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CONTENTS

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Low-Cost Solar Pump Irrigation System for Irrigated Rice Production

P K Kundu[1*], P L C Paul[2], M B Hossain[2], D Roy[2], M N H Mahmud[2], M S Yesmin[2] and M T Islam[3]

ABSTRACT

Irrigation pumps operated by diesel and electricity are commonly used for irrigated rice cultivation, but fuel cost expansion and doubtful accessibility of power hampers the continuous irrigation. A solar pump would be an alternative option for irrigation to contribute in expanding rice production and food security to the growing population. Field experiments were conducted at Bangladesh Rice Research Institute, Gazipur, farm during Boro season from January – May in 2015, 2016 and 2017, respectively to determine the economic feasibility of a low cost 1.5 Horsepower (hp) capacity solar irrigation pump for rice cultivation. BRRI dhan63 was tested under four irrigation treatments as flood irrigation (continuous standing water at 7 cm depth above the soil surface), 3 cm irrigation at saturation level, 3 cm irrigation in AWD (alternate wetting and drying) practice, and 5 cm irrigation in AWD practice. The CROPWAT 8.0 model was used to ascertain crop water requirement (CWR) and irrigation requirement of each rice growth phase in each year using weather data. In 3 cm irrigation in AWD practice, about 1.0 ha of paddy field can be irrigated with the 1.5 hp solar pump without any or a few water deficits in reproductive and ripening phases. In both years, rice yield did not differ among the irrigation treatments. The benefit-cost ratio was 1.09, 1.18 and 1.02 for Aman, mustard and Boro season respectively. A 1.5 hp solar pump is the best feasible when it is used year-round for three or more crops. Although solar pump irrigation system involved higher initial cost, it was found economically sound and environment friendly. Thus, proper policy support is required to encourage solar power utilization for irrigation.

Key words: Solar irrigation pump; rice cultivation; benefit-cost ratio; renewable energy; water requirement

INTRODUCTION

Bangladesh's economy is profoundly reliant upon agriculture, especially rice production (Islam *et al*., 2017; Kabir *et al*., 2015). Rice is a primary staple food of about 160 million individuals in Bangladesh. It contributes about 48% of rural employment and 66% of the complete calorie supply of a normal individual in the country. Rice is grown in about 75% of the total cropped area and 80% of total irrigated area of Bangladesh. Boro rice (dry season rice) is one of the major contributors to the total rice production in Bangladesh, which is fully irrigated. Therefore, irrigation is most crucial for Boro rice cultivation. Fossil fuel is intensively used to supply the energy for operating the irrigation pumps. However, the supply of energy is interrupted because of increasing costs and unavailability of fuel.

Bangladesh's primary energy consumption expanded to almost 28.2 million tons' oil equivalents (metric ton) in 2014 (Halder, 2016), which has become higher in recent years. The energy interest of the nation is increasing surprisingly because of fast change in the economy and industrialization. For reducing the global warming and also fulfilling the energy need, many countries are now considering sustainable energy sources from solar and wind (Islam *et al*., 2014). Solar energy is the energy that derived directly from the sun.

Geographically, solar energy is sufficiently available in Bangladesh with a range of average solar radiation in between 4 and 6.5kW/m^2/day, which can be utilized for agricultural production (Islam *et al*., 2017; Hossain *et al*., 2015). In Bangladesh, over 17.5

[1]Scientific Officer; [2]Senior Scientific Officer; [3]Chief Scientific Officer; Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701.
[*]Corresponding author's E-mail: kundu22_bau@yahoo.com (P K Kundu)

lakhs irrigation pumps are being utilized from which 82% are diesel engine operated and 18% are electricity operated (Islam *et al*., 2019; Islam *et al*., 2017). Every year, the government of Bangladesh provides a subsidy to keep the diesel price lower. This creates extra pressure on the economy. Thus, to overcome the economic pressure and increasing rice production, solar irrigation system is a possible alternative option (Islam *et al*., 2017). It is necessary to ensure food security, especially Boro rice production (about 54% of total rice production of Bangladesh), should not be hampered (Kabir *et al*., 2020). A solar-powered pumping system primarily has greater expenses than diesel or electric controlled pump, yet it needs very low maintenance and labour cost. Considering the long term benefits (20 years' period), a solar pump can be effective and an alternative choice for limited scope of water application for crop cultivation. Due to limited fossil fuel on the earth, many countries have started to produce electricity from renewable energy. Bangladesh Government has additionally intended to deliver 5% of total electricity production by 2015 and 10% by 2020 from sustainable power sources like air, waste and solar (Karmaker *et al*., 2020). Some government and non-government institutions have already installed solar pump in different areas of Bangladesh for irrigation and other purposes.

