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ORIGINAL ARTICLE

Rainwater harvesting potential for farming system development in a hilly watershed of Bangladesh

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Abstract Water resources management is an important part in farming system development. Agriculture in Chittagong Hill Tracts of Bangladesh is predominantly rainfed with an average 2210 mm monsoonal rain, but rainfall during dry winter period (December–February) is inadequate for winter crop production. The natural soil water content (as low as 7 %) of hillslope and hilltop during the dry season is not suitable for shallow-rooted crop cultivation. A study was conducted to investigate the potential of monsoonal rainwater harvesting and its impact on local cropping system development. Irrigation facilities provided by the managed rainwater harvesting reservoir increased research site's cropping intensity from 155 to 300 %. Both gravity flow irrigation of valley land and low lift pumping to hillslope and hilltop from rainwater harvesting reservoir were much more economical compared to forced mode pumping of groundwater because of the installation and annual operating cost of groundwater pumping. To abstract 7548 m^3 of water, equivalent to the storage capacity of the studied reservoirs, from aquifer required 2174 kWh energy. The improved water supply system enabled triple cropping system for valley land and permanent horticultural intervention at hilltop and hillslope. The perennial vegetation in hilltop and hillslope would also conserve soil moisture. Water productivity and benefit–cost ratio analysis show that vegetables and fruit production were more profitable than rice cultivation under irrigation with harvested rainwater. Moreover, the reservoir showed potentiality of integrated farming in such adverse area by facilitating fish production. The study provides water resource managers and government officials working with similar problems with valuable information for formulation of plan, policy, and strategy.

Keywords Rainwater harvesting · Irrigation · Cropping intensity · Hilly area · Water productivity

Introduction

Bangladesh is mainly a delta plain except the Chittagong Hill Tracts (CHT) located in the south-eastern part of the country. The geographical feature of these hilly areas is considerably different from the plain land. This area is undulating, erosive and sloppy with distinctive and specific characteristics of water resources compared to the remaining part of the country. The total area of the CHT is about 13,184 km^2 (9 % area of the country) of which 92 % is highland, 2 % medium highland, 1 % medium lowland and 5 % homestead and water bodies (Ullah et al. 2011). Agriculture being the mainstay supplies food and raw material for rural industry and provides livelihoods, so the sector is the main vehicle for rural development and poverty alleviation in this hilly region. Shifting cultivation (keeping fallow after certain number of cultivations) is still the main cultivation system in this region due to little external input, small capital, very limited irrigation facility, unavailability of updated technologies, and affinity to

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9000-year-old primitive option. As a result, the inhabitants are facing food insecurity, declining fertility of land and shrinkage of shifting cultivation cycle. Besides, the shifting agriculture had led to soil loss, nutrient loss and indiscriminate destruction of forest for food production causing ecological degradation (Bala 2010). The CHT of Bangladesh therefore needs policies and programmes for environmentally compatible and economically viable agricultural systems to alleviate poverty and protect the natural environment (Rasul 2005). The valley lands of the mountain regions are similar to the plain lands of the country, so crop and water related technologies developed/adopted for the delta plain are also suitable for the valley lands.

Bangladesh is an agro-based country with about 63 % of her cultivable land under irrigation, but irrigated area in the CHT is only 33 % (BBS 2012). Bangladesh has the highest per capita fresh water available among South Asian countries, i.e. annually 795,000 m^3 of water through surface flow and about 2030 mm of rainfall (BMD 2000) at its disposal. However, it can hardly make proper use of the resources due to poor internal water management practices. The annual rainfall in Khagrachari is 3030 mm, which is much higher than many other areas of Bangladesh (District Statistics 2013). Excess water in the monsoon season and scarcity in the dry season create a situation of water insecurity in the area, thereby affecting water supply for domestic, crop production and fisheries. In the dry season, small water bodies, canal and creeks are the sources of irrigation for farming practices of small landholders in the CHT (District Statistics 2013). However, the sources are neither dependable nor capable of supplying enough water for full-scale dry winter crop production.

