

Original Research Article

Design and Validation of a Decision Support System for Runoff Water Harvesting and Irrigation - a Case Study of Beans at Ukwe, Malawi

Abstract

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

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

1. Introduction

Recurring and cumulative damage from drought has reduced the yield of crops in many regions (Kamthonkiat, 2008). The negative impacts of droughts and dry spells on crop production in sub-Saharan Africa (SSA) strongly call for supplementary or sole irrigation which needs proper sizing of water reservoir with respect to cropped area or vice-versa. Computerized decision support systems allow users to combine technical knowledge of models that combine crop growth, environmental

diversity and economic considerations to make proper implementation decisions (Oteng-Darko *et al.*, 2013). Therefore, with use of agro-hydrological Decision Support System it is possible to make reliable decisions for synchronization of water reservoirs and field sizes.

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

In Germany, a contingent valuation method was applied in order to determine people's willingness to pay for an improvement of environmental quality and effects of the hydro-morphological measures within the different water bodies along the River Werra and its tributaries. This was followed by an economic value has been assessed by transferring the adjusted results of the Elbe study. Cost and benefit analysis as additional analysis to evaluate the acceptance and social dimension of the potential planning measure before a decision support system for integration and evaluation of hydrology, ecology, sanitary engineering, social sciences for Water Framework Directive (Hirschfeld *et al.*, 2005). Despite the existence of agro-hydrological DSSs, SSA countries, such as Malawi, have not embraced their use in catchment analyses due to hydrological parameter variations and poor understanding of their application in water storage and irrigation (Njoloma, 2010).

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

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

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

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

2 Materials and Methods

2.1 Socio-economic analysis of bean irrigation at Ukwé

Economic data measured included labour use, production costs, amount of water applied to each treatment and grain yields. Comparative gross margins and break-even analyses were conducted on rain-fed and reservoir based irrigated bean crops. The analysis was conducted to indicate profit

margin for a farming family, while break-even analysis was conducted to demonstrate a minimum yield a farming family needed to achieve in order to recover money spent on the bean production. Break-even price gives the minimum output price beyond which the farmer is likely to make profit (Kadyampakeni *et al.*, 2010).

2.2. Study framework

Design of the Decision Support System followed the framework depicted in Figure 1.

