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Integrated catchment characteristics, runoffwater reservoir capacities and irrigation - requirement for bean productivity

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Abstract Crop production in semi-arid Sub-Saharan Africa (SSA) is limited by over-reliance on rainfall, which is erratic and inadequate. Rainwater conservation and irrigation are needed to avert drought effects and dry spells, and extend crop production activities to dry seasons. A study was conducted from 2011 to 2013 at Ukwe area in Malawi, to determine the size of seasonal open surface reservoir and crop field in relation to catchment characteristics among smallholder farming communities, using beans as a case study crop. There is positive linear relationship between seasonal harvested watershed runoff and rainfall (over 75%). Based on the catchment characteristics and crop water requirement, catchment/cultivated area ratio was 2.1. Harvested runoff water is linearly related to seasonal rainfall amount. About 6000 m^3 of water was required to irrigate a hectare of beans. Total volume harvested was estimated to support six-fold the current field area at bean water productivity of 0.7 g L^{-1}. It is possible to determine dry season bean water productivity based on integrated effects of catchment characteristics, runoff water reservoir capacities and irrigation water requirement.

Key words: Beans, irrigation, productivity, runoff

Introduction

Sub-Saharan Africa experiences frequent dry spells that have serious repercussions on crop production. Food security and income assurance for farming communities are only possible when irrigation is practiced using stored rainwater, mostly intercepted as it runs from highlands. A small proportion of smallholders in SSA use stored water from small catchments (5 - 15 ha) to produce crops such as common beans (*Phaseolus vulgaris* L.) during the dry season.

Common bean is an important food and cash legume, and a major component of farming systems for the smallholder farming communities in Sub Saharan Africa. Production of the crop is, however, threatened by increasing frequency of droughts (Eriksen *et al.*, 2008). There is need to increase yields and production stability of the crop in drought prone but flood susceptible areas (Kambewa, 1997).

Available research recommendations have been based on single system entity without establishing appropriate variable combinations of the technologies for increased and sustainable crop water productivity. Results from small scale experiments in Central Malawi plains, have shown positive relationship between harvested watershed runoff and rainfall, and that runoff water harvesting technique can contribute to food security through irrigation (Singa & Chirambo, 2008). The current study, therefore, focused on search for relationships among runoff, stored water amounts and dry season bean crop water requirement. The amount of runoff water harvests basically depends on rainfall characteristics (amount, intensity and duration), initial soil moisture content, infiltration capacity of the soil, soil surface features and watershed size and slope.

Materials and methods

Study site. The study was carried-out in Ukwe Area, Lilongwe North–West, Malawi, about 1150m above sea level, 13° 46' S and 33° 37' E to 13° 55' S and 33° 38' E, extending 13° 46' S and 33° 31' E to 13° 50' S and 33° 32' E, occupying flat *dambo* margins, with Vertisols. The most predominant soil textural class is sandy loam. The area has predominantly sandy loam soils. An ephemeral Kalembo stream feeds a small Mphetsankuli dam. The stream is influent during the rainy season and effluent during the dry season. The study was conducted from 2012 to 2014, and involved 3 farming families, supported by a field agricultural assistant from Total Landcare (non-governmental, non-profit making organization).

The main methodology involved assessment of catchment runoff attributes (area, vegetative cover, soil characteristics, slope and rainfall) and determination of reservoir water volume, irrigation water and crop water productivity. Temperatures ranged from 18 to 24°C, with low relative humidity (May to August), rising to 29°C just before the rains (October – November). It is a drought-prone area and farmers have a bean irrigation farming club. The catchment area is about 12 ha, lying on gentle slope towards the dam (2 to 3%), with savannah woodland vegetation, regenerated shrubs and scattered trees (mostly exotic cassia type). Cultivated fields had loam soils with organic matter of 1.75%, pH 5.5 and bulk density 1.35.

Main methodology involved assessment of catchment area attributes for runoff rainwater, measuring and calculating of volume of water harvested and determination of irrigation water and crop water productivity, depicted in the conceptual framework in Figure 1.

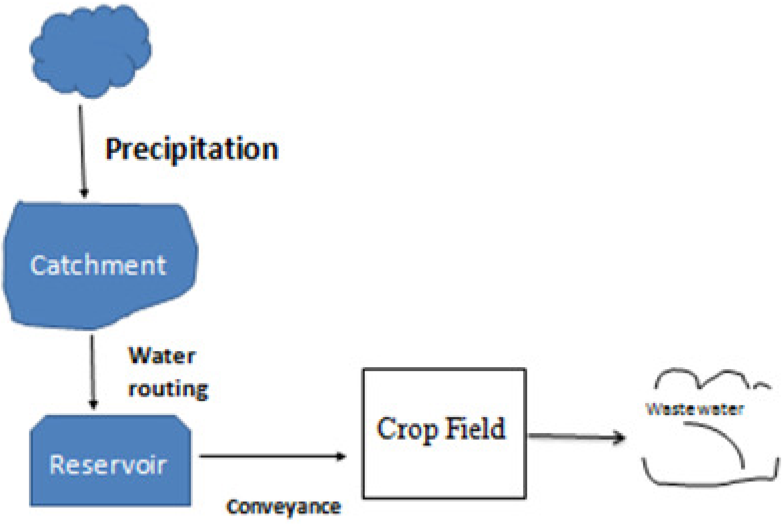

Figure 1. Conceptual framework of harvested water and use on a bean crop.