There is rainwater potential in the hilly areas to harvest for irrigation purposes because of its high annual average rainfall and availability of suitable landscape. In this type of condition, developing rainwater harvesting technologies for irrigation would be very useful for local agricultural production (Zhang et al. 2014). By constructing small water reservoirs in upstream hilly canyon, rainwater can be harvested to irrigate both hilltop and hillslope areas by pumping and the valley areas by gravity flow. Conversion of fallow land in the areas to irrigated-agriculture with the harvested rainwater will enhance local food security. Introduction of suitable crops with conservation management practices would sustain farm productivity, soil and water quality, and improve livelihood of poor farmers. Literature on the feasibility of rainwater harvesting in the CHT of Bangladesh is very limited. Rainwater harvesting is preferable because of the potentiality of increased production, early recovery cost, low construction cost, high benefit–cost ratio, and easy to use and maintenance (Domènech et al. 2012; Goel and Kumar 2005; Oweis and Hachum 2006; Sultana et al. 2005). Performances of rainwater harvesting systems in different studies were summarized by DeBusk et al. (2013). Rainwater harvesting is not a new technique to the indigenous people of different parts of the world (Mbilinyi et al. 2005; Charlesworth et al. 2014), but better management options are needed (Wallace and Bailey 2015). In the hilly areas of Bangladesh 52 indigenous methods for sustainable soil-water conservation, agro-forestry and increasing availability of potable water were recently identified. Indigenous rainwater harvesting techniques like jhurjhuri (1 m^2 dug well in a sedimentary rock), phour (7–8 m^2 pond), Thagalok-Kum (collection of water from hill with bamboo split and earthen pitcher for household), ghoda (earthen cross dam of small hill creek for navigation and multipurpose use) and thelya-thok (similar to ghoda but for larger area) are not suitable to meet the increasing water demand for food production (Ahmed et al. 2013). A study was thus conducted to investigate the potential of rainwater harvesting and its impact on local cropping system development. It was hypothesized that harvesting rainwater during monsoon and its proper use and management can develop a better farming system with increased crop production and cropping intensity.

Materials and methods

Site

The study was conducted at Hill Agricultural Research Station, Khagrachari (92°0′2″E and 23°8′12″N) (Fig. 1). The elevation of the site ranges from 56 to 85 m relative to mean sea level and the elevation difference between hill valley and hilltop is about 29 m. The monsoonal rainfall starts in May and ends in October, and 90 % (seasonal total 2210 mm) of total annual rainfall occurs during this time. The annual average temperature varies from maximum 34.6 °C to minimum 13 °C and humidity ranges from 62 to 78 %. The daily total sunshine hours range 4–8 h and the mean wind speed is about 190 km/day. High wind speed is generally observed in June–August and low wind speed in November–December. The geographical feature of the catchment is undulating terrain with slopes ranging from 1 to 10 %. The natural topographic feature facilitated construction of a cross dam between two hills. The top soil layer (0–150 mm) of the command area is sandy clay or sandy loam. The infiltration rate varies from 10 to 570 mm/day at different places of the catchment.

Rainwater harvesting system

The reservoir system at the study site consisted of a cross dam, spillway, gate valve, pump, storage tank, water

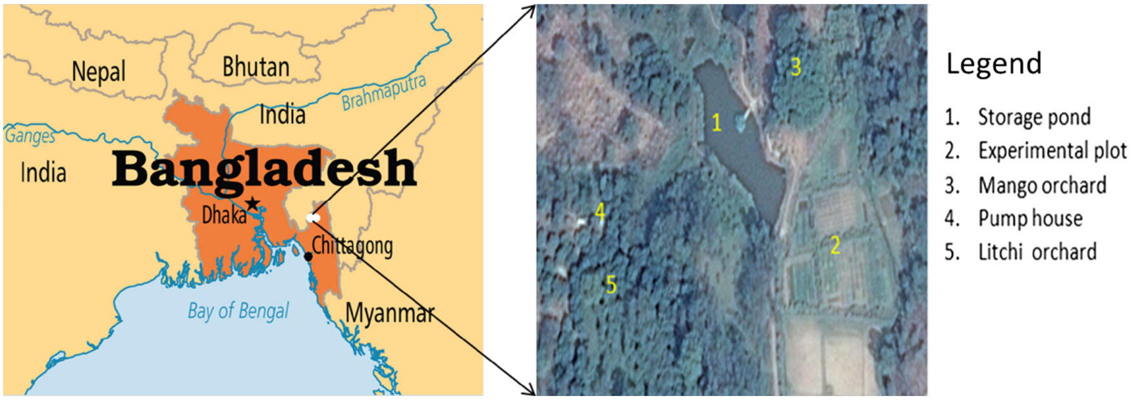

Fig. 1 Map of the study site (*source* http://www.operationworld.org/BANG)

