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Optimal Sizing of On-Farm Rain Water Harvesting Structure for Supplemental Irrigation

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ABSTRACT

Inferring the behavior of rainwater harvesting systems and accurate model simulation are crucial for the efficient management of water resources and optimal storage size design in the dry highlands of Ethiopia. Hence optimizing on-farm reservoirs for supplemental irrigation using the water balance model along with economic analysis is a crucial task. The study was carried out in Gondar Zuria district in the Upper Blue Nile River Basin, Ethiopia. The generated optimal reservoir sizing was based on a demand-driven operation policies for a one-year period for different inflows, outflows, and losses. The proposed model was implemented under normal rainfall year, using green pod hot pepper as a test crop. The optimum reservoir size, reliability, marginal rate of return and payback period under actual rainwater harvesting system is 273 m^3, 67.7%, 124%, and 15 years, respectively for 0.2 hectare of land. The recommended rainwater harvesting structure will be a 3 m depth trapezoidal structure; 13*13 top dimension, 10*10 bottom dimension with a side slope of 1:1. However, for wet years the reservoir capacity can drop up to 171 m^3 with 36 % reliability. In contrast, for dry years the reservoir capacity rises to 399 m^3 with 100% and 102.4% reliability and marginal rate of return, respectively. Thus, the study reveals that the rainwater harvesting irrigation system is economically viable in the study area. Moreover, the optimization method is relatively easy to apply and can be used as a decision-support tool for effective management and utilization of water resources.

1. INTRODUCTION

Hot pepper (Capsicum annuum L.) is the world's most important vegetable after tomato and used as fresh, dried or processed products, as vegetables and spices or condiments (Acquaah, 2004). It is also the leading vegetable crop produced in Ethiopia. Green pod hot pepper covered 3.82%, of the total estimated area under vegetables in the country with the national production of 41250.357 ton with average productivity of 6.688 ton ha^{-1} (CSA, 2014). Among major constraints associated with the low productivity are fragmented land holdings, lack of assured irrigation supply, and poor economic conditions of farmers towards intensive agriculture.

Ethiopia receives mean annual rainfall of1090 mm; while 70% of the entire cultivated land is below 750 mm (ERHA, 2003). An estimated 110 billion cubic meters of rainwater is lost each year through surface runoff. This corresponds to 1m deep square pond with side lengths of 330 km. In contrary, the majority of the people in the country suffer from shortage of water due to different reasons. Efficient utilization of this vast water resource is important to alleviate food security and raise resilience of communities to drought (Hugo Rämi, 2003; Maimbo *et al*., 2007). As to the other regions in the country, the people and farming systems in the dry highlands of Amhara region are largely impacted by shortage of water due to rainfall variability. According to many investigators, variability of annual rainfall in the region is high, ranging from 20% to 40% (ERHA, 2003; Abera *et al*., 2017). Most of the rain water is lost from the soil through surface evaporation and surface runoff. The areas experiencing insufficient and unreliable rainfall suffer from frequent drought and poor crop yield. Population density, climate change and land degradation exacerbate the problem of water availability in the region (AGRA, 2014).

Studies in dry highlands of the region have shown that the rain water harvesting (RWH) are adopted by some farmers for providing supplemental irrigation (SI) for green pod pepper production in the rainy season and are found to be economically viable (ICARDA, 2016). In the region, the use of the RWH in the form of dug out tank and trapezoidal reservoir in moisture stress area is an age-old practice. But its design is based on thumb rule. Some percentage of watershed runoff is used for determining the volume of stored water in the tank. These estimates typically tend to be conservative, resulting improper sizing.

A water balance model is used to optimize the size of a storage reservoir for supplemental irrigation. A previous study in this field by Carty and Cunnane (1990) revealed that the model gives lowest bias and standard error of results and therefore are most accurate. The data requirements for this method are flow, evaporation, precipitation, other loss and demand. The outputs are the capacity and reliability.

Several investigators have performed optimization and/or economic analysis of RWH. Chiu *et al*. (2009) conducted a cost benefit analysis of water and pumping energy costs for RWH in a hilly portion of Taiwan and found that the optimal storage tank size per residence ranged from 5 to 10 m^3. Monzur *et al*. (2011) used a daily water balance model to optimize tank size for large roof catchments in Melbourne, Australia and he evaluated different climatic conditions and water rates and subsequent predicted effects on investment payback, which was found to range from 15 to 21 years. In another study in Barcelona (Domènech and Saurí, 2010) found that RWH could meet many domestic indoor and outdoor demand needs, but often had extremely long payback periods due to high capital outlays. Mohamed *et al*. (2015) also held to optimize reservoir size in Sudan, the required optimum cultivated area to safely cultivate is about 2000 ha, and the required reservoir volume is about 29.23 Mm^3 per ha of field area. These optimal values of reservoir capacity, minimum silt load and maximum age occurs at maximum demand rate of a crop mix of 25% sorghum, and 75% sesame.