Catchment characteristics and climatic factors. The catchment area and topographic determinations were carried-out using Differential Global Position System (DGPS) – LEICA model G509, with a measurement error of less than 3 mm. Double-ring infiltrometers were used to measure the infiltration rates in the field. Undisturbed soil samples were analyzed for texture, soil moisture and structure at the Lilongwe University of Agriculture and Natural Resources.

Daily 2012/2013 rainfall data were collected using rain gauges. Twenty year rainfall data were obtained from Chitedze Agricultural Research Station (8 km west of the study site) in the same agro-ecological zone. Temperature data were collected using portable mini total station (Kestrel 4000) and verified using data from Chitedze Research Station (5 km west of the study site) in the same agro-ecological zone.

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Rainfall data collection. Rainfall data from installed automatic rain gauges in the catchment area would have given negligible errors. But these gauges were found damaged within a few days. Nine daily point-sampled measurement rain gauges were hence installed in the catchment sites (three at each of hilly, arable and dambo areas) to record rainfall amounts for 3 hour storm durations. Average minimum and maximum precipitation values were then computed using

$$Pav = \left(\sum_{i=1}^{n} Pi\right)/N \quad \text{.......... (1)}$$

Where P = Precipitation depth at station i, and N is the total number of station, ie, 9 in this case. Long term (30 year) rainfall data was obtained from Chitedze Agricultural Research Station.

Rainfall data homogeneity and consistency tests. Average rainfall data obtained (Equation 1) were subjected to Thiesen polygon method as internationally recommended (Patra, 2000). The catchment area was subdivided into polygonal sub-areas using rainfall stations as centres. This made use of lines that are equidistant between pairs of adjacent stations subjecting sub-areas as weights in estimating the average. The entire map was further criss-crossed with small boxes drawn from lines at right angles to each other. The procedure helped to provide areal rainfall values Ø using Equation 2.

$$\bar{R} = \sum_{i=1}^{n} \frac{R_i a_i}{A} \quad \text{.......... (2)}$$

Where $\bar{R}$ is mean areal rainfall, R_i is rainfall measurements at each rain gauge station, A is total area of catchment and Q_i is polygon area corresponding to rain gauge station. Analysis was then made based on impact of sampled years of excess, optimum and drought rainfall years with respect to bean crop production.

Runoff data collection and analysis. Historic data on runoff was obtained from Surface Water Division of the Water Resources Department, Ministry of Irrigation and Water Development. Runoff as inflows into the water reservoir was measured using the DGPS and surveying staff in a boat. Relationship of rainfall and runoff was developed. Of vital concern for the reservoir capacity were the annual frequencies of peak runoffs. Therefore, analysis of a frequency distribution of peak flows from a data set was made to define an average probability level or average return period.

Frequency distribution analysis. Frequency of extreme runoff was obtained using Gumbel extreme value (GEV) distribution procedure. Gumbel had used with success to describe the populations of many hydrological events since 1963 (Gumbel, 1963). In this study distribution was carried out using the following parameters:

Non-exceedence probability:

$$F_i = (i - \alpha)/(n + 1 - 2\alpha);\ \alpha = 0.44 \text{ (the Gringorten formula)} \quad \text{.......... (3)}$$

Plotting position: $y_i = -ln\,(-ln\,F_i)$ .... (4)

Scale parameter, a: $\sigma^2 = \pi^2 a^2/6$ .... (5)

Location, c: $\mu = c + 0.5772a$ .... (6)

Estimate: $X = ay + c$ .... (7)

Variance of estimate: $Var\ (X) = a^2\ (1.17+0.196y +1.099y^2)/n$ .... (8)

95% Confidence limits of estimate: $CL\ (X) = X +/- t_{97.5,n-1}\ SE_x$ .... (9)

$SE_x = (var\ X)^{0.5}$ .... (10)

Measured runoff of annual extreme peaks from each of the 16-year daily data sets were isolated and subjected to extreme value analysis. The resulting data (annex IV) were then fitted to a Gumbel distribution as shown in Figure 7.

Catchment, reservoir and irrigation data analysis. Linear regression was used to establish relationship between rainfall and runoff into the reservoir. The reservoir volume divided by total seasonal crop water requirement over a hectare provided the total area (ha) the reservoir water volume could irrigate. This relationship in turn established optimum sizing of either area or reservoir for maximizing crop productivity based on runoff generating catchment attributes and climatic conditions.