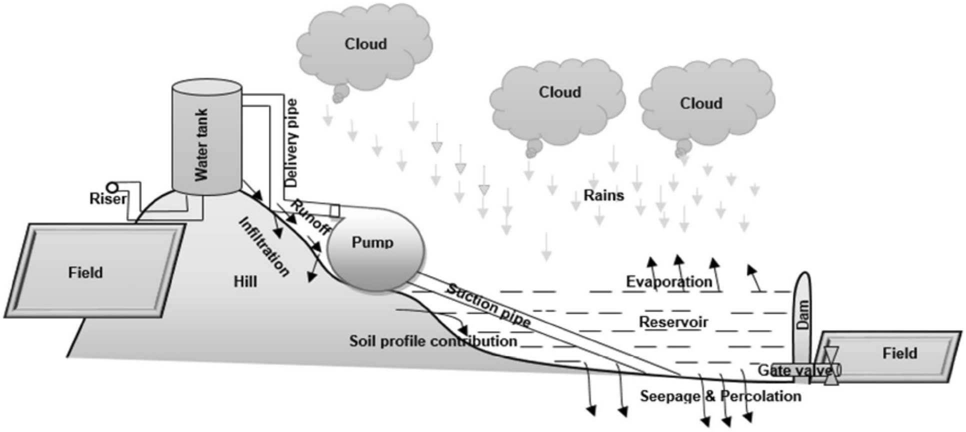

Fig. 2 Sectional sketch of the rainwater harvesting reservoir system studied (not to scale)

conveying channel, pipe networking and risers. A cross dam between two hills collects surface runoff during rainy season from June to November. Zhao et al. (2009) suggested that large gentle slope hills with slight modification are better rain collecting surface. The overland runoff part of rainfall was stored in the reservoir. The runoff water was not treated because it was enriched with wash load including silts and clay particles and suitable for irrigation. A simplified sketch of the rainwater harvesting reservoir system is shown in Fig. 2.

The following equation estimates the volume of surface runoff (SR) assuming a constant catchment area loss factor ‘*K*’ ($K = 0.50$, for the wooded land and forest areas with 10 % slope) and using measured precipitation ‘*P*’ (Garg 2008):

$$\mathrm{SR} = K \times P. \tag{1}$$

For the reservoir, successive areas A_1, A_2, A_3, …, A_n were calculated at a contour interval of Δh and the storage was then determined by the following relationship:

$$\text{Storage} = S = \frac{\Delta h}{3}\{(A_0 + A_n) + 2(A_2 + A_4 + \cdots) + 4(A_1 + A_3 + \cdots)\}. \tag{2}$$

A US Class A evaporation pan and an open cylinder installed at the studied reservoir were used to measure the evaporation, seepage and percolation (S&P) losses. The evaporation pan measured evaporation, and the open cylinder installed in the reservoir measured evaporation plus S&P losses. The difference of reading between open cylinder and evaporation pan gave the values of S&P loss. Considering all the losses a storage volume of reservoir to be available during dry season was designed so as to meet the crop water demand. The following relationship was used to calculate the volume of reservoir:

$$\begin{aligned}\text{Volume of reservoir} = {} & \text{command area} \\ & \times \text{ irrigation depth} \\ & \times \text{ loss factor,}\end{aligned} \tag{3}$$

where loss factor indicates the reservoir loss due to S&P and evaporation.

The designed rainwater harvesting reservoir had a storage capacity of 7548 m^3, catchment area of 8 ha, command area of 2 ha, and water area of 5445 m^2. The reservoir occupied 6.8 % of the total catchment. The reservoir was not lined because the S&P loss (3 mm/day) was low. Lining is recommended where S&P loss is more than 10 mm/day (Srivastava et al. 2004). As water was stored at upstream of the valley, the potential energy of reservoir water was enough to make gravity flow irrigation to the lower valley land. A gate valve was used to regulate water flow to the downstream channel, which involved no energy cost. However, a suction mode pump was used to deliver the reservoir water at hilltop and hillslope land.

Pumping features

In this work, two comparative studies were conducted with different pumps to implement irrigated hillslope and hilltop farming. The information of pump operation and installation cost, total lift, energy consumption, operating hour, specific discharge and overall efficiency were studied. The first study was between two suction mode low lift pumps to deliver water from the rainwater storage reservoir to hilltop land. The other comparative study was between (a) pumping water from the reservoir to hilltop using a suction mode low lift pump and (b) pumping water from the aquifer to hilltop using a low capacity force mode pump.