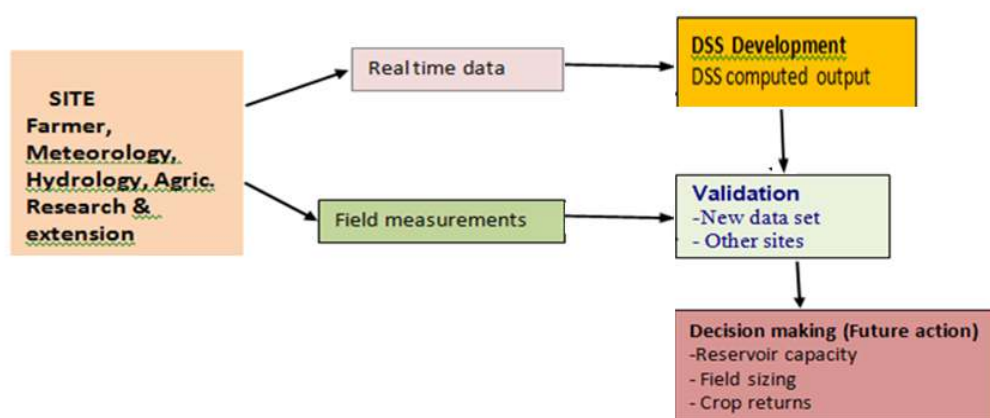


Figure 1: Study framework

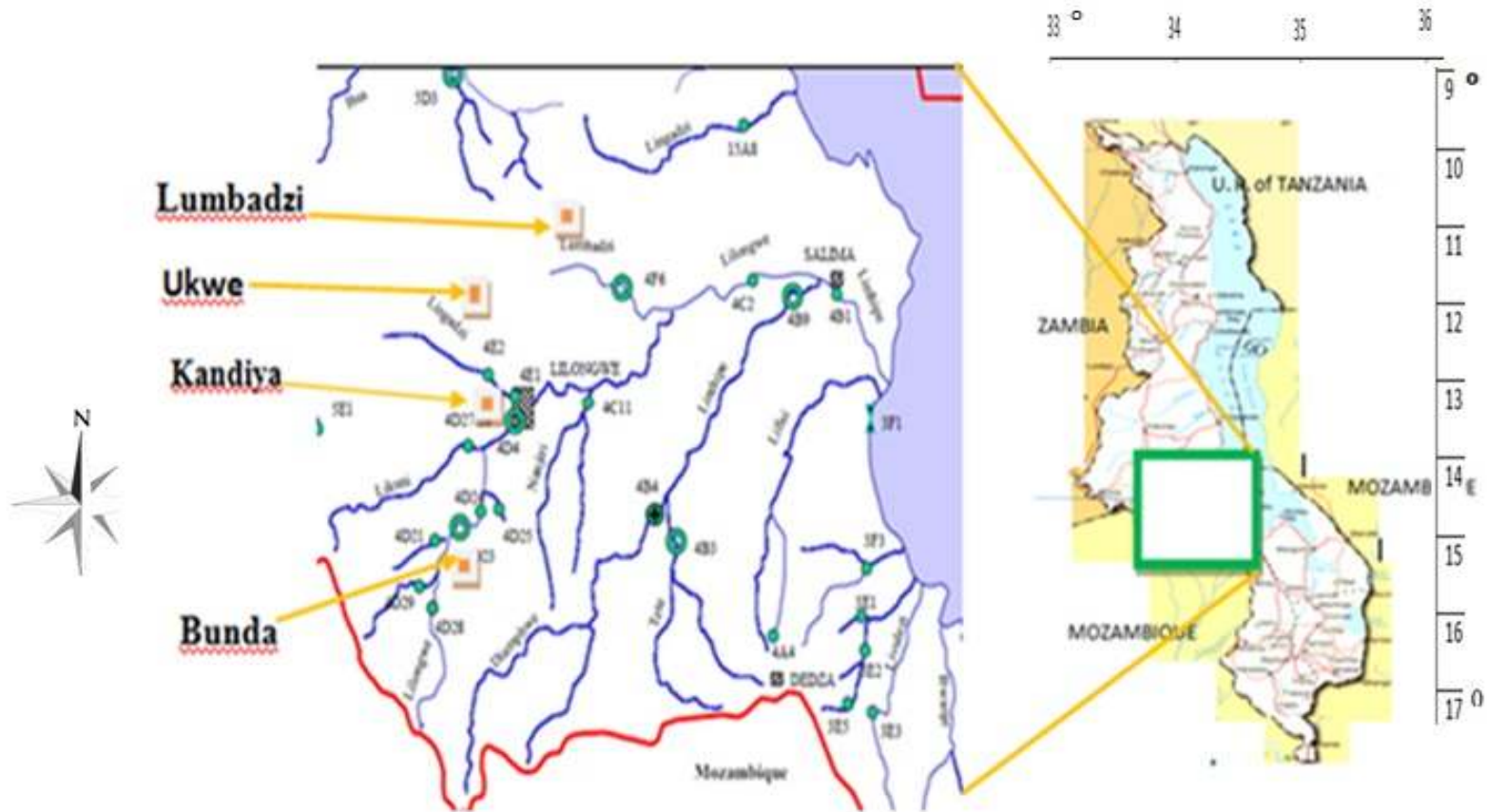
2.3 Input Data

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

101 In Malawi, the Hydrology Section in the Water Division of the Water Resources Department
102 (Ministry of Irrigation and Water Development), located in the same agro-ecological zone of Ukwe
103 area, is a strong data quality control institution with package of HYDATA software, a powerful tool
104 for hydrological data storage, analysis and routine processing (Njoloma, 2010). Rainfall data
105 collection, coordination and storage, in Malawi, is the responsibility of Meteorological and Climate
106 Change Department (Ministry of Transport and Communication) which also trains personnel manning
107 gauging stations on daily basis. For this study, data for DSS validation were sourced from four
108 stations in the drought prone plateau region of Central Malawi, within the agro-ecological zone of the
109 study area (Figure 2).