Soil water infiltration. Double ring infiltrometers were used to measure the infiltration rates at the places where soil samples were obtained. A multiple regression method was used to analyse the data based on Genstat computer package. The results were used to come up with equations for infiltration rates based on the soil properties and rainfall regimes.

The model for these equations is: -

$$Y_k = \alpha + \beta_0 X_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \ldots + \beta_k X_k + \varepsilon \quad (11)$$

for $k=1,2,3\ldots n$ ....(12)

Where: Y_k is the response variable (Infiltration rate-cm/min), X_0 is moisture content, (%), X_1 is pH of the soil, X_2 – is structure of the soil, X_3 is Bulk Density (g/cm^3), X_4 is texture, X_5 is organic matter content percentage, β_k is soil compaction and ε is random error component.

Catchment area/cultivated area ratio. To estimate synchronization of crop water requirement with runoff water harvested, Catchment area/ cultivated area ratio was obtained using Crop Water Requirement and Design Rainfall, Runoff Coefficient, Catchments characteristics and Efficiency factor. Recommended Bean crop water requirement in the area is 600 to 700 mm per growing season (Kambewa, 1997; Katunga, *et al.*, 2009). The design rainfall was obtained at 33 % probability of occurrence to make the system more conservative and reliable, thus meeting the crop water requirement more frequently. The available rainfall data of 20 years was ranked in a descending order of values in form of probability and return period as recommended by (Finkel & Segerros, 1995).

Probability of occurrence = Rank of rainfall depth (m)/(No of Events + 1) ....(13)

and probability of repeat of same rain storm magnitude by

Return Period = (No of Events +1)/Rank of rainfall (m) .... (14)

Where ***No***. of events is the number of rainfall (m) and Rank of rainfall is position of the rainfall (m). Runoff Coefficient was determined by dividing the runoff depth by the rainfall depth over the catchment area. Efficiency factor was obtained by considering the amount of the runoff water that could be efficiently used by the crop with respect to the overhead water can application. Efficiency factor of 65% was used based on evaporation losses and deep percolation. The catchment area/ cultivated area ratio was obtained using Doorenbos & Pruitt equation (1977):

Catchment Area/Cultivated Area Ratio =

$$\frac{\text{Crop Water Requirement - Design Rainfall}}{\text{Design Rainfall*Runoff Coef.*Efficiency Factor}} \quad (15)$$

Design rainfall of 600 mm (normal mean rainfall), average runoff factor was 0.0276 and average efficiency factor of 0.59 were used in the catchment/cultivated ratio equation on the 12 hectare land.

Determination of reservoir water capacity and bean dry season irrigation. Relationship between evaporation from a calibrated standard (Class 'A') open pans installed at the site and evaporation from the reservoir was established to quantify the water loss from the reservoir, as the season progressed, and verify the values with those from physical site measurements. An E_{pan}/Reservoir coefficient of 0.7 was established. The inflow rate into the reservoir following a storm was measured using the DGPS as a change of water surface level in the reservoir on a calibrated staff installed in the reservoir. The reservoir inflows were related to the change in water volume obtained by using equation 16 below. The Hudson (1998) equation, is recommended for Eastern and Southern Africa, and is used to estimate stored water in the open surface reservoir (Hudson, 1998 in FAO, 2010):

$C = DWT/6$ .... (16)

where C is the reservoir water volume (m^3), D is the water depth (m), W is the dam width (m), and T is the throwback distance (m).

Bean production and determination of dry season irrigation on beans. Common dwarf bean (Kalima variety) was used as production was followed, viz: planted in 2 rows (1 seed per station), as a study crop, planted at 10 cm apart, on ridges 75 cm apart. In line with recommendations, by the Ministry of Agriculture and Food Security (2012), all agronomic, pathological and practices to avoid allelopathy, and biocides for the crop's potential growth and protection. In this regard, fertilizer of type 23: 21: 0 + 4 was applied at 100 kg/ha and cypermethyline insecticide was applied 7 weeks after planting.

Three water regimes (2.5 cm, 5 cm and 7.5 cm) were applied in plots randomised 3 times using upper, arable and *dambo* areas as blocks. Pre-planting application water application was 100 cm, followed by the aforementioned water depths. Research recommended amount is 5 cm (Min. of Agriculture, 2012). 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 al lowable depletion (P) of 50%. A relationship between applied water and bean water productivity *(P)* was established

$$P = Y/W \quad (17)$$

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

Results

Soil characteristics and their attributes on soil moisture and runoff. Catchment area soil variations were categorised into values based on their characteristics with respect to topographic positions of lower dambo (LD), middle dambo (MD), upper dambo (UD), Lower Arable (LA), Middle Arable (MD), Upper Arable (UP), Lower Hilly (LH) and Upper Hilly (UH) lands. Results of the awarded values are shown in Table 2. Results indicated lower values of pH in the arable lands than in *dambo* and hilly areas. Similar cases are indicated by low organic matter content in the arable lands.