Electric horsepower supplied to the motor was considered as input hp and the water horsepower supplied by the pump as output hp to calculate the combined efficiency of pump and motor using the following equation (Michael 2010):

$$E = (\text{output hp/input hp}) \times 100. \tag{4}$$

In this study, discharge per unit energy consumption is termed as specific discharge for a pump, which indicates discharge energy consumption ratio (Samad 2009) expressed as m^3/kWh.

Cropping system

Cropping systems development in an area depends on many factors including suitability of soil, water and climate, specific food/feed demand and economical benefit of the producers. The valley land in the study area was suitable for irrigated farming, but the hilltop and hillslope were not. Under the studied watershed two primary cropping systems were evaluated (a) irrigated vegetables and grain crops based valley land farming and (b) irrigated horticultural crop based hillslope and hilltop farming. Mango (*Mangifera indica*), litchi *(Litchi sinensis)* and malta (*Citrus sinensis. CV BARI Malta-1*) were cultivated at hilltop/hillslope with no-till to prevent soil and nutrient loss and with mulching for soil moisture conservation. For sustaining crop production, a priority list of agronomic and horticultural crops were selected in this study based on the water productivity, yield and benefit–cost ratio. A wide range of crops including bottle gourd (*Lagenaria siceraria)*, sweet gourd *(Cucurbita maxima),* cabbage *(Brassica oleracea var. Capitata),* chilli *(Capsicum annuum),* country bean *(Lablab niger)*, cucumber *(Cucumis Sativus),* onion *(Allium cepa)*, rishak *(Brassica campestris)*, red amaranth *(Amaranthus gangeticus)*, tomato *(Lycopersicon esculentum)*, maize (*Zea mays*), and rice (*Oryza sativa*) were studied at the experimental field of valley under harvested rainwater irrigation. These crops were selected because these are the representative crops in the study area.

Water productivity

The seasonal water used (SWU) for each crop irrigated by buried pipe with riser irrigation system under the studied reservoir system was calculated from the information of average discharge rate (Q), total number of irrigation (N), time of each irrigation (T) and area of plot (A) using the following relationship:

$$\text{Seasonal water use (SWU)} = \frac{N \times Q \times T}{A}. \tag{5}$$

The crop yield per unit water utilization is generally described in terms of water productivity (Mollah 2004), and it is determined by using the formula:

$$\text{WP} = \frac{Y}{\text{WR}}, \tag{6}$$

where WP = water productivity (kg/ha/mm), Y = crop yield (kg/ha) and WR = total amount of water used in the field for the crop (mm).

Economic benefit

The economic benefit of the system was calculated based on gross benefits obtained from different outputs of the cultivated area and cost for the inputs of the system. Benefit–cost ratio was calculated on the basis of annual benefit and cost of the system. The items included for benefit calculation were the outputs for agronomic and horticultural crops. For cost calculation the items were labour, seed/seedling, fertilizer, manure and irrigation. The cost of the items was calculated based on the prevailing rates in the area.

Results and discussion

In this study, a series of steps were completed for investigating the rainwater harvesting potential to improve the farming system at a small watershed in the hilly area of

Bangladesh. The steps of investigation included rainwater potential for harvesting, suitability of water storage, efficiencies of pumping from the reservoir and aquifer, performance of different crops cultivated. All those steps have been discussed in the following sections.

Rainwater potential

The rainfall pattern in the hilly area is high (30-year annual average rainfall is 3030 mm) and erratic. The area is one of the high rainfall areas of Bangladesh. The months from December to March are dry with 4.6 % rainfall. The time between April and May is transitional period between dry and wet season with irregular rainfall of 16.3 %. The rainfall data shows that the duration between May and October is rainy season with 90 % annual rainfall (Fig. 3). The surface runoff (SR) calculated using Eq. 1 shows that the rainwater can potentially be harvested in this hilly area during the period from May to October (Fig. 3), which can be used during the dry period spanning from December to April. The system collected surface runoff (overland flow) directly without any treatment because the runoff water quality was well suited to irrigation.

The inflow to the reservoir was determined using empirical formula (Eq. 1) from the relationship of catchment area loss factor and rainfall. The capacity of the studied reservoir was 7548 m^3. For the year 2011 and 2012, the volume of the available surface runoff in the rainy season was enough for the full storage of the reservoir (Fig. 4). It was also evident from the direct observation that reservoir became full before end of May. Excess water bypassed through the spillway during the rainy season (from mid-May to October).