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112 Figure2: Central Malawi agro- ecological zone weather stations

2.4 Rainfall data screening and operation of the DSS

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

2.5 Decision Support System Development Procedure

Development of the DSS followed the trend of operation of the system. Initially the system operation requires three main input data sets. Firstly, it requires catchment parameters and time constants, precipitation and potential evaporation so that it can simulate land water storages, and flows which are routed to the reservoir as output. Secondly, it requires data of evaporation and seepage, livestock number (and domestic water use, if any) before it displays reservoir water balance for irrigation. Thirdly, it needs crop water use entry for it to display the required land area to be prepared. The Microsoft (MS) Excel version 1997-2003 NAM based procedure followed the structure depicted in Figure 3.

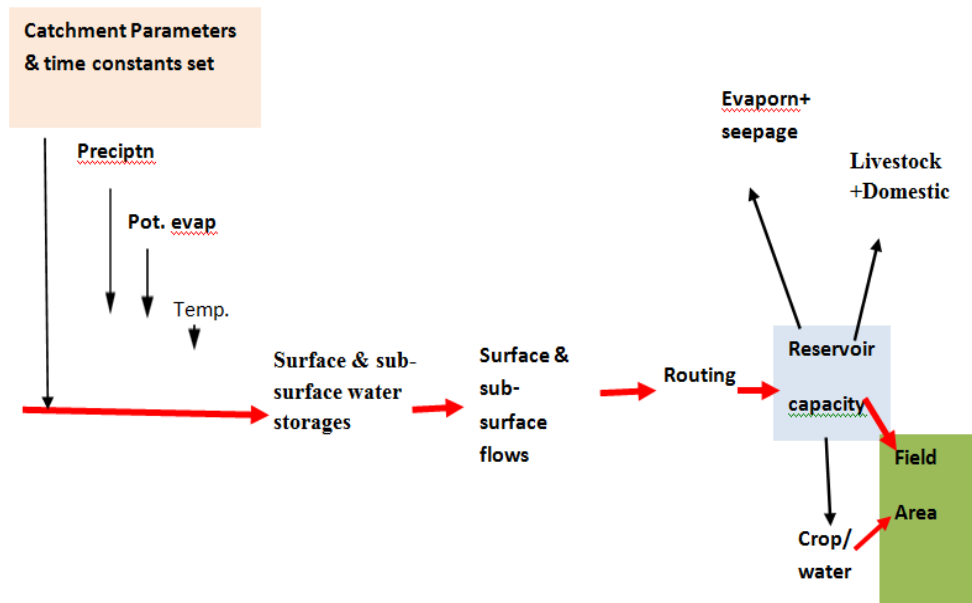


Figure 3: DSS flowchart as per excel based NAM spreadsheet programmed commands

2.6 Catchment characteristic factors

Impacts of the catchment characteristics on runoff and reservoir capacity, as simulated by the modified NAM DSS excel spreadsheet, are quantified by parameterization. The optimized model catchment parameters and routing constants computed in Chapter three, during the model development, were used in the design and validation of the DSS (Tables 1 and 2).

Table 1: Model Parameter constants in the spreadsheet

Parameter	Name	Constants
Lower zone storage capacity: maximum water storage in the root zone	Lmax	> 0
Upper zone storage capacity: maximum water content in the surface storage.	Umax	> 0 First estimate Umax=0.1Lmax.
Snow melt coefficient	Cmelt	0 for Ukwe site
Overland flow runoff coefficient: extent to which excess	CQOF	0 – 1. Since Ukwe

rainfall runs off as overland flow and the quantity that infiltrates.

