Evaluation of Rain Water Harvesting Systems for coping water shortage in the Upper Blue Nile Basin, North West Ethiopia

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Abstract

The applicability and functionality of rainwater harvesting structure is very poor in the North West Ethiopia despite the government had engage in a massive expansion of on-farm RWH structures for improving agricultural productivity. Therefore, this research was initiated to evaluate the performance of a rainwater harvesting structure and put possible strategies for dry season challenges. This study was carried out for three successive years in North West Ethiopia. A total of 117 water harvesting structures were observed and characterized, of which 10 were selected as experimental sites. The data were analyzed using the daily water balance model and other performance indicators (number of water days, relative irrigation supply, runoff storage efficiency and marginal rate of return). At the inception, it was established that the existing rainwater harvesting system performs very low, with runoff storage efficiency below 46%, no zero water day above 50%, relative irrigation supply below 27 % and marginal rate of return from 12 to 65%. However, the greater the volume of the rainwater harvesting structure the higher runoff storage efficiency, higher relative irrigation supply, and lower no water day under different irrigation technique was achieved. For attaining household irrigation water demand in the dry season, the user should adopt a storage capacity of 630 m3 in Nitisols and 361 m3 in Vertisols for double cropping and 273 m3 in Rigosol for supplemental irrigation. Hence, applying rainwater harvesting technologies with efficient water management techniques enhances the net benefit of the system.

Keywords: Pond, optimization, performance efficiency, water scarcity and water shortage

Introduction

In Ethiopia, drought occurs once every three or four years due to various reasons (Fentaw 2011) and the drought occurred between 1965 and 2008 and affected about 54 million people (EM-DAT 2010). These extreme events result in economic losses and negative impacts on ecosystems and human health (Mulatu, et al. 2016). Moreover, 40 % of the population lives below the national poverty line (Yesuf Abdella et al. 2020). Rainwater harvesting (RWH) has been practiced and promoted to address the temporal and spatial variability of rainfall. Between 2003 and 2005, the government has been engaging in a massive expansion of on-farm RWH structures and constructed about 952,120 ponds and cultivated about 20,000 ha of land (Daniel 2007). However, the average adoption rate of water harvesting technology is as high as to 22¬ - 42% at the regional as well as at the national level (Begashawe 2005; Mekonnen et al. 2012). The major factors are funding, material availability, high water loss to seepage and evaporation and limited technical design capacity and irrigation calendar skills (Begashawe 2005; Mekonnen et al. 2012; Teka K 2018).

The rainwater harvesting system incorporated technical components to ensure good harvested water quantity and a water-level monitoring system. Performance assessment parameters no water days (NWDs), rainwater storage efficiency (RSE), relative irrigation supply (RIS), marginal rate of return (MRR) and water level in storage pond (WL) were defined and used. However, the system was inadequate because water users suffered for several days without water during the dry season. In an attempt to minimize NWDs and increase RIS and RSE using the existing system, a socio-technical strategy with variable

in some demand scenarios, demand still poses a challenge for this technology and daily water demand is hard to meet. Therefore, this research initiated to evaluate the performance of rainwater harvesting system and put possible strategies in the study area.

Materials and methods

Description of the Study area

The study was conducted in the upper Blue Nile basin, Northwest Ethiopia (Figure 1). The rainfall pattern is a unimodal regime, while the rainy season runs from April to October in the South West and June to September in the North East (Bekele, 1997). The mean annual rainfall is estimated between 800 to 1600 mm, with 74 % in the four wet months of June to September (Figure 2). The farming practice of the Nile gorge in north east side mostly used the early sate variety and the plain was medium to late sate variety, mainly Wheat, Maize and Tef. The topography is very complex, with elevations ranging from 500 m in the lowlands at the Sudan border to 4160 m in the upper parts of the basin. The basin has five major soil groups, Nitisolss, Leptosols, Luvisols, Vertisolss, cambisols, Alisols, Phaeozems, Regosols and Fluvisols (Teklu Erkossa, 2009).