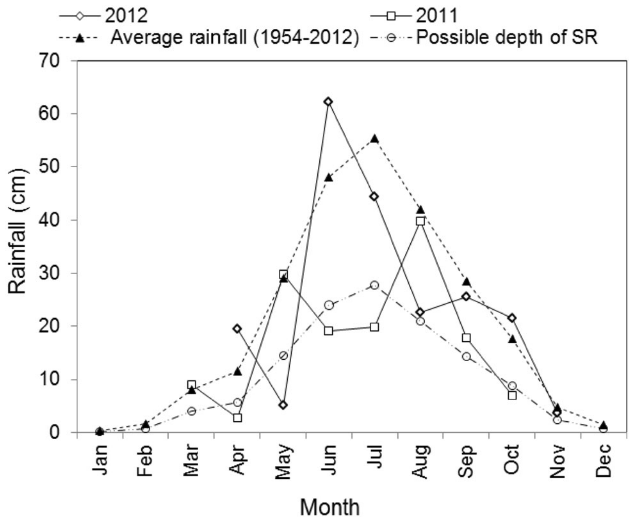

Fig. 3 Rainfall pattern of the study area (SR is for surface runoff)

Suitability of rainwater storage reservoir

Various features including size, shape, slope and depth of the suitable place between two parallel ridges influence the area–elevation relation and storage capacity of the reservoir. The area–elevation of this reservoir was almost linear (Fig. 5). The contour elevation of this reservoir was taken up to the height of 102.5 m and the reduced level of the dead storage was considered as 100 m. The area–elevation relationship curve represents the slope of this reservoir. The cumulative capacity of the reservoir up to the level of 102 m was 7548 m^3. The effective use of the water in the reservoir varied due to the losses of seepage and percolation (S&P), evaporation and outflow. The intermediate value of storage capacity of the reservoir can be taken from the graph, from which decision can be made how much water to be used at different time intervals. The reservoir facilitated gravity flow irrigation of valley land and low lift pump irrigation of both hilltop and hillslope land.

The losses due to S&P and evaporation characterize the suitability of a site for a rainwater harvesting reservoir. The dry seasonal S&P and evaporation losses of the reservoir gradually increased from December to April (Table 1) due to higher temperature and wind speed in the later months. Cumulative loss due to S&P and evaporation was 645 mm during these dry months. There would be deficit of water during irrigation period if this amount of loss is not considered during the design of a reservoir. Dry seasonal evaporation exerted water stress condition in soil due to more evaporation than rainfall. The average annual

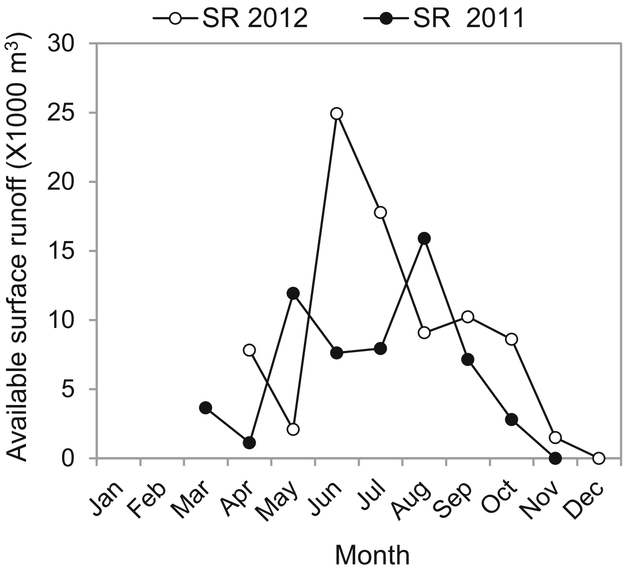

Fig. 4 Surface runoff (SR) available for harvesting in the studied watershed for the year 2011 and 2012