In Bangladesh, the limit of solar pumps fluctuated from 300 to 1,190 watt-peak (Wp) and discharge rate differed from 2,000 to 800,000 l/day (Hossain *et al*., 2015). The solar pump can be used to withdraw both surface and groundwater, which is able to pump up to 2000 gallons/minute (Tietjen *et al*., 2008). In Bangladesh, only 60% areas are covered by irrigation but a huge scope is available to extend te area especially in coastal, hilly and charland areas by using solar power. For increasing agricultural production and fulfilling the sustainable development goal (SDG) 7.2, i.e., increase substantially the share of renewable energy, solar irrigation pumps can be used for improving crop production through increasing irrigated areas. Currently, the available solar pumps are large in size, installation and maintenance costs are too high that are hard to afford for farmers. Hence, a low-cost solar pump would be feasible for marginal farmers if they grow both rice and non-rice crops. In this context, a study was undertaken to evaluate the economic performance of a 1.5 hp low cost solar pump for Boro rice cultivation under different irrigation regimes.

METHODOLOGY

Experimental site

Field experiments were conducted at Bangladesh Rice Research Institute (BRRI), Gazipur research farm, which is located between 23^{0}59′ N and 90^{0}24′ E (Fig. 1) and the elevation is 34 m above sea level. The soil type of the site is clay loam (Paul *et al*., 2013). The seasonal (December- May) average maximum and minimum temperatures of this area are 30.6 ^{0}C and 18.3 ^{0}C, respectively, and the average seasonal (December- May) rainfall is 310 mm (Hossain *et al*., 2021).

Set up and component of solar pumping system

The solar pump system consists of the panels, supporting structure with a tracking mechanism, electronic parts for regulation, cables accessories, pipes, and the pump itself. Solar panels or modules were the main forces driving the solar pump, which used the sunlight to produce electricity. Eight solar panels, size of 1 × 1.5 m^2 each connected in arrays, produce 1600 watt (W) DC (direct current) energy. A 1.1 KW AC 3-phase submersible pump was connected with a pump controller using cables. A pump controller was connected to convert DC from the solar array into AC (alternative current) for

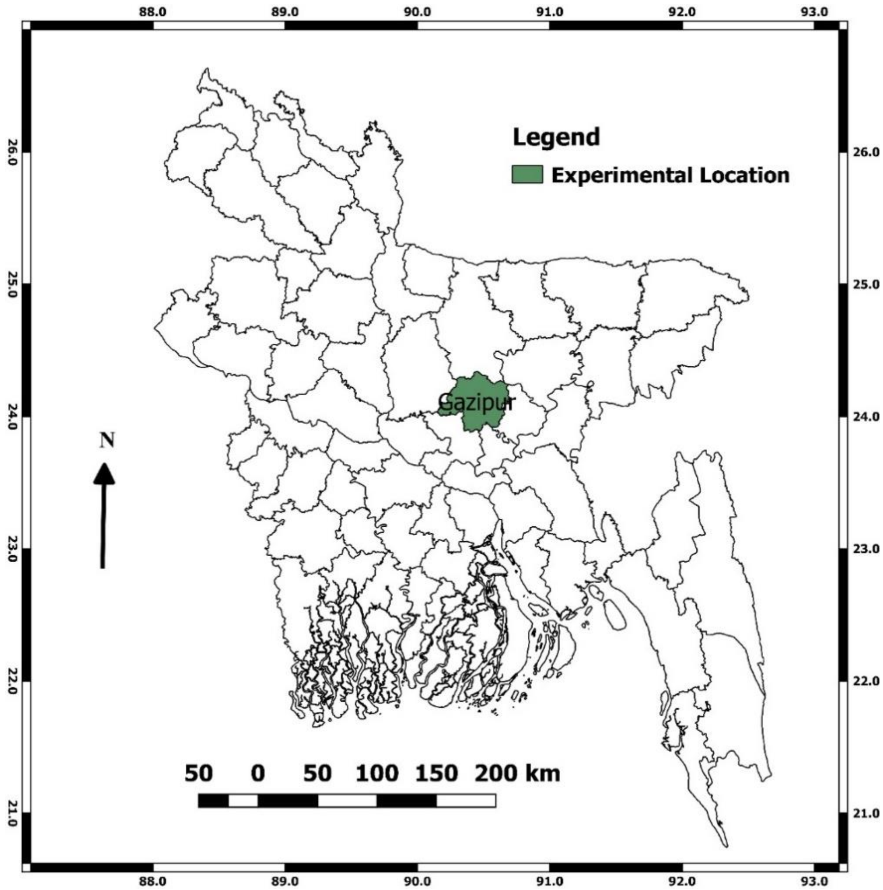

Fig. 1. Location of the experiment.