Response of supplemental irrigation (SI) to the crop yield under the rain fed farming system is highly site specific, depending on the climate, soil, and availability of water. It is essential to use simulation model of water balance for the whole system; catchment, storage and command areas to determine the optimal RWH size to ensure availability of irrigation. Since excessively large RWHs are wastage of precious land resources with high cost of construction and lower chance of being filled up to its full capacity and the RWHs that are too small cannot meet the SI demands, so proper sizing is crucial.

The objective of this paper is therefore to develop the optimal RWH size and reliability of the system for supplemental irrigation to a rain fed green pod pepper in dry highlands of Ethiopia using water balance principles along with an economic analysis.

2. Methodology

2.1. Site description

The Gumara-Maksegnit watershed research site, named after the district Maksegnit and river Gumara, lies in the Lake Tana basin of the North West Amhara region of Ethiopia. The 53.7 km² watershed drains into the Gumara-Maksegnit River, which ultimately reaches Lake Tana. The watershed is located at about 45 km southwest of Gondar town on the way to Belesa district; it is located between 12° 24’ and 12° 31’ north and between 37° 33’ and 37° 37’ east. The altitude of the study area ranges from1933m to 2852m above sea level. The area has a temperature ranging from 11 to 32 ºC and the average annual rainfall from 500 mm to 733 mm. More than 85% of rainfall occurred in the months of mid-June, July and August. Average annual rainfall varies over quite short distances due to a variety of local factors, such as nearby topography which is steep and mountainous. The average land holding of the farmers in the watershed is 0.2 ha. The dominant soil type of the experimental area is clay loam. Soil depth is apparently related to soil type and varies from 10 - 57 cm. Average measured values of volumetric moisture content of the soil (average of 30 cm depth) at permanent wilting point, field capacity, and saturation are 23.2, 39.2, and 16%, respectively.

2.2. Model Formulation

Parameters required for the determination of the optimum size of the RWH are: runoff production of catchment, irrigation requirement for cropped field; water balance model of the RWH; yield response to soil water and economic analysis.

Meteorological data collection methods: The rainfall data were recorded in the watershed at five minute intervals with an automatic tipping bucket rain gauge. From continuous readings of the automatic rain gauge, rainfall characteristics like amount, intensity, and duration were determined. Average annual rainfall data were used for modeling purposes.

Evaporation data were recorded using galvanized barrel (local pan device) from July 4 to October 27 and then calibrated using Koga Class A metrological station. The pan evaporation data then converted to reference evapotranspiration by multiplying its multiple factor (0.7). The reference evapotranspiration value of the water shed for the study period (June to October) found in the range of 1.41 to 4.35 mm/day.

2.3. Hydrological and sediment data collection methods:

Concrete weirs at the inlet of RWH were constructed for runoff stage recorded by Gondar Agricultural Research Center in 2013. The depth of the runoff stage was taken manually for both weirs. One-liter samples for sediment measurement were taken every 10 and 20 minutes from the inlet and outlet of the silt trap, respectively. Velocity and runoff depths were measured at the weirs of the two contributing areas to determine the total runoff and to estimate the suspended sediment carried by the flow at that specific time interval. The amount of sediment load within the sample was determined by oven drying the sediment obtained from the one liter sample and then weighing the oven dried soil.

An analysis of the rainfall-runoff relationship and subsequently an assessment of relevant runoff coefficients were based on actual, simultaneous measurements of both rainfall and runoff in the study area. The runoff coefficient from an individual rainstorm is defined as runoff divided by the corresponding rainfall both expressed as a depth over the catchment area (mm).

Prediction of Length of growing period: The growing period defines the period of the year when both moisture and temperature conditions are suitable for crop production. The estimation of growing period is based on a water balance model which compares rainfall (P) with potential Evapo-Transpiration (PET). If the growing period is not limited by temperature, the ratio of P/PET determines the start, end and type of growing period. Soil moisture storage must therefore be considered in defining the length of the growing period. As a result the beginning of humid period occurs at the third decade of June and ends on the first decade of September. So, pepper was transplanted on the third week of June.