A lot of variation in texture was obtained from the arable lands and to a less extent in the *dambo* lands. Due to minimal water retaining capacity of the soil, dry spell of more than one week tended to result in initiation of wilting in the bean crop. Dry seasons could not support production of the crop even in the dambo land unless irrigation was practised.

Rainfall pattern and analysis. As shown in the methodology section simulation of rainfall was done using the Thiesen areal rainfall predicted during 2011/2012. The resulting computation was the aerial rainfall, which was used to represent rainfall time series from the catchment for the year 2012. The areal rainfall results trend was responsively in tandem with the measured ones (Fig. 3). The areal (corrected) values were, henceforth, used in all the following rainfall analyses, as depicted in Figure 3.

Average annual rainfall of about 900 mm is annually experienced in the Ukwe area as depicted in Figures 4 and 6. Without frequent dry spells and droughts the amount would suffice for bean production which requires least seasonal rainfall of 600mm. Unfortunately, the seasons are usually frequented by dry spells and/or droughts once in about 4 years (Fig. 5).

During the normal or high rainfall years dry spells are often experienced within the rainy season. Although high rainfall years provide excess water for rainy season production of beans, (Fig. 6), there is lack of water for dry season crop production to bridge the gap between produce supply and demand by the ever increasing population.

The unimodal pattern rainfall in Ukwe area commences as heavy storms in December when the soil is dry and highly absorbent with negligible runoff (Fig. 7). Runoff relatively peaks up between December and April but again rescinds as the season progresses.

Rainfall and runoff analyses. Seasonal rainfall data at Ukwe were related to runoff. Runoff trend followed the magnitude of rainfall (Fig. 7). As stated from the fore-going paragraph, seasonally, the runoff depicted by flow

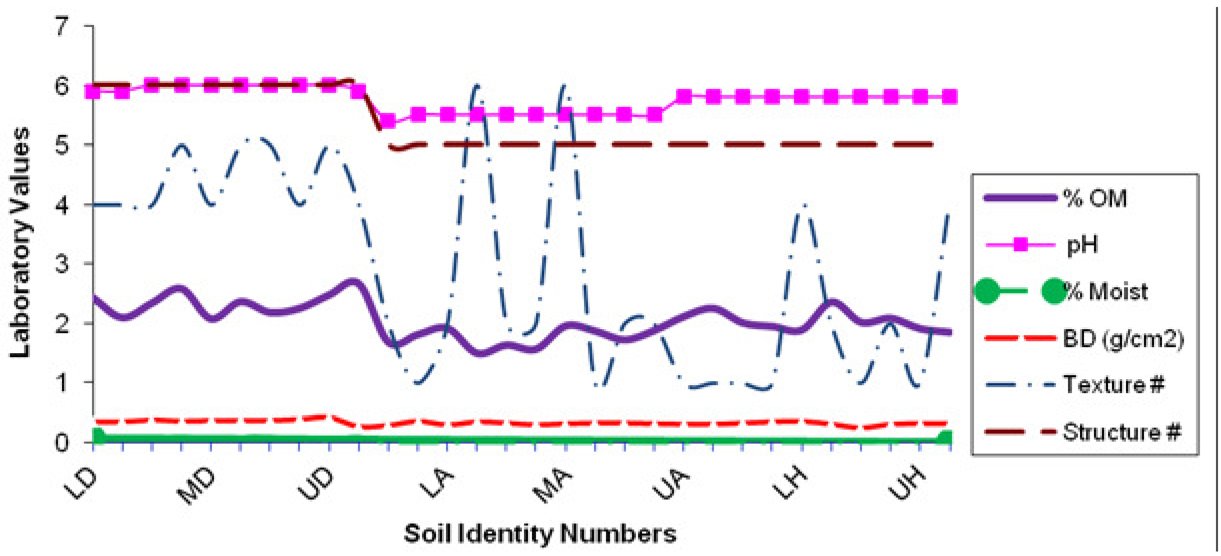

Figure 2. Dry season variations in characteristics from laboratory analysis.