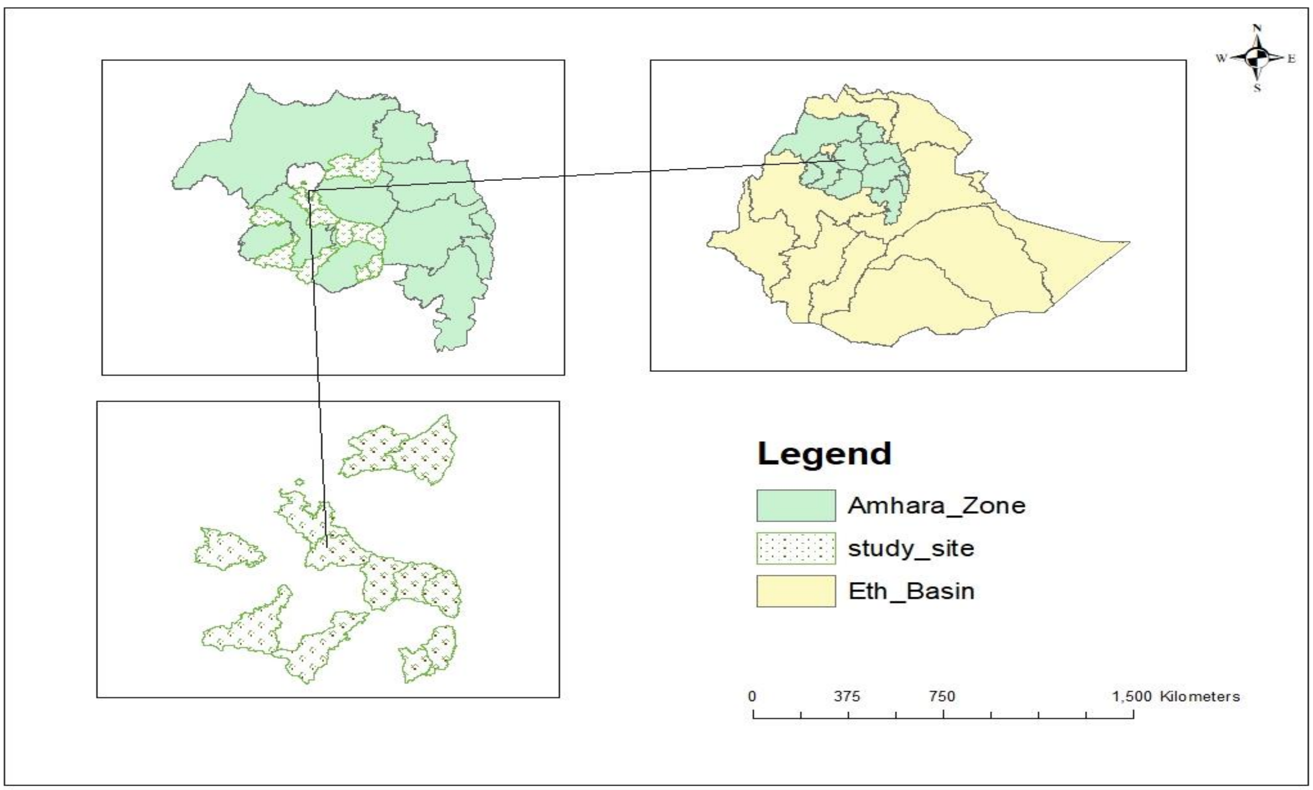


Figure 1. Location map of the study area

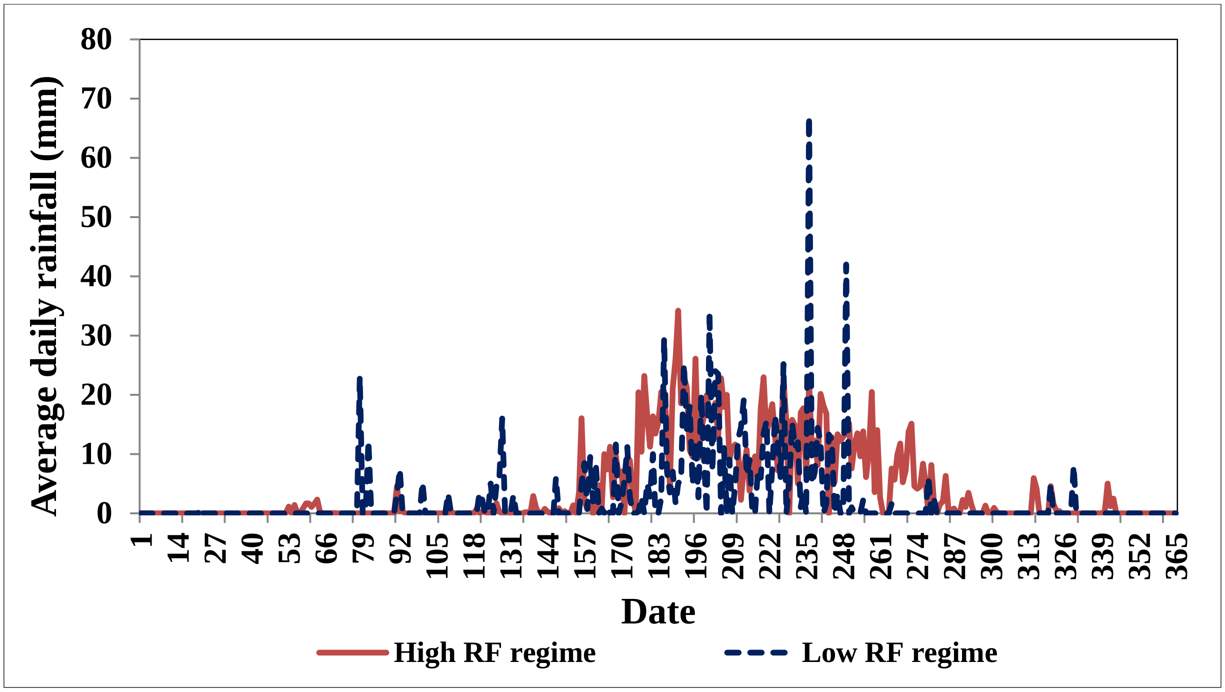


Figure 2. Rainfall pattern of the study area

Data collection

Primary and secondary data were collected from different districts through questionnaires, group discussions, and field observation. Besides the functionality of the structure was categorized based on the fulfillment of pre-defined purposes, having near-optimal functionality, maintaining acceptable safety, economically justifiable and meeting environmental, legal, social, and other relevant requirements Table 1.

Twelve weredas were purposively chosen (Figure 1) from the North West Amhara Regional States. The selection process was in consultation with zonal experts. Accordingly, a total of twelve peasant kebeles were chosen from the sample weredas in consultation with wereda experts. The selection of RWH Users was undertaken through a systematic sampling technique. Moreover, the selection of 10 experimental rainwater harvesting structures was done based on rainfall pattern, soil types, road accesses and functionality of the structure. Measurements of daily water input and output (abstraction, rainfall, runoff, evaporation and seepage) from the storage were measures following international standards.

Table 9. Status of rainwater harvesting systems (RWHS)

Types of the pond	Number of structure	Fulfillment of intended purpose	Functionality (%)	Non-functional (%)	economical justifiable	maintain ELS status		
						Environment	Legal	social
Trapezoidal /plastic lined/	19	No to little	47.4	52.6	No	moderate	moderate	No
Trapezoidal /unlined/	89	No to little	7.9	92.1	No	moderate	moderate	No
Circular /cemented	9	No	0	100	No	moderate	moderate	No
Total	117(10*)							

Note * is an experimental water harvesting structure

Data type and source

The basic parameters adopted for performance evaluation of the RWH system included a storage volume of 129 m3, irrigable land of 200 m2, and average landholding size of 2000 m2and catchment area less than200 m2 (mixed land use type), a runoff coefficient of 0.56. ETo, water level and irrigation demand data were used as shown in Figures 3 and 4.

Irrigation demand is estimated using the CROPWAT 8.0 model. All calculation procedures used in CROPWAT 8.0 are based on FAO No. 56 and No. 33. Then the generated crop water and irrigation requirements values under furrow irrigation are shown in Figure 5 and Table 2. At the inception full irrigation was given for all treatments to create a favorable environment for crop root distribution and emergencies.