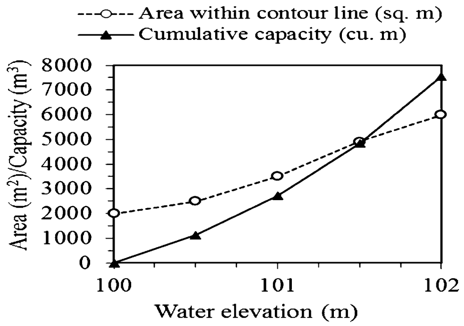

Fig. 5 Area–elevation and capacity–elevation relationship of the rainwater storage reservoir

evaporation in Bangladesh varies from 51 to 183 mm in different parts. The evaporation is lower in this eastern part than western part of the country. The dry seasonal daily average evaporation and S&P loss of studied reservoir was 3 and 1.2 mm/day, respectively. However, the S&P losses can considerably vary with the soil condition. Seepage loss is high in porous sandy soil and reduces gradually due to siltation in 1 or 2 years. The losses from the reservoir can be reduced considerably by lining with soil-cement, bentonite, brick and low-density polyethylene lining (LDPE) of reservoir bottom and covering water surface by monolayer alcohol. On the other hand, the S&P loss increases groundwater storage (Jebamalar et al. 2012). The evaporation losses can be reduced 60 % by covering of water surface by 600 gauge LDPE sheets (Panigrahi et al. 2006). Recent research shows that environmentally innocuous surfactant monolayer on water surface reduced evaporation rate about 40–70 % (Dawood et al. 2013). Biocrete, clay and polythene reduced seepage losses by 93.81, 56.73 and 76.37 %, respectively, as observed by Jayanthi et al. (2004). Wallace and Bailey (2015) suggested that catchment area, system efficiency and storage capacity of rainwater harvesting system had strong influence of on water volumes and the depletion of water during dry seasons and drought periods.

Pumping from rainwater reservoir

Choice of an efficient pump and operating condition is important for an economic and environmentally friendly operation. Small savings of energy consumption and operating cost at micro-level can contribute to the economic benefit of the system as well as the overall sustainability of farming system. Pumping was needed to lift water from the storage reservoir to hillslope and hilltop. The pump discharge varied due to suction lift, delivery lift, rpm (revolutions per minute) of the motor, suction pipe diameter, delivery pipe diameter and pump capacity. The measured values of water horsepower, efficiency and discharge of two locally available pumps installed at the rainwater harvesting reservoir showed their relative performances (Table 2). Pump-1 was 1.5 hp with a suction pipe of 381 mm diameter and a delivery pipe of 254 mm diameter. Pump-2 was 2 hp with a suction and delivery pipe of 254 mm diameter. It is notable that the suction pipe diameter of pump-1 is much larger than that of pump-2. The total lift of pump-1 was 10.2 m and for pump-2 was 13.27 m. The discharge of pump-1 was therefore higher than pump-2 despite the higher capacity of pump-2. The efficiency of both pumps was low. The operation of pumps at field condition without setting optimum stipulation (rpm and head) made the performance low. The performance of a pump can vary considerably with the variation of rpm, blade angle, blade number, impeller outlet diameter as well as pipe diameter and total lift as suggested by Bacharoudis et al. (2008) and Islam and Kader (2015).

Pumping from groundwater

Choice of water pumping modes (suction or forced mode) depends on the water source to be pumped and the related technical feasibility. Suction mode pumping of surface water is preferred because of its low construction cost and easy-to-use features. Due to the created facility of rainwater harvesting reservoir, suction mode pumping was

Table 1 Water losses from the reservoir in different months and subsequent water level changes (water level at full capacity of the reservoir = 2000 mm from the dead storage)

Month	Losses (mm)		Total loss (mm)	Cum. loss (mm)	Water level (mm)
	E	S&P			
Dec	62	33	95	95	1905
Jan	72	24	96	191	1809
Feb	84	21	115	306	1694
Mar	110	59	169	475	1525
Apr	122	48	170	645	1355

E evaporation, *S&P* seepage and percolation

Table 2 Performance of suction mode pumps to lift harvested rainwater to hilltop

Pump name	Suction lift (m)	Delivery lift (m)	Total lift (m)	Discharge (lps)	Output (hp)	Input (hp)	Efficiency (%)
Pump-1 (1.5 hp)	1.4	8.8	10.2	2.06	0.28	2.09	13.4a[1]
Pump-2 (2 hp)	1.52	11.75	13.27	1.04	0.18	2.57	7.0b

[1] Means followed by the same letter within each column are not significantly different ($p < 0.05$)

Table 3 Comparison between suction mode pumping of harvested rainwater to hilltop and force mode pumping of groundwater to hilltop