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

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

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146 **Table 2: Ukwe DSS adjusted catchment parameters and time constants**

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

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2.7 Decision Support System Validation

Factors of water routing (modified function of total flows), storage and crop water use and productivity have been incorporated to the NAM based operation using an excel spreadsheet version 2007. Table 3 shows the spreadsheet data input, merged computer simulation (simuln) columns, cumulative (cummul) dam inflows and dam water balance (dwb). At this point the DSS operator inputs data of pot evaporation (PotEvap), seepage and abstractions by livestock and persons.

Table 3: Decision support system operational spreadsheet

Date	Rainfall (mm)	Pot. Evap. (mm)	Temp °C	Computer Simuln Cummul Inflows	Dem m ³	DWB	PotEvap	Seepage	Cattle	Goat	Persons	Computer Simuln Available Water	Pote Irrige Area

3. Results and Discussion

3.1 Rainfall data screening for design of the Decision Support System

The accumulated rainfall means from Ukwe were plotted against accumulated data means of Bunda, Kandiya, and Lumbadzi, 50 km South, 12 km South-east and 8 km North-east respectively, to test reliability of data. Results of the double mass analysis shown in Figure 4 indicate that Ukwe rainfall data as tested against the other three weather station data produces spurious relationship showing data inconsistency and non-homogeneity. It would not be reliable, therefore, to use the data for the validation of the DSS unless the source of anomaly is established to be a station other than Ukwe.

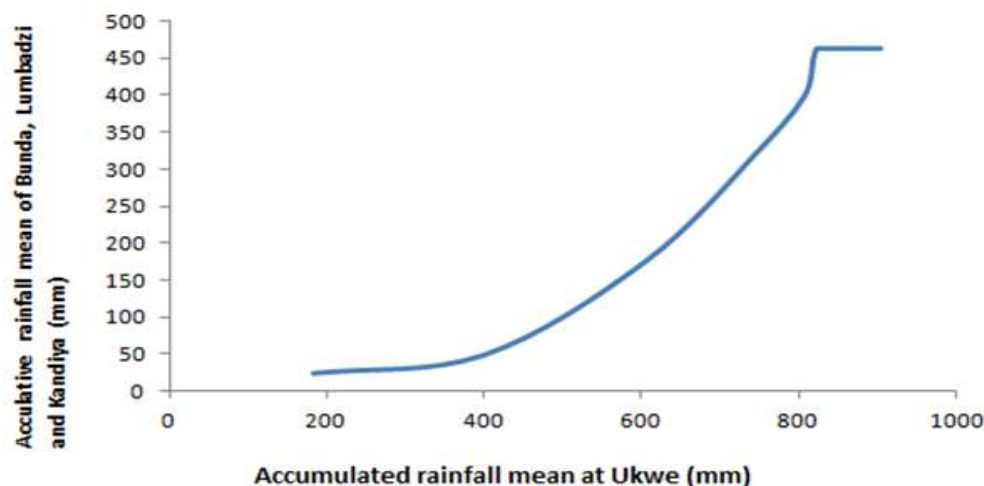


Figure 4: Rainfall double mass analysis of all the stations including Bunda

Although Bunda, Kandiya and Lumbadzi are in the same agro-ecological and agro-hydrological zones, the daily rainfall data from each site was eliminated during each analysis to trace source of the anomaly. Errors were discovered in the Bunda data. Infact, Bunda site is far removed (55 km) from the rest and is between two mountains, hence it is suspected to have some rainfall variations during some seasons. Weather conditions are reported to gradually change over distances of 50 to 150 km (MARS, 2014). Double mass analysis test was hence run, excluding this Bunda site. The results, as shown in Figure 5, indicate straight line relationship revealing absence of spurious trends. It is worthy pointing-out that Double Mass analysis interpretation is dependent on data line shape rather than use of coefficient of determination (R^2). The analysis, therefore, demonstrated that the rainfall data were valid for runoff and water storage, hence used for the DSS validation.