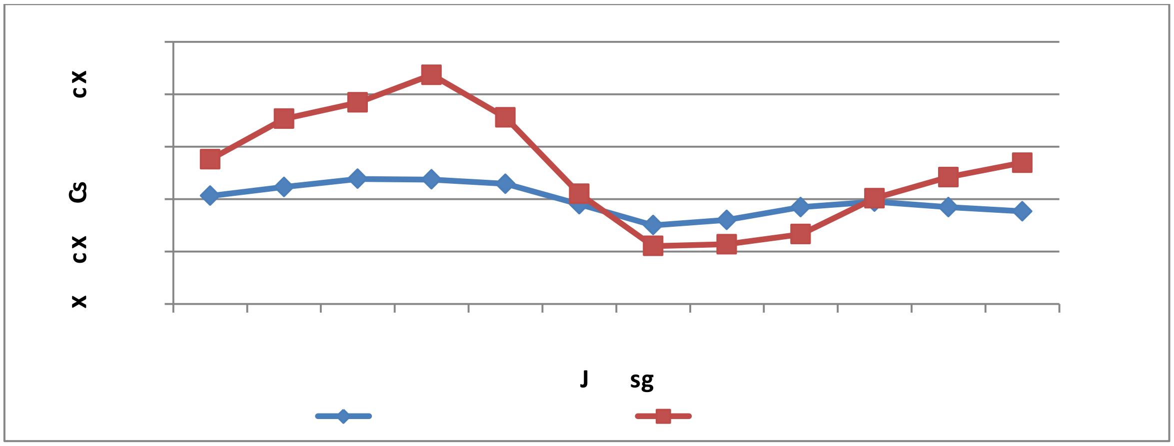
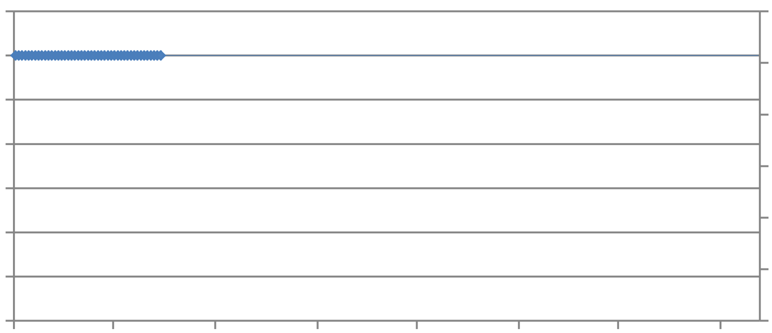


Figure 3. Reference evapotranspiration pattern of the study area

a) High rainfall regime



b) Low rainfall regime

Figure 4. Rain water harvesting structure Water level and irrigation demand of the study area

irrigation merit. Regulated deficit irrigation strategies reduced actual crop evapotranspiration by 2 27% (Yang et al. 2018) and alternate furrow irrigation methods saved 33 to 50% of water as compared with every furrow irrigation (Eba AT2018). Besides, the treatment setup considers the allowable depletion level of the hot pepper, 30 %. This approach is a better strategy for water stress areas.

Table 10. Irrigation water requirement for different irrigation method

Irrigation depth	Nitisols (mm)	Vertisols (mm)	Rigosols (mm)
Full irrigation (conventional furrow)	582	362	285
80 % ETc (Regulated deficit irrigation)	500	304	228
60 % Etc (Alternative furrow irrigation)	418	246	171

The performance of a system is usually measured using its efficiencies, operational methods, and construction cost. It was carried out for both the existing system and the consideration of additional systems in the community.

Table 11. RWHs investment cost

a) high rainfall pattern

	Catchment size (m^2)	Irrigable land (m^2)	Rainwater harvesting structure size (m^3)	Construction cost (Ethiopian Birr)	Remark
Plastic lined (Nitisols)	<300	125	129	35966	Existing case
Unlined (Vertisols)	<300	150	129	19791	Existing case
Plastic lined (40% deficit Niti/Vertisols)	>1000	1550/1676	669/367	167250/91750	Proposed case
Plastic lined (20% deficit Niti/Vertisols)	>1500	1507/1639	800/453	200000/113250	Proposed case
Plastic lined (Full irrigation Niti/Vertisols)	>2000	1471/1600	931/540	232750/135000	Proposed case

b) Low rainfall pattern

	Catchment size(m^2)	Irrigable land (m^2)	Rainwater harvesting structure size(m^3)	Construction cost (Ethiopian Birr)	Remark
Plastic lined	>1000	200	129	35966	Existing case
unlined	>1000	200	129	19791	Existing case
Plastic lined (40% deficit)	<1500	1804	171	42750	Proposed case
Plastic lined (20% deficit)	1500-2000	1744	273	68250	Proposed case
Plastic lined (Full irrigation)	>2000	1676	399	99750	Proposed case

