0	0	0.41	0	0	0.01	0.246	0.297	0.56	8.08788	0.6566	0	9978.7	0	9978.657
04-12-11	0.003	0	1.69	23.7	0	0	108.75	0.68	0	0	0	0	0	0.12	0	0	0	0.222	0.295	0.52	1.20301	0.6277	0	9978.6	0	9978.628
05-12-11	0.003	3.7	1.7	23.7	0	0	108.63	0.68	0	0.61	0	0	0	0	0	0	0	0.201	0.293	0.5	1.12684	0.5908	0	9978.6	0	9978.591
06-12-11	0.007	0	1.9	22.5	0	3.1	108.63	0.68	0	0.46	0	0	0	0	0	0	0	0.182	0.292	0.48	4.29692	0.5646	0	9978.6	0	9978.565
07-12-11	0.005	0	1	24.7	0	2.6	108.63	0.68	0	0.41	0	0	0	0	0	0	0	0.165	0.29	0.46	22.3935	0.542	0	9978.5	0	9978.542
08-12-11	0.002	0	1.86	24.4	0	2.2	108.63	0.68	0	0.15	0	0	0	0	0	0	0	0.149	0.289	0.44	82.8049	0.5202	0	9978.5	0	9978.52
09-12-11	0.002	6.7	1.88	24.8	0	2.1	108.63	0.68	0	0.37	0	0	0	0	0	0	0	0.135	0.287	0.42	42.7158	0.4994	0	9978.5	0	9978.499
10-12-12	0.002	0	1.85	23.7	0	8.4	108.63	0.68	0	0.25	0	0	0	0	0	0	0	0.122	0.285	0.41	246.188	0.5021	0	9978.5	0	9978.502
11-12-11	0.003	0	1.84	24.1	0	8.2	108.63	0.68	0	0.21	0	0	0	0	0	0	0	0.11	0.284	0.4	94.1628	0.5097	0	9978.5	0	9978.51
12-12-11	0.002	3.1	1.74	23.2	0	7.9	108.63	0.68	0	0.1	0	0	0	0	0	0	0	0.1	0.282	0.38	36.7964	0.5149	0	9978.5	0	9978.515
13-12-11	0.002	9.3	1.66	23.5	0	11	108.63	0.68	0	0.08	0	5	0.84	0	2	2	0.72	0.109	0.291	1.02	15.8046	0.9272	0	9978.9	0	9978.927
14-12-11	0.001	0	1.54	23.6	0	15	110.94	0.69	0	0.51	0	0	0	0	0	0	0.1	0.099	0.289	0.56	3.96393	1.0747	0	9979.1	0	9979.075
15-12-11	0.001	1	1.55	24.8	0	14	110.94	0.69	0	0.16	0	0	0.06	0	0	0	0.06	0.091	0.288	0.46	3.54768	1.0939	0	9979.1	0	9979.094
16-12-11	0.001	6.4	1.44	25.4	0	15	111.08	0.69	0	0.49	0	6	1	0	2	3	0.87	0.105	0.299	1.16	0.52609	1.3671	0	9979.4	0	9979.367
17-12-11	0.001	3.4	1.37	24.2	0	15	113.59	0.71	0	0.23	0	3	0.55	0	1	1	0.61	0.108	0.304	1.04	0.24059	1.5795	0	9979.6	0	9979.579
18-12-11	0.001	2.2	1.33	22.2	0	15	114.84	0.72	0	0.32	0	2	0.33	0	1	1	0.39	0.105	0.306	0.83	0.8412	1.6743	0	9979.7	0	9979.674
19-12-11	0	0.2	1.21	22.8	0	15	115.56	0.72	0	0.1	0	0	0.01	0	0	0	0.09	0.096	0.304	0.53	9.15222	1.6213	0	9979.6	0	9979.621
20-12-11	0.025	0	1.2	22.9	0	15	115.59	0.72	0	0.36	0	0	0	0	0	0	0.04	0.087	0.303	0.44	1.98748	1.513	0	9979.5	0	9979.513
21-12-11	0.198	0	1.3	23.6	0	15	115.59	0.72	0	0.34	0	0	0	0	0	0	0.03	0.078	0.301	0.41	1.78958	1.3912	0	9979.4	0	9979.391
22-12-11	0.198	0	1.1	25.7	0	14	115.59	0.72	0	0.38	0	0	0	0	0	0	0.03	0.071	0.299	0.4	1.27878	1.2743	0	9979.3	0	9979.274
23-12-11	0.198	0	0.91	25.1	0	14	115.59	0.72	0	0.36	0	0	0	0	0	0	0.03	0.064	0.298	0.39	1.16776	1.1687	0	9979.2	0	9979.169
24-12-11	0.198	1.2	0.86	23.9	0	13	115.59	0.72	0	0.38	0	0	0	0	0	0	0.03	0.058	0.296	0.38	1.4624	1.0758	0	9979.1	0	9979.076
25-12-11	0.206	1.2	0.83	25.7	0	14	115.59	0.72	0	0.17	0	0	0.05	0	0	0	0.07	0.054	0.295	0.41	1.465	0.9989	0	9979	0	9978.999
26-12-11	0.162	5.9	0.78	23.3	0	15	115.68	0.72	0	0.17	0	6	1.03	0	3	2	0.93	0.072	0.306	1.18	0.25557	1.1831	0	9979.2	0	9979.183
27-12-11	0.086	0	0.72	24	0	15	117.84	0.74	0	0.35	0	0	0	0	0	0	0.16	0.065	0.304	0.62	16.3009	1.2163	0	9979.2	0	9979.216
28-12-11	0.09	0.7	0.74	25.3	0	15	117.84	0.74	0	0.28	0	0	0	0	0	0	0.06	0.059	0.302	0.45	3.27775	1.1802	0	9979.2	0	9979.18
29-12-11	0.109	4	0.69	24.7	0	15	117.84	0.74	0	0.2	0	4	0.7	0	2	1	0.65	0.07	0.309	0.95	203.002	1.296	0	9979.3	0	9979.296
30-12-11	0.115	0.1	0.66	24.8	0	15	119.17	0.74	0	0.23	0.1	0	0	0	0	0	0.14	0.063	0.308	0.57	587.21	1.2883	0	9979.3	0	9979.288
31-12-11	0.09	33.7	0.63	23.2	0	15	119.17	0.74	0	0.23	0.1	33	6.33	0	15	11	5.54	0.204	0.383	5.38	516.288	3.1279	0	9981.1	0	9981.128