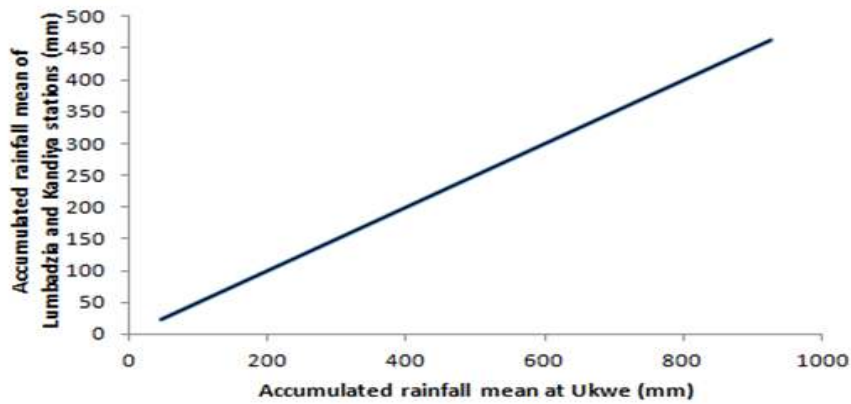


Figure 5: Rainfal double mass analysis of all stations excluding Bunda

3.2 Socio-economic analysis

3.2.1 Gross margin and break-even analyses

Gross margin and break-even analyses were conducted on the grain yield of rain-fed and reservoir water irrigated beans. Variable cost data included production, processing (drying, threshing, treatment) and transportation costs, while fixed costs included contribution towards annual reservoir maintenance (Table 4). Output was in terms of grain yields.

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

Table 4: Gross margin and break-even analysis for rainfed and irrigated beans

DETAILS	Unit	Without irrigation			With irrigation		
		Quantity kg	Unit price MK	Total cost MK	Quantity kg	Unit price MK	Total cost MK
Output value	kg	801.2	150	120 000	1400	165	231 000
FIXED COSTS							
Reservoir contribution	Annual fee	-	-	-	-	-	5 000
Irrigation	Mandays	-	-	-	346	157	54 352
Sub total							59 352
C. VARIABLE COSTS							
INPUTS							
Seed	kgs	75	250	18 750	75	250	18 750
Insecticides	litres	10	1500	15 000	10	1500	15 000
fungicide	kgs	25	1000	25 000	25	1000	25 000
Sub Total (inputs)				58 750			58 750
LABOUR							
Land preparation	Mandays	42	200	8 400	42	200	8 400
Planting	Mandays	15	200	3 000	15	200	3 000
Supply	Mandays	3	200	600	3	200	600
Weeding/banking	Mandays	23	200	4 600	23	200	4 600
Harvesting/drying /threshing	Mandays	36	200	7 200	40	200	8 000
Drying/packing/loading	Mandays	15	200	3 000	20	200	4 000
Subtotal Labour	Mandays			26 800			28 600
OTHER COSTS							
Sacks	50 kg bag:	12	80	960	30	80	2 400
transport	bags	12	100	1 200			
					30	120	3 600
Subtotal				2 160			6 000
Total Costs				87 710			152 702
Gross Margin (A-B)	MK/ha			32 290			78 298
A. Break-even Yield	MK/ha			585			925
B. Break-even Price	MK/ha			110			109

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

3.2.2. Willingness to invest in irrigation

Farmers were interviewed to know their willingness to pay for runoff water harvesting and irrigation (Table 5). The cost calculated by the dam committee, which an irrigation household was paying for water preservation, is MK5 000 (US\$16.67).