Results and Discussion

Performance evaluation of the existing RWH system

The existing system showed poor performance in both parameters under any of the scenarios (Figure 5). The runoff storage efficiency in Vertisols was as high as 0.46 percent and the plastic-lined rainwater harvesting structure performs above 0.70 while expecting an approach to one. The major reasons for the low storage performance of Vertisols are evaporation and seepage loss. It shares 6.5% evaporation and 40% seepage from the total harvested water. Consequently, reduce irrigable land by 33.4 %. The finding is in close agreement with Amare et al. (2018) and Eyasu et al. (2006) who reported protecting the net harvested water from evaporation and seepage loss had a great contribution to irrigating more land. Besides, the relative irrigation supply gives 16 to 27% while expecting 70 to 100 % (Mwamila et al. 2015). No water day contains 40 to 80% while expecting an approach to zero (Mwamila et al. 2015). This implies the planning was poor and needs a revisit. The result concedes with the finding of MoARD (2000), Begashawe (2005), Mekonnen et al. (2012), and Teka K (2018), who reported diversity and economics is not well taken into account when a program is designed

Performance evaluation of extending rainwater-harvesting technology

To promote and uphold the efficiency and effectiveness of a system, graphical extrapolation was done until the relative irrigation supply approach to one and no water day approach to zero as shown in (Figure 6). The graph serves as a menu to design the program considering diversity, economics and operation scenario. When an attempt was made to reduce NWD and increase RIS, 42,68 and 100 % RIS with uniform zero water day for Alternative furrow irrigation, regulated deficit irrigation and full irrigation were achieved respectively. The implementation cost is 4.6 to 6.8 times that of the existing system. The finding is in line with Mwamila (2016), the implementation cost increase more than four times as RIS goes to one and NWD to zero.

Plastic-lined Vertisols shows higher RIS and low initial investment cost than plastic-lined Nitisols. This is due to the water holding capacity of irrigable land. Tesfaye et al. (2018) reported similarly, the irrigation requirement for pepper in Vertisols is much less than in Nitisols.

Performance indicatro (ratio)

reservoir size, relative irrigation supply, marginal rate of return and irrigable area were determined using the water balance principle under normal rainfall years (Table 4).

Table 12.Optimization values

irrigation type	soil type	Rainwater harvesting structure size(m3)	Relative irrigation supply (%)	MRR(%)	Irrigable area(m2)
Double cropping	Nitisols	630	75	127.4	1500
	Vertisols	361	80	230.7	1600
	any	129	18	12	250
Supplemental irrigation	Regosols	273	67.7	124	1744
	any	129	27	65	1530

Despite the optimal value, the construction cost per irrigated land was extremely high; it was as high as 541500 to 1177500 Birr ha^{-1} for planned irrigable land in the humid area. However, the cost/ha for river diversion and storage dams in the Amhara region and East Africa range was70,000 to 120,000 and 250,000 to 400,000 respectively (BOA, 2019; Inocencio A et al. 2007). Therefore, it was wise to give priority to alternative irrigation technologies based on the water resource available instead of constructing the same type of systems all over the region.

CONCLUSION

The applicability and functionality of the rainwater harvesting system in the Northwest Amhara region is very poor against the intended purpose of increasing crop production, and productivity and thereby improving the socio-economic standard of the society. The existing rainwater-harvesting system showed poor performance in both parameters under any of the scenarios. Increasing the volume of rainwater harvesting structure and applying deficit irrigation technique improves the performance parameters; relative irrigation supply and runoff storage efficiency to one and no water day to zero and reasonable marginal rate of return. Thus to mitigate water shortage the society should adopt a size of 630m^3(Nitisols) and361m^3 (Vertisols) for double cropping and 273 m^3 (Rigosol) for supplemental irrigation. Moreover, the study reveals that the rainwater harvesting system is economically viable in the study area. The simulation test and analysis described in this study are based upon the main assumption of flow and demand will repeat them in the future. The performance of the system can be improved by monitoring water levels and adhering to demand and supply guidelines.

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