driving the pump, which regulates the output frequency according to irradiation in real-time to achieve the maximum power. For any low or high voltage and over the current situation, the pump controller controlled the pump and motor. A set of appropriate size cables were connected with junction boxes, switches, and motor to run the pump. The supporting structure (concrete base) and tracking mechanism were fixed with the solar system for the stability of solar panels and protecting them from theft or natural calamities. Both manual and the auto-tracking systems were used for the maximum output. The manual system produced less energy than auto-tracking. For obtaining the maximum output of energy, the panels were set along the direction to face the sun as it moved across the sky and increased the output of discharge. A submersible pump of 1.5 hp capacity was installed for testing discharge output and irrigated area coverage. The delivery pipe diameter was 50 mm and the discharge head was 4-5 m. Data were collected, including voltage and current of each panel, hourly and daily discharge of the pump, rice irrigation amount and yield components. A flow meter was connected between delivery pipes to measure the water volume.

Solar radiation and pump discharge

Solar radiation (W/m^2) and discharge (m^3/hr) was measured at a regular interval from dawn to dusk in each year. Hourly discharge (m^3/hr)

was recorded in April 2015, 2016, and 2017 to see the variation of discharge with radiation. The maximum and average discharge during the dry period from January to June in 2015, 2016, 2017, was also measured. The measured solar pump discharge was adjusted with the irrigation requirement for rice cultivation in each growing season.

Treatments and crop management

The solar pump was operated for the Boro rice cultivation in four irrigation treatments during 2014-15, 2015-16 and 2016-17 growing seasons. The treatments were: T_1 = Flood irrigation (continuous standing water at 7 cm above the soil surface), T_2 = 3 cm irrigation at saturation level, T_3 = 3 cm irrigation in AWD (alternate wetting and drying), and T_4 = 5 cm irrigation in AWD. The rice cultivar was BRRI dhan63. Forty-day-old seedling was transplanted on 19 December 2014, 22 December 2015 and 23 December 2016. The experiment was carried out by randomized complete block design (RCBD) with three replications. The fertilizer rate was 258 kg urea-100 kg TSP-120 kg MOP-112 kg, zypsum-11 kg zinc per hectare (BRRI, 2020). All fertilizers except urea were applied during land preparation. Urea was used at three splits at 15, 30 and 45 DAT. Weeding and other cultural practices were followed BRRI guidelines. To practice AWD, perforated PVC pipe was installed ten days after transplanting in each plot. Paddy was harvested on 01 May 2015, 03 May 2016 and 05 May 2017, respectively. In each plot, sample crop from 6 m^2 area was harvested to calculate the final yield adjusted at 14% moisture content (w/w).

Estimation of irrigation requirement

Crop water requirement (CWR) is the amount of water that plant uptake through rooting system to meet water loss by evapotranspiration and maintain plant growth and development. CWR can be calculated by the following equation (Michael, 1974).

$$\mathrm{CWR} = \sum(\mathrm{ET_0} \times \mathrm{k_c}) \qquad \text{(i)}$$

Where CWR = crop water requirements in mm, ET_0 = reference crop evapotranspiration (mm) and k_c = crop coefficient. The daily maximum and minimum air temperature, relative humidity, wind speed, sunshine hour, daily rainfall during the growing period were collected from Plant Physiology Division, BRRI, Gazipur. The Penman-Monteith method is used to calculate the reference crop evapotranspiration using the following equation

$$\mathrm{ET_0} = \frac{0.0408\,\Delta\,(\mathrm{R_n} - \mathrm{G}) + \gamma \frac{900}{\mathrm{T}+273} \mathrm{U_2}(\mathrm{e_s} - \mathrm{e_a})}{\Delta + \gamma(1 + 0.34\,\mathrm{u_2})} \qquad \text{(ii)}$$