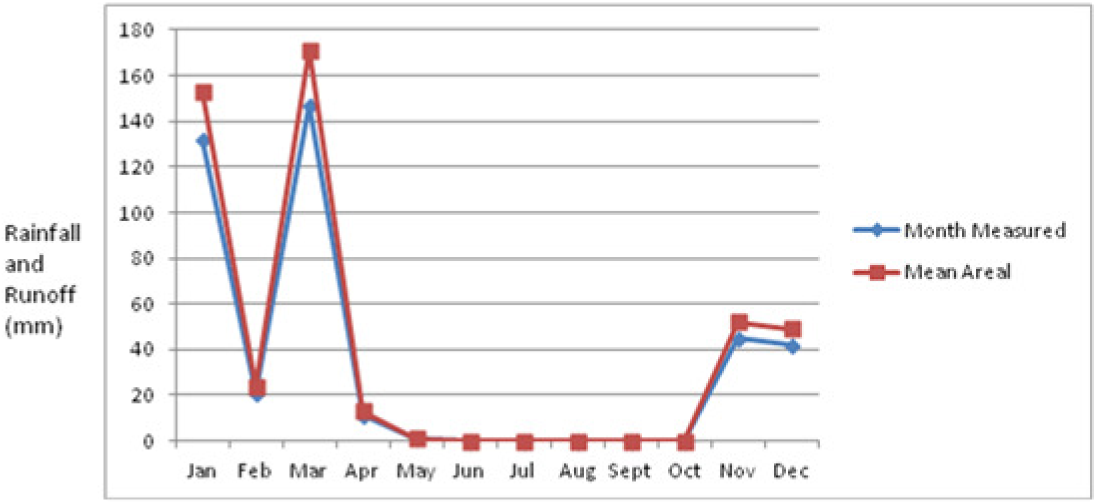

Figure 3. Areal rainfall in relation to measured rainfall, year 2012.

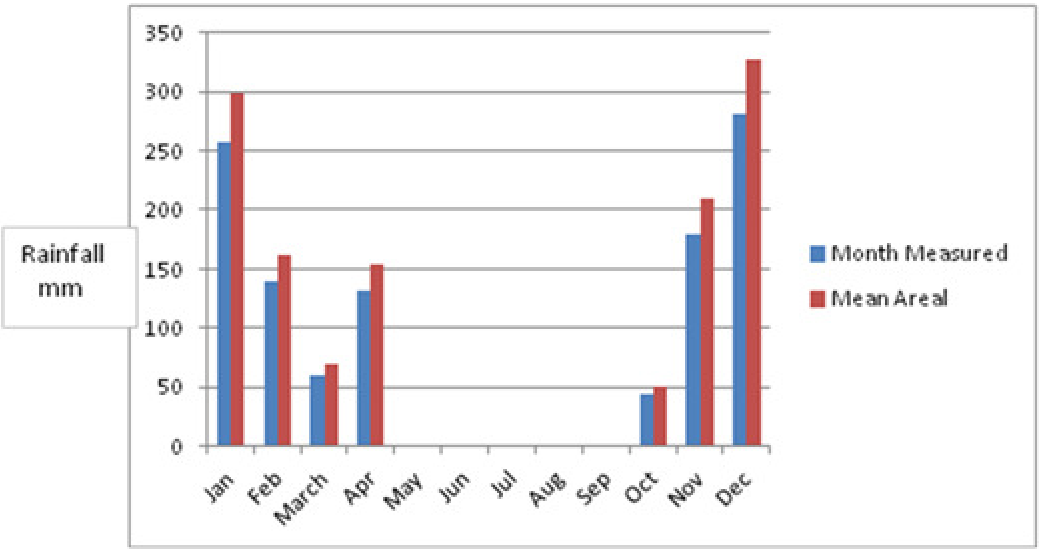

Figure 4. Optimum rainfall year (case of 1997).

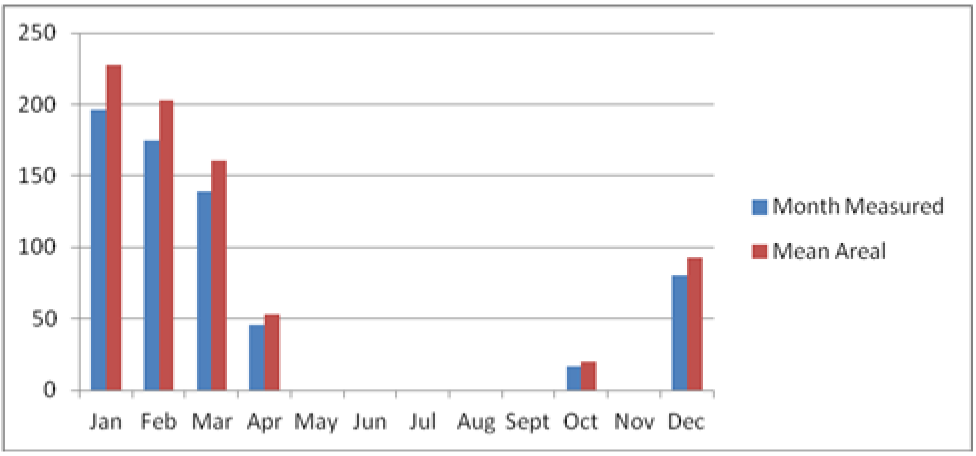

Figure 5. Mean drought rainfall and runoff at Ukwe (case of year 2000).

