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

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Research

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Abstract

Background

The applicability of rainwater harvesting structure is very poor while the intended purpose is achievable in the Blue Nile basin. Therefore, this research was initiated to evaluate the performance of a rainwater harvesting structure and put possible strategies for dry season challenges. The study carried out for three years in the North West Ethiopia.

Methods

The data were analyzed using daily water balance model and other performance indicators (number of water day, relative irrigation supply, runoff storage efficiency and marginal rate of return).

Results

At the inception, it was established that the existing rain water harvesting system performs very low, 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 rain water harvesting structure the higher runoff storage efficiency, higher relative irrigation supply, and lower no water day under different irrigation technique was achieved.

Conclusions

For attaining household irrigation water demand in the dry season, the user should adopt storage capacity of 630m³ in Nitisol and 361m³ in Vertisol for double cropping and 273 m³ in Rigosol for supplemental irrigation. Hence, applying rainwater harvesting technologies with efficient water management technique enhance the net benefit of the system.

Background

Most rural households in Ethiopia, especially in the Upper Blue Nile basin, depend on rain-fed agriculture for their livelihoods (Yesuf Abdella et al., 2020). The agricultural productivity in the region is constrained by climate change (Deressa and Hassan, 2009) and land degradation (Teka K et al., 2015). Climate change is already happening, with multi-faceted effects on human being and the ecosystem (Gomoro, 2014). The rainfall variability in the region is a high coefficient of variation (CV) ranges 20 to 40 (Mekonnen et al. 2012; Amare et al. 2018).

Access to water provides a basis for human livelihoods, culture, and progress (Smit and Wandel, 2006). Adams et al. (2009) and Smith et al. (2009) found that water stress undermines societies' place-specific livelihood systems and strategies that, in turn, induce new patterns of human migration (Black et al., 2011). Water scarcity can mean scarcity in availability due to physical shortage, or scarcity in access due to the failure of institutions to ensure a regular supply or due to a lack of adequate infrastructure (UN water 2018). As many of developing countries, the increasing population, improving living standards, unplanned migration, rising of temperature, and expansion of irrigated agriculture are the main driving forces for the rising of human demand for water (Ercin et al., 2014) This water scarcity result in declining subsistence agricultural production may accelerate migration patterns (Nawrotski and Bakhtsiyarava, 2017).

In Ethiopia, the drought occur once every three or four years due to various reasons (Fentaw 2011) and drought occurred between 1965 and 2008 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 living below the national poverty line (Yesuf Abdella et al. 2020). Besides the average adoption rate of water harvesting technology is as high as 22–42% in the regional as well as in the national level (Begashawe 2005; Mekonnen et al. 2012). The major factors

are funding, material availability, potential sites for disease, 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 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 increasing RIS and RSE using the existing system, a socio-technical strategy with variable demand application was introduced (Mwamila et al. 2015). Despite the strategy’s potential in some demand scenarios, demand still pose 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 conducted in the upper Blue Nile basin, Northwest Ethiopia. The rainfall pattern is 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 estimated between 800 to1600 mm, with 74% in the four wet months of June to September (Figure 1). The topography is very complex, with elevation 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, Nitisols, Leptosols, Luvisols, vertisols, cambisols, Alisols, Phaeozems, Regosols and Fluvisols (TekluErkossa,2009).

Data collection

Primary and secondary data were collected from different district through questionnaires, group discussion, and field observation. Besides the functionality of the structure was categorized based on fulfillment of pre-defined purposes, having near-optimal functionality, maintaining acceptable safety, economically justifiable and met environmental, legal, social, and other relevant requirements Table 1. Moreover, the selection of experimental rainwater harvesting structure was done based on rainfall pattern, soil types, road accesses and functionality of the structure. Measurements of water input and output (abstraction, rainfall, runoff, evaporation and seepage) from the storage were measures following international standards.

Table 1. 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							

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, 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 from Figure 2 and 3.

Irrigation demand estimated using the CROPWAT 8.0 model. All calculation procedures used in CROPWAT 8.0 are based FAO No. 56 and No. 33. Then the generated crop water and irrigation requirements values under furrow irrigation shown in Figure 4 and Table 2. At the inception full irrigation was given for all treatments to create favorable environment of the crop root distribution and emergency.