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. Rosales-Serna et al. [25] 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.

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

Date	**Factors**	**Comp Simuln**			**Water losses**		**Water withdrawals**			**Comptr simutg**			
1	**2**	**3**	**4**	**5**	**6**		**7**			**8**	**9**	**10**	**11**
Plantg Dec. Time step (day) End season	Climate Land	→	Cumml dam inflows (m^3/day)	DWB (m^3)	Pot evap mm	Spg (m^3)	Goat (m^3)	Cattle (m^3)	Human (m^3)	→	Crop Availab Water (m^3)	Appld 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	ha 16.9

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

Crop growth (wks)	**Seasonal measured**			**Cummulative field use m^3/ha**	**Total removal m^3/ha**	**Seasonal**		**Simulated Yield (kg/ha)**	**Water Prdcty g/L**
	Dam vol. m^3	**Evapor m^3**	**Seepage m^3**			**Water balance m^3**	**Dam irrigable crop area (ha)**		
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**

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

Details		**Without irrigation**			**With irrigation**		
		Quantity	**Unit price**	**Total cost**	**Quantity**	**Unit price**	**Total cost**
	Unit	**Kg**	**MK**	**MK**	**kg**	**MK**	**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							
Inputs							
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**
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	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**
Other costs							
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**

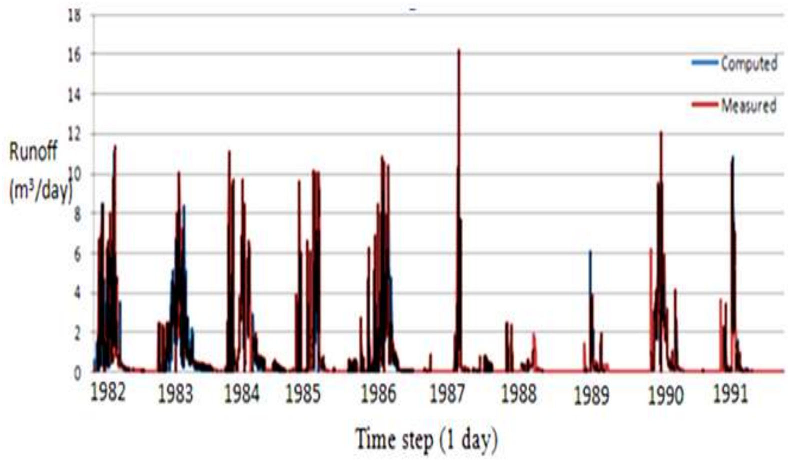

Fig. 6. Hydrographs of simulation using adjusted catchment parameters and time constants

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.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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