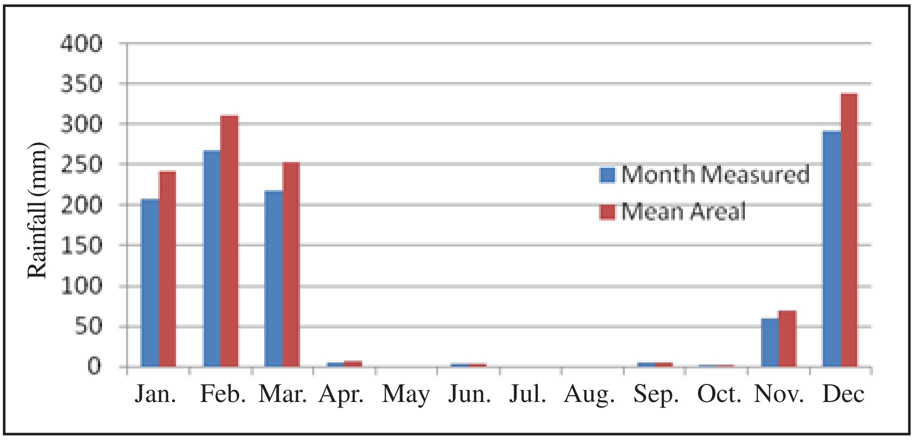

Figure 6. Excess rainfall year (case of 1997).

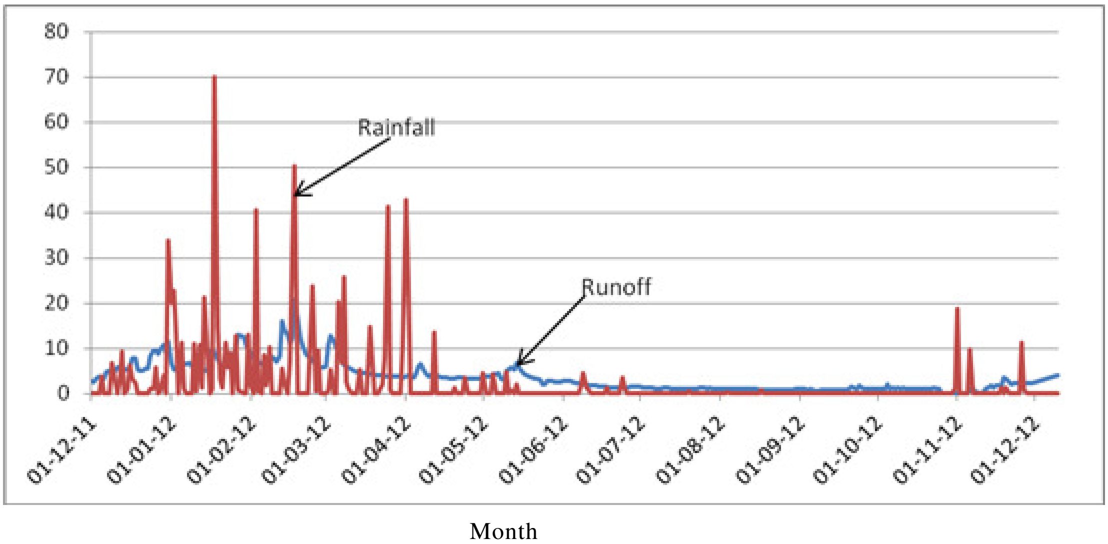

Figure 7. Relationship between rainfall and runoff during 2012 drought season.

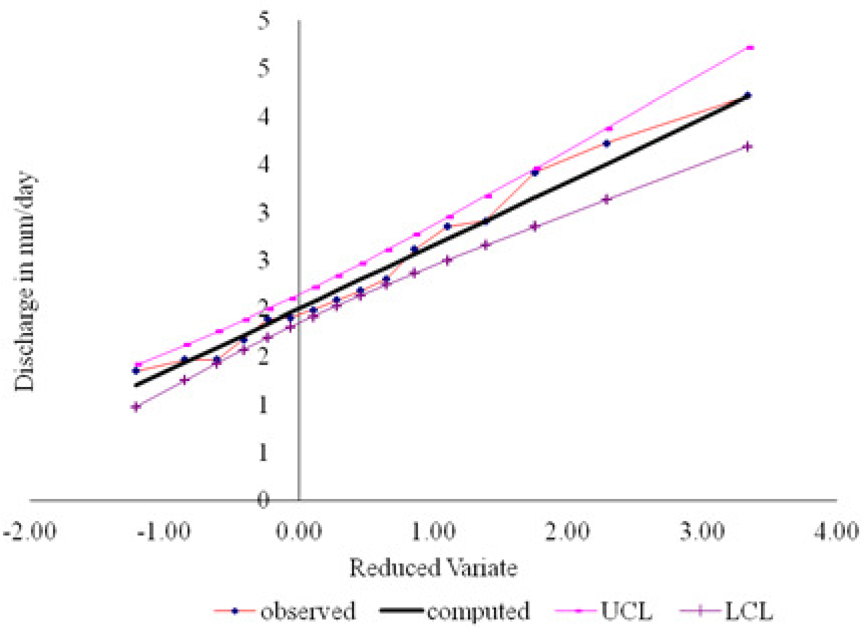

Figure 8. Gumbel Distribution Fitting for 1960 to 1975 runoff at Ukwe.

in Kalembo stream is negligible in the dry season. Normally, surface flow is hardly observed during then.