Data analysis

The analysis was performed using a simple daily water mass balance model with an overall cumulative water storage Equation (1). This incorporates the performance parameters both for a dry spell and dry season quantification, NWD, RSE ,and RIS (Mwamila et al. 2015) (Equations (2)–(4)).

$$St = St - 1 + Qt - Rt - Ot \text{-----}$$

-----1

$$NWD = \left(\frac{T - \sum_{i=1}^T WD}{T} \right) \text{-----}$$

-----2

$$RSE = \frac{\text{Water input} - \text{Loss}}{\text{Water Input}} \text{-----}$$

-----3

$$RIS = \frac{\text{Irrigation supply}}{\text{Irrigation demanded}} \text{-----}$$

4

Where: St-1 is storage at end of previous time interval (m³), St is storage at end of current time interval (m³), Qt is inflows at a current time interval (m³), Rt is release at a current time interval (m³), and Ot is loss (evap/seepage) at current time interval (m³), NWD is number of water day, WD is the number of irrigation day on which the demand is fully met; T is the total number of irrigation days in the season, RSE: Runoff storage efficiency, and RIS Relative irrigation supply.

The analytical method considers variable daily demand scenarios for both rainfall pattern (Table 2). Variable demand, based on water resource reliability, apply using deficit irrigation technique is a novel approach devised by (Moshel and Mikael 1995). The treatment was set based on the previous findings of regulated deficit and alternative furrow irrigation merit. Regulated deficit irrigation strategies reduced actual crop evapotranspiration by 2–27% (HuiyingYang et al. 2018) and alternate furrow irrigation method saved 33 to 50% of water as compared with every furrow irrigation (Eba AT2018). Besides, the treatment setup considers the allowable depletion level of hot peeper, 30 %. This approach is a better strategy for water stress area.

The performance of a system 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 2.Irrigation water requirement for different irrigation method

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

Table 3.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(Niti sol)	<300	125	129	35966	Existing case
Unlined(Verti sol)	<300	150	129	19791	Existing case
Plastic lined (40% deficit Niti/verti sol)	>1000	1550/1676	669/367	167250/91750	Proposed case
Plastic lined (20% deficitNiti/verti sol)	>1500	1507/1639	800/453	200000/113250	Proposed case
Plastic lined (Full irrigation Niti/verti sol)	>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 scenario (Figure 4). Unlike the common sense runoff storage efficiency in vertisol was as high as 0.46 percent while plastic-lined rainwater harvesting structure performs well above 0.70. The major reasons for the low storage performance of vertisol 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 % . Reduce the loss by possible mechanisms is very important. 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 by shade and lining material save water for irrigation operation.

As shown in Figure 4. All performance indicator parameters perform poorly. Runoff storage efficiency for unlined vertisol is very low(45%) unlike the plastic lined pond(70-74%) and the common sense of vertisol water holding capacity. 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 approach to zero (Mwamila et al. 2015). This implies the planning was poor. The result concedes with the finding of MoARD (2000), Begashawe (2005), Mekonnen et al. (2012),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 relative irrigation supply approach to one and no water day approach to zero as shown in (Figure 5). 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 was 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 vertisol shows higher RIS and low initial investment cost than plastic-lined Nitisol. This is due to the water holding capacity of irrigable land. Tesfaye et al. (2018) reported similarly, irrigation requirement for pepper in vertisol is much less than nitisol.

Proposed strategies to mitigating water shortages for the dry season and dry spell

The simulation model runs for different degree of water availability to a given crop. The result showed that as the availability of irrigation water increases, the yield also increases while water resource availability increment above 75% (nitisol), 80 % (Vertisol) and 66.7 %(Rigosol) the rate of increment in yield was insignificant. Thus the optimum reservoir size, relative irrigation supply, marginal rate of return and irrigable area were determined using water balance principle under normal rainfall year (Table 4).

Table 4.Optimization values

irrigation type	soil type	Rainwater harvesting structure size(m3)	Relative irrigation supply (%)	MRR(%)	Irrigable area(m2)
Double cropping	Nitisol	630	75	127.4	1500
	Vertisol	361	80	230.7	1600
	any	129	18	12	250
Supplemental irrigation	Rigosol	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 planed irrigable land in the humid area. However, the cost/ha for river diversion and storage dams in 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 status and adoption rate of rainwater harvesting system in the upper Blue Nile basin is very poor against the intended purpose of increasing crop production, productivity and thereby improve 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 rain water harvesting structure and applying deficit irrigation technique improve 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 630m³(Nitisol) and 361m³(vertisol) for double cropping and 273 m³ (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 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.

Declarations

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Figures

Figure 1

Rainfall pattern of the study area

Figure 2

Reference evapotranspiration pattern of the study area

a) high rainfall regime

b) Low rainfall regime

Figure 3

rain water harvesting structure Water level and irrigation demand of the study area

Figure 4

Average performance efficiency on rainwater harvesting systems

Figure 5

Performance of proposed RWHS with cost implication