2.4. Irrigation practice and irrigation requirements for green pod hot pepper

production: Rainfall was not adequate on the reproductive stage of hot pepper in the study area to increase crop productivity. The required amount was applied to irrigate pepper during the reproductive stage with seven days intervals. Other stages of pepper were kept rain fed without supplemental Irrigation. Field experiments were undertaken by Gondar Agriculture Research Center side by side with hot pepper under rain fed; 33.3%, 66.67% and 100% (0, 62,123 & 185mm depth) crop water requirement conditions in the study area.

2.5. Water balance model of the RWH

Proper sizing of the RWH must be designed by considering all inflows and outflows to and from the RWH. The inflows are the direct rainfall in RWH and surface runoff coming from the field to it. The outflows are evaporation, seepage and percolation and supplemental irrigation given to the crop(s) from the RWH.

Considering all inflow and outflow to and from the RWH, the generalized water balance model for RWH is given as

$$\boldsymbol{St-1\ +\ Qt - Rt\ - Ds - Lt = St - - - - - - - - - - - - - - - - - 1}$$

Where; St-1 is storage at end of previous time interval (m^3)

S_t is storage at end of current time interval (m^3) Q_t is inflows at current time interval (m^3)

R_t is release at current time interval (m^3) D_s is volume of dead storage (m^3)

L_t is loss (evap/seepage) at current time interval (m^3)

Reservoirs have a fixed storage capacity, K (m^3), so

$$\boldsymbol{St\ \leq\ K\,for\ each\ interval - - - - - - - - - - - - - - - - - - 2}$$

The simulation was continued for only four years (from 2012 to 2014) recorded data. Based on four year recorded data, rainfall is effective up to end of August. Storing water during excess time and release later was a crucial task for hot pepper production in the dry highlands of the region.

For present simulation study, most common farm area of 2000 m^2 was considered. In order to determine the optimum size of the RWH, an initial 4% of the land was assumed and a daily soil water balance of cropped fields and the RWH water balance were computed during simulation period. To satisfy required demand the RWH size increase by 33%. The simulation was terminated once the proper size was attained. An excel program version 2010 was used to compute the size of the RWH.

Evaporation loss of water depends on the water spread area that is the top surface area of water in the RWH at any given storage depth. Water spread area in the RWH changes daily depending on the storage depth in it. For any storage depth in the RWH, the water-spread area can be computed by known dimensions.

Seepage and percolation data were determined from the water level of the pond using graduate staff gauge installed at the middle of the pond on daily basis.

2.6. Economic analysis

The linear Programming technique has been presented here to optimize the size of water harvesting structures for supplemental irrigation depending on runoff volume using Excel (Ahmed *et al*., 2007). The objective function is to maximize the total return by considering the benefit per unit mass of yield per unit of irrigable area, losses from not-cropped (constructed) area under rain fed conditions, and RWH cost per unit volume. The total cost of a RWH includes its construction, lining cost and cost of inlet and spillway structure,

$$\boldsymbol{Bny = Y.Ry.Ar - Cc.All - Cr.Vw - Voc - - - - - - - - - - - - - - - 3}$$

Where:

B_{ny} = Net yearly benefit in Ethiopian Birr (ETB),

Y= Yield per unit area (kg/m^2),

R_y= Return per unit mass of yield,(ETB)

A_r= irrigated area (m^2)

C_c = Cost per unit constructed area, reflects yearly loss of rain fed production per unit area of structure (ETB)

A_{ll} = land area lost due to construction (m^2),

C_r = Cost per unit volume of reservoir, includes its construction, lining cost and cost of inlet and spillway structure (ETB).

V_w = Volume of RWH (m^3)

Voc = other variable cost (ETB) (seed, fertilizer, diesel, labor and maintenance)

This function was subject to a number of constraints that must be considered. The first constraint was a mass balance equation, for variable intervals (Mohammed *et al*. 2015). Mass Balance Equation of Reservoirs as stated in equation 1&2.

Constraint regarding the limitation on the total area of land is also added to the set of constraints of the equation. The land area constraint is in the following form:

$$At = Al + Ai \quad (4)$$

Where;

A_l = land area lost due to construction (m^2), A_i = Irrigated area (m^2), and

A_t= total area (m^2) considered in the problem, given as a limited value.

In the economic analysis, the different costs involved for the RWH irrigation system and returns were considered as: initial investment; maintenance cost; land lease cost; irrigation cost; production cost of Pepper and annual returns from irrigation. The benefit obtained from SI was evaluated against the investment and operational costs for developing the RWH irrigation system. All the costs and returns were worked out with Maksegnite district cooperative office report of 2014.