The results are in line with recommendation by Stephens (2010), who states the rule of thumb that where the average percentage of runoff is not known, the guide be 10 percent of the mean annual rainfall for the catchment area. Furthermore it has been noted that the ordinary events occur regularly than the extreme events.

Regression between runoff and rainfall for Ukwe area demonstrates that without rain, the flow rate in stream feeding the reservoir is only 0.408 mm/day (Table 1).

The results indicate that without rain, the flow rate (Q) in stream to the reservoir is only 0.408 mm/day. For every 1mm rainfall at Ukwe, 0.165 mm runoff is generated. Results are in tandem with report by Patra (2000) that there is a definite relationship between the frequency of rainfall occurrence and the magnitude of runoff.

Historical rainfall and runoff data analysis. Sixteen year data obtained from the Water Division of the Water Resources Department, Ministry of Irrigation and Water Development was used as historical data for rainfall-runoff analyses. Reliability of the runoff data was hence assessed against the Lower Confidence Limit (LCL) and the Upper Confidence Limit (UCL). Results in Figure 7 shows that the data fits well within the two limits hence are reliable for use in runoff analysis for Ukwe study site. There is no disparity between observed and computed runoff results.

Table 2 shows the magnitude of the 10, 20, 50, 100 and 1000 year runoffs, that would contribute to the reservoir water capacity, estimated by the Gumbel distribution parameters. There is about 50% runoff difference between 10 year and 1000 year estimated return period given sustenance of prevailing catchment characteristics and climatic conditions. However, observations over the 3 year research duration have, however, only shown cultural and not biological conservation practices.

Seasonal runoff water harvested and catchment/cultivated area ratio. Relationship between evaporation from a calibrated standard (Class 'A') open pans installed at the site and evaporation from the reservoir established a coefficient of 0.75. The value helped in estimating evaporative losses from the reservoir. Rainfall probability of occurrence was ranked as low as 33% to ensure reliability of the research results since the current decade has experienced wide variation in seasonal rainfall pattern. The design rainfall of 600mm (normal mean rainfall), average runoff factor was 0.0276 and average efficiency factor was 0.59 were used in the catchment/cultivated ratio equation on the 12 hectare land. Results showed Catchment Area/ Cultivated Area ratio of 2.1. ie, quantity of runoff water harvested from 2.1 ha of catchment with the attributes indicated in the introduction section is adequate to sustain seasonal water requirement for 1.0 ha of beans.

Dry season irrigation and crop water productivity. Table 3 shows the crop yield statistical analysis for the three irrigation regimes. Results have statistically not shown significant difference among the irrigation depths despite obvious difference in food supply and income for farmers. The recommended water application depth of 5 cm gave the highest returns.

Table 4 shows the seasonal open surface reservoir and crop field water productivity. Results indicate that through field measurements and computation verifications it is possible to determine reservoir volume. The dam water change indicates the seasonal water volume in the reservoir as computed and verified by measurement. Volume change was the weekly water amount that remained

Table 1. Regression analysis: Runoff vs Rainfall amount.

Response variate:		Qm (Runoff)		
Fitted terms:		Constant, P (Precipitation)		
Estimates of parameters				
Parameter	estimate	s.e.	t (363)	t pr.
Constant	0.4081	0.0199	20.55	<.001
P	0.01657	0.00256	6.47	<.001

Relationship : Q =0.165P + 0.408

Table 2. Maximum expected return runoffs estimated by the Gumbel Distribution.

Return period	y	a	c	Estimated Xest mm/day
1000	6.91	0.66	2.00	6.56
100	4.60	0.66	2.00	5.04
50	3.90	0.66	2.00	4.58
20	2.97	0.66	2.00	3.96
10	2.25	0.66	2.00	3.49

Table 3. Yield responses to four different water application depths.

Water regime on beans	Pod yield (t/ha)	Total biomass (t/ha)	Pod length (cm)
Rain fed	2.35	5.19	13.20
2.5 cm	2.01	4.53	13.27
7.5 cm	2.10	4.58	13.02
5.0 cm	3.59	6.99	13.78
LSD (5%)	2.431	4.445	1.844
s.e.d.	1.054	1.928	0.799
C V %	51.4	44.4	1.844
F Prob	0.452	0.568	0.799
Signf	N S	N S	N S

NS = Not significant.