Pump	Working mode	Suction lift (m)	Delivery lift (m)	Total lift (m)	Discharge (l/s)	Specific discharge (m^3/kWh)	Installation cost (Tk)
Pump-1 (1.5 hp)	Suction	1.4 (ground)	8.8 (hill)	10.2	2.06	4.61	16,000
Pump-3 (2 hp)	Force	27.4 (ground)	14.5 (hill)	41.9	0.64	1.28	350,000
Pump-4 (1 hp)	Force and submersible	27.4 (ground)	0 (ground)	27.4	1.04	3.47	14,000

possible in the studied hilly area to irrigate hilltop and hillslope. The suction mode principle usually does not work to pump groundwater in this hilly region because of the deep groundwater level (>8 m). Three pumps namely pump-1: suction mode 1.5 hp pump, pump-3: force mode submersible 2 hp pump, and pump-4: force mode submersible 1 hp pump were tested at field condition (Table 3). The results showed that the discharge of pump-1, pump-3 and pump-4 was 2.06, 0.64 and 1.04 l/s, respectively. For the suction mode pump, volume of water lifted per unit energy consumption was 4.61 m^3/kWh, which was higher than that of the both force mode pumps. The operating cost of suction mode pump was less than the force mode pump. Besides, the suction mode pump had much less installation cost than the force mode pumps. Cost of 7548 m^3 groundwater pumping by a force mode pump was Tk 21,744 and the energy requirement was 2174.4 kWh (data not shown in Table). Installation and operation cost of groundwater pumping was more than the construction cost of the rainwater harvesting reservoir.

Effect on farming system

Selection of water conserving crop and crop rotation in watershed scale can increase crop production per unit water and land. Before the intervention of this new water management system, most of the land remained fallow during the dry season due to the lack of irrigation facility (Table 4). A comparison of cropping pattern between site with and without rainwater harvesting reservoir irrigation system is shown in Table 4. The cropping system was mainly rainfed and the cropping intensity of the studied region was 155 %. The low yielding indigenous variety was dominant during the kharif season and the major cropping pattern was fallow-rice or maize-fallow with somewhat irregular fashion as observed during a pre-project field survey. At the study site, the cropping pattern was changed and the cropping intensity increased to 300 % with sustainable crops compared to local conventional crops (jum rice) as shown in Table 4. Jum cultivation (shifting cultivation) is believed to be non-ecofriendly (Bala 2010).

Performance of crops

Performance in terms of water use efficiency (water productivity) and benefit–cost ratio of different crops studied under the rain water harvesting irrigation system is shown in Table 5. For farming system development in the water-deficiency region selection of water saving crop is one of the important decision making tasks (Wang et al. 2010). Wang et al. (2012) suggested that adoption of water conserving cropping system can reduce irrigation cost significantly, which contribute to the economic, social, ecological benefit of sustainable agriculture system for water deficit or arid region. Water productivity of vegetable production in the study was much higher than that of fruits and grain crops (Table 5). Pascale et al. (2011) also suggested that vegetables are with higher economic return and water productivity compared to grain crops. The water productivity values of crops studied were close to the literature values. The water productivity of onion variety (59.6 kg/ha/mm) was within the literature values, i.e. 4.5–3.8 kg/ha/mm by Roy et al. (2014) and 121.8–168.5 kg/ha/mm by Zheng et al. (2012). The water productivity of cabbage (193.5 kg/ha/mm) in the study was higher than the values (64.3–140.4 kg/ha/mm) found by Asare (2010). Both water productivity (40.5 kg/ha/mm) and seasonal water use (370 mm) of the cucumber variety

Table 4 Comparison of cropping pattern between sites with and without harvested-rainwater irrigation system in three crop seasons of a year

Without rainwater harvesting facility			With rainwater harvesting facility		
Rabi	Kharif-1	Kharif-2	Rabi	Khari-1	Kharif-2
Fallow	Aroid	Aroid	Cabbage	Chilli	Aroid
Fallow	Yard long bean	Brinjal	Raishak	Chilli	Aroid
Fallow	Galong (jum rice)	Sesame	Potato	Red amaranth	Yard long bean
Fallow	Choroivati (jum rice)	Sesame	Onion	Red amaranth	Yard long bean
Fallow	Rice/Maize	Fallow	Red amaranth	Maize	Aroid

Table 5 Yield, water productivity, and economic performance of grain and horticultural crops produced under irrigation with harvested rainwater