Where, ET_0 = reference crop evapotranspiration (mm d^{-1}); R_n = net radiation at the crop surface (MJ $m^{-2}d^{-1}$); G = soil heat flux (MJ $m^{-2}d^{-1}$); T = average air temperature (°C); U_2 = wind speed measured at 2 m height (m s^{-1}); $(e_s - e_a)$ = vapor pressure deficit (kPa); Δ = slope of the vapor pressure curve (kPa °C^{-1}); γ = psychometric constant (kPa °C^{-1}) and 900 conversion factor. Irrigation requirement (IR) was calculated according to FAO (2009) as:

$$\mathrm{IR} = \sum(\mathrm{ET_c} - \mathrm{P_{effective}}) \qquad \text{(iii)}$$

Where, IR = irrigation requirement (mm), ET_c = crop evapotranspiration in mm, and $P_{effective}$ = effective rainfall in mm.

Effective rainfall is the part of total annual or seasonal rainfall that is directly or indirectly useful for crop production (Dastane, 1972). The effective rainfall was calculated using the soil conservation service method (Geleta, 2019) is given below:

$$\mathrm{P_{effective}} = \mathrm{P} * \frac{(125 - 0.2\,\mathrm{P})}{125} \text{ For P<250 mm} \qquad \text{(iv)}$$

$$\mathrm{P_{effective}} = 125 + 0.1\,\mathrm{P} \text{ For P>250 mm} \qquad \text{(v)}$$

Where, $P_{effective}$ = effective rainfall (mm) and P = monthly rainfall (mm)

Economic analysis

The installed solar pump only tested for Boro rice cultivation. However, there is a possibility to use the solar pump for irrigation in the Aman and Rabi season. If we consider Aman (15 July-15 October) – Mustard (25 October-10 January) – Boro (15 January- 30 May) cropping pattern, then the whole year can be irrigated by solar pump. We calculated the benefit-cost ratio for Boro rice and year-round crops (considered the rice equivalent yield). Total cost of solar pump was the summation of fixed cost and the variable cost. The variable cost included the total annual depreciation due to use and time, interest on capital cost, repair and maintenance. Solar pump life was assumed to be 20 years. The annual interest rate was normally 14% of the capital price of the pump. The variable cost was the total of input and operating cost. Variable cost depended on some factors. If a farmer had his own land and machinery to cultivate the land, then the variable cost would be lower than the other farmers.

Statistical analysis

Analysis of variance (ANOVA) among the irrigation treatments was regulated by using the STAR software. The comparison of means was tested using the least significance difference (LSD) at the 95% confidence level.

RESULTS AND DISCUSSION

Relationship between solar pump discharge and radiation

Pump discharge was positively correlated with solar radiation (Fig. 2). Pump discharge increased with increasing solar radiation. Pump discharge increased from 2 m^3/hr at 100 W/m^2 radiation to 11 m^3/hr at 1000 W/m^2 radiation. Manar *et al*., (2019) also found the same result in their research.

Variation of the pump discharge

In each year, the pump discharge was monitored from dawn to dusk in April. Pump discharge was low in the morning, below 7 m^3/hr until 9 am (Fig. 3). Pump discharge increased with the increase the sunshine hour. The highest discharge was recorded at noon at 12 pm. After that, discharge decreased gradually until of the evening at 6 pm. The reason for higher pump