Table 5: Willingness to pay for runoff water harvesting and bean irrigation

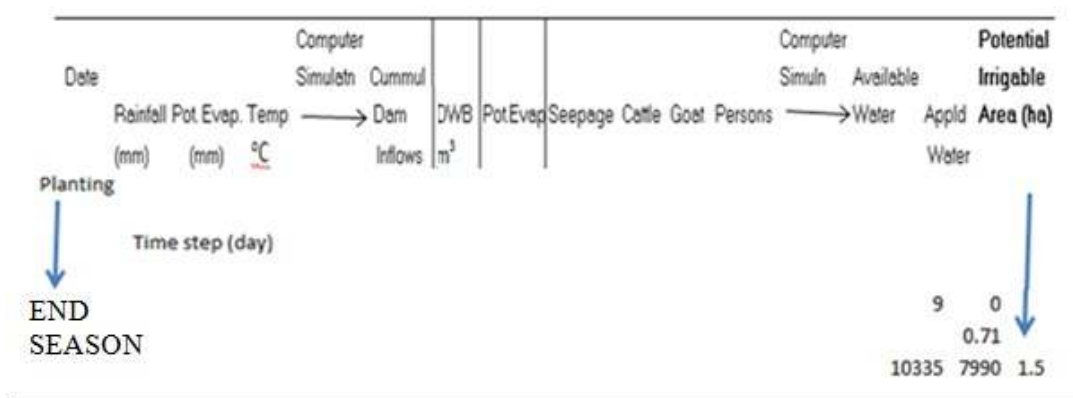
<u>Maximum willingness to pay</u>		<u>Percent</u>
<u>MK</u>	<u>US\$</u>	
<5 000	< 16.67	48.20
5 000 - 10 000	16.67 - 33.34	25.30
10 000 - 15 000	33.34 - 50.01	18.10
>15 000	>50.01	8.40
Total		100.00

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

3.3 Decision Support System Spreadsheet Simulation

Operational spreadsheet workbook inputs, with hidden computer simulation command columns (computer simuln) are shown in Table 6. The results of validation based on 2011-2012 data (with hidden command rows and columns for December 2, 2011 to December 31, 2012) displaying Dam Water Balance (DWB) and potential irrigable area are highlighted in the table.

Table6: Operational spreadsheet workbook simulation highlight for computer simulated and available reservoir water (m³), and potential field area



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

4. Conclusions and Recommendations

4.1 Conclusions

Socio-economic analyses have indicated clear benefits for the farmers producing the common beans using stored runoff. Once the socio-economic benefits of water storage and irrigation are revealed, it is then feasible to endeavour into the development of a decision support determination of required crop field area in relation to the reservoir water capacity or vice-versa. The conceptual framework, structure and spreadsheet entries of the DSS have been designed and validated using Ukwe Area data on common beans (*Phaseolus vulgaris*, L.). Two dry season crop production cycles, at crop water productivity of 0.7 g/L, as the case at Ukwe Area, would require potential crop command field area of 1.5 ha.

The DSS requires few parameters and input data to simulate accumulated reservoir capacity and its appropriated crop field size to be irrigated. The DSS has comparative advantage to others, developed

for rainwater harvesting for irrigation, because apart from using simple data entry it is versatile in simulating runoff, long term surface water storage capacity and synchronized crop land area farmers need to prepare to meet the recommended crop water requirement. Stakeholders can use the DSS developed information to support their decision in planning field area for farmers based on reservoir capacity or build a reservoir to suffice crop land area to mitigate drought and dry spell impacts.