Crop	Yield (t/ha)	WU (mm)	WP (kg/ha/mm)	Total benefit (×1000 Tk/ha)	Total cost (×1000 Tk/ha)	Net benefit (×1000 Tk/ha)	Benefit–cost ratio (×1000 Tk/ha)
Sweet gourd leaf	60	340	176.5	140	35	105	4
Chilli	14.8	290	51.03	444	188	257	2.36
Red amaranth	14	270	51.8	260	140	120	1.86
Cucumber	15	370	40.5	300	125	175	2.4
Black cumin	1	250	4	200	100	100	2
Raishak	30.6	270	113.3	517	277	240	1.87
Cabbage	60	310	193.5	600	300	300	2
Onion	20	335	59.6	–[a]	–	–	–
Bottle gourd	66.9	345	193.8	669	345	324	1.94
Country bean	2	310	6.45	600	238	363	2.52
Tomato	20	360	55.55	–	–	–	–
Maize cob	14.5	270	53.8	167	43	124	3.88
Maize grain	3.5	490	7.1	65	46	19	1.41
BRRI Dhan-28	4	1100	1.4	40	29	11	1.38
BRRI Dhan-29	4.5	1250	1.2	45	38	8	1.18
BARI Malta-1	10	600	16.7	1025	106	919	9.67
BARI Litchi	7.1	510	13.9	575	117	458	4.91
BARI Mango	10.6	650	16.4	818	188	630	4.35

WU water use, *WP* water productivity

[a] Refers not-determined

studied was less than the values reported by Yaghi et al. (2013) as 56 kg/ha/mm and 671.5 mm, respectively. Maize grain was produced with water productivity of 7.1 kg/ha/mm. Ullah et al. (2013) obtained similar water productivity of maize grain production (7.64 kg/ha/mm). The water productivity of BRRI Dhan-28 and BRRI Dhan-29 was 1.4 and 1.2 kg/ha/mm, respectively, and the lowest among all crops studied. The water productivity of the rice varieties was lower than the national standard (3.06–4.59 kg/ha/mm), but it is in agreement with the findings of Alauddin and Sharma (2013) who stated that water productivity of boro rice was just above or below one for the area of Chittagong, Chittagong Hill Tracts, Sylhet and Khulna. The water productivity for boro rice production in fine textured soil can be higher, i.e. 4.8–6.1 kg/ha/mm (Amin et al. 2003) and 5.8–6.8 kg/ha/mm (Sarker et al. 2006) for silt loam soil. The study results also provide options for farmers and managers to choose crop based on water productivity if needed.

The economic performance of different crops cultivated under the harvested rainwater irrigation system varied considerably (Table 5). The horticultural crops performed better with the highest benefit–cost ratio of 9.70 for BARI Malta, 4.9 for BARI Litchi and 4.35 for BARI Mango. Among vegetables, the highest benefit–cost ratio was 4 for sweet gourd leaf followed by country bean (2.52), cucumber (2.4), chilli (2.36), cabbage (2) and black cumin (2). The benefit–cost ratio of red amaranth, raishak and bottle gourd was less than two. Maize cob was produced with higher benefit–cost ratio (3.8) compared to maize grain production. BRRI Dhan-28 gave slightly higher benefit–cost ratio than BRRI Dhan-29.

The crops with higher benefit–cost ratio and water productivity should be selected especially in the water scarce dry winter period. A preferred list of suitable crops in this hilly region can be identified from these two lists of ranking. It is important to mention that the rainwater harvesting reservoir also facilitated fish cultivation. About 0.3 ton of different fish species, such as carp, mrigal and rohita, was grown in the reservoir.

Conclusions

The study shows that there is high potential for rainwater harvesting during rainy season and subsequent use of harvested water for gravity-flow valley land irrigation and suction mode pumping to hilltop and hillslope with a low capacity 1–2 hp pump. The findings of the study can be useful for the hilly agriculture of the tropical climate zones around the globe. The improved water supply system can facilitate triple cropping system for valley land and permanent horticultural intervention at hilltop and hillslope. The perennial vegetation in hilltop and hillslope would also act as a soil and water conservation practice. Perennial vegetation is considered as a best management practice to reduce sediment and nutrient loss from hillslope farming. Yield, water productivity and benefit–cost ratio of different crops studied were reasonably good. Vegetables were produced with higher water productivity compared to grains and horticultural crops, but horticultural crop returned higher benefit–cost ratio followed by vegetables and grain crops. As per demand of possessor, choice of crops cultivation may be optimized from this study. Up scaling of the practices can bring the vast hilly region under sustaining cultivation, which will improve livelihood of the local farmers. The study can provide recommendation for appropriate policy guidelines for future development of hill farming in similar regions to maintain healthy environment and ecological balance.

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