Table 4. Reservoir and seasonal bean water requirement.

Crop growth stage (weeks)	Dam Vol. (m^3)	Vol. change (m^3)	Field use (m^3/ha)	Bean water prodty (g/L)
Pre-planting	9978		500	
1 to 4	9015	913	1500	
5 to 9	4646	4368	2000	
6 to 10	2541	2105	2000	
Total		7437	6000	0.7

in the dam after deep ground losses and evapotranspiration. The total volume is estimated to irrigate 6 ha of beans if a single crop is produced or 3 ha if two crops are grown in sequence during a single dry season. At the realised yield production of 1400 kg ha^{-1} the seasonal bean water productivity of 0.7g L^{-1} is in line with common findings by researchers in the same drought prone and ecological area. Katungi *et al.* ((2009). Similarly, Xavery *et al*., 2005 and Kambewa, 1997, reported that bean crop requires moderate effective rainfall of about 600 mm which translates to 0.7g L^{-1} at recommended yield of 1400kg ha^{-1}.

Discussion

Catchment soil analysis shows lower values of pH in the arable lands than in *dambo* and hilly areas due to farmers' annual application of nitrogenous fertilizers and natural ground cover clearing. The later also contributed to erosion with eventual silting and depositions in the *dambos.* The minimal water retaining capacity of the soil was indicative of bean crop proneness to wilting under incidents of dry spell of more than one week. Consequently, dry seasons could not support production of the crop even in the dambo land unless irrigation was practised.

Results are conclusive that rainfall pattern in the drought prone area is unreliable and poorly distributed over the season. Rain amounts in drought and optimal rainy seasons are not adequate to meet the bean water requirement. The average rainfall of 900mm in Ukwe, under optimum and high rainfall seasons, would adequate support production of beans which require at least 600 mm per season, but the seasonal amount is poorly distributed and is frequented by dry spells and droughts. Sivanappan (2009) that in Eastern and Southern Africa rainfall failure occurs once every 3 to 5 years and is usually below 50% of the average annual rainfall. Occurrence of agricultural drought year can often be worsened by dry spells (Fig. 5). Excess rainfall seasons provide adequate water to meet seasonal crop water requirement but the there exist long dry seasons which are non-productive if long time water storage is not practiced.

Runoff tends to pick-up as the rainy season progresses (December to February) but gets minimised by regenerated vegetative cover and eventually becomes almost non-existent during the dry season due to lack of precipitation and high evaporative pressure (Fig. 7). The strong relationship between frequency and intensity of rainfall on one hand and magnitude of runoff on the other is supported by many hydrological researchers (Patra, 2000). No disparity has been revealed between the observed and computed runoff results. Definite relationship between the frequency of rainfall occurrence and the magnitude of runoff has been depicted.

Based on the prevailing catchment and climate factors a Catchment Area/Cultivated Area Ratio of 2.1 is prevalent. This ratio is in tandem with the findings that the stored water volume from 12 ha catchment can irrigate a single dry season bean crop of 6 ha or two crops of 3 hectares at crop water productivity of 0.7g/L. Parallel work in Lilongwe East, under similar catchment attributes, climate factors and irrigation water have shown similar catchment/ cultivated area Ratio. This study has shown that it is possible to predict sizes of seasonal open surface reservoir and crop field size in relation to catchment characteristics, runoff rainwater and crop-water productivity.

Gumbel analysis has shown reliable simulation of data, fitting reasonably well within the lower and upper confidence limits. Calibration and verification of runoff data from field measurements has been possible usingg the analysis. Although results indicate probability of runoff being doubled would be in 100 years, considering the rate of vegetation clearing in the catchment area, this may not be the case due to erosion and siltation interactions. This will increase the seasonal catchment area/cultivated area ratio beyond that of 2.1: 1 and also increase the catchment area required to harvest water to be stored for dry season irrigation of 1 hectare, beyond 2:1.

Although results of crop yield statistical analysis for the three irrigation regimes have not shown significant difference among the irrigation depths in terms of food supply and income for the farmers, the pod yield and biomass differences are substantial. Results indicate that, through field measurements and computation verifications, it is possible to determine water reservoir capacities, irrigation water requirement and bean water productivity.

Recommendations

Since rainwater during drought and optimal rainy seasons is not adequate to meet the bean water requirement there is need to offset dry spell or droughts water shortages. Although excess rainfall seasons provide adequate seasonal bean water requirement it is recommended that rainwater is still harvested and stored for irrigation during the idle dry seasons.

There is need to establish catchment area/cultivated area ratio through determination of catchment attributes, climate factors and irrigation in order to plan for field area to be adequately irrigated instantly. For the long term it is recommended that farmers should be assisted with procedures of determination of water reservoir water capacities in order to plan for dry season field crop sizing.

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