Initial investment cost for RWH supplemental irrigation system considered were: construction cost of RWH and silt trap, PVC, lining material. The selected experimental RWH structure has 3 m depth trapezoidal structure; 8*8 top dimension, 5*5 bottom dimension with side slope of 1:1. The RWH maintenance of annual desilting was assumed constant at the rate of 2% of initial investment of RWH (Palmer *et al*., 1982). The existing land rate tax in North West Ethiopia was 240 ETB $ha^{-1}year^{-1}$ for rained farming system. Supplemental irrigation was provided to crops by diesel pump-set. The existing hired rate of the aforesaid pumping unit was 604 ETB/ha for providing the intended demand. The economic life of lined RWH was assumed as 15 year.

3. Result and Discussion

3.1. Model application result

As shown in Table 1 the evaporation and seepage loss of experimental RWH shares of 21% to 31 % of the total harvested water. This leads to reduction of reliability or land shrinkage by 21% to 31%. Reducing the loss by possible mechanisms is vital for the expansion of irrigated land or minimizing the initial investment cost. This was in line with Eyasu *et al*. (2006) who indicated that protecting the net harvested water from evaporation and seepage loss can increase the irrigated area or reduce the loss.

The System efficiency of experimental RWH were poor because of the total runoff that could be harvested from the catchment was very large compared to the water consumed for irrigation. This goes in in line with Begashaw (2005) and Eyasu *et al*. (2006) reports. Therefore, the excess runoff coming from the catchment needs to be diverted away from the storage to protect reservoir damage or pass to the next reservoir for further storage.

The blanket recommendation of RWH size was 129 m^3 for all over the region while the seasonal water deficit of the green pod hot pepper was in the range of 62 to 185 mm (171 to 399 m^3), which must be compensated from some other sources. This implies the blanket recommended RWH size was not sufficient to satisfy the demands of the crop. These findings were in line with Feyisa (2013) and Hugo Rämi (2003).

The simulation model was run for different degree of water availability to crop by supplementing the rainwater to different levels varying from only rain fed to 100% crop water requirement. As the level of water availability to the crop is increased, the land lost (storage structure) area increases while the cropped area decreases. As the RWH size increase from 4% to 11.2% of the land, the availability of irrigation water increase from 62 mm to 185 mm.

The result also showed that as the availability of irrigation water increases incrementally from 62 mm to 123 mm, the average percentage increase of green pod hot pepper yield over rain fed condition is found to be high. With further increases of the availability beyond 123 mm, the rate of increase of yield is small. The result was in line with Panigrahi *et al*. (2005); optimal demeaned was optioned at maximum net benefit.

From the experimental result, the most important factors that determine the required harvesting area, command area and reservoir size are the unit cost of command area, land lost due to construction and unit cost of reservoir volume. For the maximum demand rate (185 mm), the optimal ratio of harvesting area to planting area was about 2.5. The required reservoir volume was about 399 m^3 per 0.2 hectare with 100% reliability. The demand rate was gradually decreased to about 62 mm to study its effect on harvesting area, cropping area and reservoir volume. The optimal ratio of harvesting area to planting area was 2 and the required reservoir volume was about 171 m^3 with 33.3 % reliability. This finding was in line with Dipankar Roy *et al*. (2008), who indicated that the RWH sizes were dependent on the irrigation management practices.

As shown in Table 1 & 2, the maximum benefit was obtained from the demand rate of 123 mm. Moreover, the optimal RWH size found to be 273 m^3 with 67 % reliability at 2.5 harvesting area to planting area ratio. Based on this result, suitable RWH dimensions of 3 m depth with trapezoidal structure; 13m *13m top dimension, 10*10 bottom dimensions with side slope of 1:1 was suitable. Generally, if the reservoir is designed at a lower probability level of assured rainfall and runoff, it will have a larger capacity and lower chance of being filled up to its full capacity. On the other hand, a reservoir designed on a higher probability level of assured rainfall will have a lower storage capacity but chances of being filled to full capacity will be greater and thus the expected cost of reservoir will be higher.