4.2 Recommendations

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

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

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

7. References

- Kamthonkiat, D. 2008. 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 12120, Thailand.
- Oteng-Darko, P., Yeboah, S., Addy, S. N. T., Amponsah, S. and Danquah, O. E. 2013. Crop modeling: A tool for agricultural research – A review, E3 Journal of Agricultural Research and Development Vol. 2(1). pp. 001-006.
- Yalewa, S. G., Pilz, T., Schweitzerc, C., Liersch, S. van der Kwast, J. Mul, M. L., van Griensven, A. and van der Zaag, P. 2014. Dynamic Feedback between Land Use and Hydrology for Ecosystem Services Assessment, International Environmental Modelling and Software Society (iEMSs), 7th Intl. Congress On Environmental Modelling and Software, San Diego, CA, USA.
- Hirschfeld, J., Dehnhardt, A. and Dietrich. 2005. Socioeconomic analysis within an interdisciplinary spatial decision support system for an integrated management of the Werra River Basin, Limnologica - Ecology and Management of Inland Waters, Magdeburg, 35:3. Pp 234–244
- Njoloma, H. M. 2010. Synchronizing Irrigation Development with Hydrology of the Local Catchment Areas by Use of Rainfall-Runoff Modeling in Lilongwe in Malawi, PhD Thesis, Tottori, Japan.
- Research into Use (RIU). 2007. Rainfall modelling can predict future yields NRSP13, New technologies, new processes, new policies: tried-and-tested and Ready-to-use resource from DFID-funded research, Research Into Use Programme, Ayiestora, Kent, UK
- Larbi, P. A. 2011. Development of a Model to Predict Spray Deposition in Air-carrier Sprayer Applications, A PhD Dissertation, University of Florida
- Tumbo, S. D., Mpulila, T., Mzirai, O. B., Mahoo, H. F., Rwehumbiza, F. B., Semoka, J .M. R. and Hatibu, N. 2006. Maize Yield Simulation Under Rain-fed and Rainwater Harvesting Systems using Parched-Thirst Model, Harvesting Systems Using PARCHED-THIRST Model, Soil Water management Research Group, Sokoine University of Agriculture, Morogoro, Tanzania. pp 1. https://www.academia.edu/1104952/Maize_

- 307 Wani, S. P., Rockstrom, J. and Sahrawat, K. L. 2011. Integrated Watershed Management in Rainfed
308 Agriculture, Taylor and Francis Group, NW, Florida, USA. CRC Press.
309 <https://books.google.co.tz/books?isbn=1466512822>.
- 310 Kadyampakeni, D., Longwe, A., Mangisoni, J.H., Mloza Banda, H. R., Singa, D. D., Ferguson, A. and
311 Snapp, S. 2010. A Comparative Assessment of Benefits of Irrigation and Water Management
312 Practices on Bean Production in Chingale, Zomba, Southern Malawi, Bunda Journal of
313 Agriculture, Environmental Science and Technology, University of Malawi, Malawi, Volume
314 4, Pp 1 – 8.
- 315 Ali, H. 2011. Double Mass Curve, Precipitation Presentation, Technology and Business Publication,
316 London, United Kingdom. <http://www.slideshare.net/hamza07/precipitation-presentation>.
317 Accessed: Feb. 11, 2015.
- 318 Monitoring Agricultural Resources (MARS) Mars (2014), Spatial interpolation of daily
319 meteorological data. Theoretical evaluation of available techniques, Report 53.1, DLO,
320 European Commission Joint Research Centre, EU Common Agricultural Policy (CAP). Pp 43.
- 321 Kadyampakeni, D. S. 2004. Comparative Analysis of Agronomic, Technical and Financial Aspects of
322 Dry Season Cultivation of Beans (*Phaseolus vulgaris*, L.) under Different Irrigation
323 Technologies and Water Management Techniques for Chingale Area Development Program
324 (ADP) – Zomba. An MSc Research Thesis, University of Malawi, Bunda College, Lilongwe.
325
- 326 Hashim, M. A. A., Shiam, A., Al-Dosari, A., Asl-Gaad, K. A., Patil, V. C., Tola, E. H. M.,
327 Rangaswamy, M. and Samdany, M. S. 2012. Determination of Water Requirement and Crop
328 Water Productivity of Crops Grown in the Makkah Region of Saud Arabia, Australian Journal
329 of Basic and Applied Sciences, 6(9), Pp196 – 206
330
- 331 Mloza-Banda, H.R.1, Makwiza, C.1 & Kadyampakeni, D. 2010. Improving smallholder irrigation
332 performance in Malawi, Bunda College of Agriculture, University of Malawi, Second
333 RUFORUM Biennial Meeting 20 - 24 September 2010, Entebbe, Uganda