Table 1. Daily Water balance simulation for optimal RWH size

Date	Evapo-Transpiration from pond m^3	Irrigation demand m^3	Direct rainfall to pond m^3	Runoff to pond m^3	Final storage m^3	Initial storage m^3
6/30/2014	0.15	0.00	0.32	1.74	2.03	1.79
7/1/2014	0.20	0.00	0.14	8.50	1.79	10.22
7/2/2014	0.23	0.00	0.25	2.95	10.22	13.19
7/3/2014	0.21	0.00	0.14	1.65	13.19	14.76
7/4/2014	0.21	0.00	0.22	2.60	14.76	17.37
7/5/2014	0.17	0.00	0.43	24.58	17.37	42.20
.	.	.	.	.	.	.
.	.	.	.	.	.	.
8/1/2014	0.18	0.00	0.36	2.31	273.00	275.50
8/2/2014	0.16	0.00	1.25	4.53	273.00	278.63
8/3/2014	0.11	0.00	1.00	5.17	273.00	279.05
8/4/2014	0.12	0.00	0.45	4.99	273.00	278.31
8/5/2014	0.14	0.00	1.15	5.11	273.00	279.13
8/6/2014	0.12	0.00	0.82	13.45	273.00	287.15
9/20/2014	0.24	0.00	0.00	0.00	272.79	272.54
9/21/2014	0.26	20.00	0.00	0.00	272.54	252.29
9/28/2014	0.25	66.00	0.00	0.00	251.11	184.87
10/5/2014	0.26	80.00	0.00	0.00	183.39	103.13
10/12/2014	0.19	80.00	0.00	0.00	101.61	21.42
10/17/2014	0.24	0.00	0.00	0.00	20.41	20.16
10/18/2014	0.25	0.00	0.00	0.00	20.16	19.91

Partial budget analysis was done for the actual RWH irrigation system considering all variables as stated in equation 3. The payback was estimated about 15 years with 10% discount rate. So by using straight line depreciation method, the cost of pond construction was calculated for one year. As shown in Table 2, the maximum net

benefit of 13917.90 ETB was found with 123mm SI and 273 m^3 RWH. Moreover, 123 mm and185 mm of crop water requirement for supplementary irrigation gives 124 and 102

MRR over rain fed cropping system, respectively. Thus, the study reveals that the RWH irrigation system will be economically viable in the study area.

Table 1. Partial budget analysis of RWH system

CWR	Rain fed	1/3 CWR (62 mm)	2/3 CWR (123 mm)	Full CWR (185 mm)
Cultivated land size (m^2)	2000	1919	1879	1775
Actual pond size (m^3)	0	171	273	399
Mean yield (kg/m^2)	1539.80	1751.47	2189.60	2198.35
Total Revenue (10 ETB/kg) (Ethiopian birr)	15398.00	17514.71	21895.99	21983.50
Total costs (ETB/total area)	2500.00	2398.75	2348.75	2218.75
Gross field benefit (ETB/total area)	12898.00	15115.96	19547.24	19764.75
Present value investment cost with 10% discount rate and 15 year payback period		3541.81	4609.25	5885.21
Total costs that vary (ETB/total area)				
Fertilizer				
Urea	140.00	134.33	131.53	124.25
DAP	90.00	86.36	84.56	79.88
Pump rent (ETB)	0.00	436.00	504.00	604.00
Water application labor (ETB)	0.00	240.00	240.00	240.00
Land lease rate(ETB)	60.00	60.00	60.00	60.00
	290.00	956.69	1020.09	1108.13
Total	290.00	4498.49	5629.34	6993.34
Net benefit (ETB/total area)	12608.00	10617.47	13917.90	12771.41
Marginal cost (ETB/total area)		4208.49	5339.34	6703.34
Marginal net benefit (ETB/total area)		2217.96	6649.24	6866.75
Marginal Rate of Return (MRR) (%)		52.70	124.53	102.44
Reliability	0.00	0.36	0.68	1.00

4. CONCLUSIONS

A water balance model for determining the optimum RWH size for supplemental irrigation under rain fed farming conditions based on linear programming was presented. The volume of water stored in the reservoir depends on the available runoff water, sediment load, evaporation losses and the water demand for each interval during the growing season. By implementing the proposed model, under normal rainfall year, using important input parameters and types of crops grown in the district, the results showed that the required optimum reservoir size is 273 m^3. The average MRR, reliability & payback period of the optimal RWH is found to be 124.5%, 67% & 15 year respectively, for the average land size of 0.2 hectare. However, for wet years cultivated area increase or the reservoir capacity drops to 171 m^3 with 52.7% and 36% MRR, reliability respectively. In contrast, for dry years the cultivated area is decreasing or the reservoir capacity rises to 399 m^3 with 102.44 & 100 MRR and reliability respectively.

The study reveals that the RWH irrigation system is economically viable in the study area.

Moreover, the water balance procedure is relatively easy to apply and can be used as a decision support tool for effective management and utilization of water resources and optimal storage size design. The simulation test and analysis described in this study was based upon the main assumption of flow and demand will repeat them in the future. Further research is required to investigate long-term historic flow and water consumption of irrigation in the water deficit areas of Ethiopia. On the basis of new data, the calculation storage capacity and reliability then could be examined and modified.

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