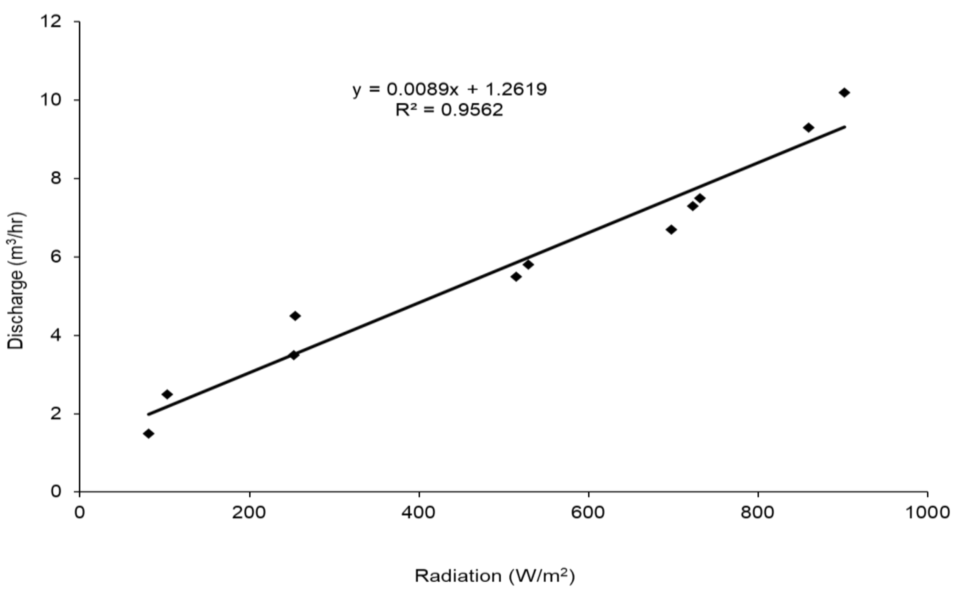

Fig. 2. Relationship between pump discharge and solar radiation.

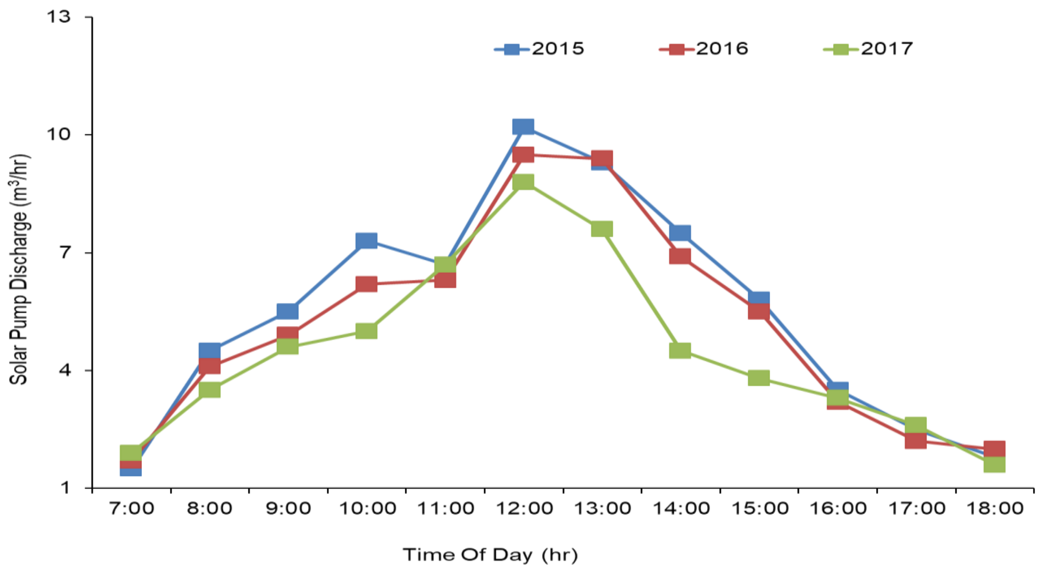

Fig. 3. Variation of pump discharge at different times of a day.

discharge at noon (12 pm) might be the sun location that was the closest to the earth during mid of the day and hence more radiation were obtained. Hossain *et a*l., (2014) conducted an experiment on a solar pump irrigation system for different crops in different regions of Bangladesh and found the same discharge trends over time. Benghanem *et al*., (2018) and Tiwari and Kalamkar (2018) also found that discharge rate was higher at noon at 12:00 pm and lower at afternoon. However, Benghanem *et al*., (2018) estimated the daily flow rate of solar powered photovoltaic water pumping systems, and they showed that discharge rate was lower at noon than afternoon because of the cloudiness.

Monthly pump discharge during the Boro season

During the Boro season, monthly (January-June) pump discharge was recorded (Figure 4) where the average discharge varied from 62 m^3/day to 40 m^3/day in 2015, 58 m^3/day to 40 m^3/day during 2016 and 2017. The maximum discharge was 68 m^3/day, 64 m^3/day and 63 m^3/day in March 2015, April 2015; March 2016; March 2017, and June 2017 respectively. The lowest discharge was 45 m^3/day, 53 m^3/day and 55.6 m^3/day in June, May and June in 2015, 2016 and 2017 respectively. The variation of discharge in the different months was related to the variation of day length, sunshine hour and radiation (Manar *et al*., 2019). In the current study, even though the day length was longer in May and June in 2015, the discharge rate was lower due to less sunshine hour.

Irrigation water requirement and pump discharge for different irrigation treatments during the Boro season

For every month (January-April) of Boro season irrigation water requirement was measured by CROPWAT (version 8.0) software. It was observed that during land preparation in January, irrigation requirement was higher than solar pump discharge in each irrigation treatment in every year (Figure 5). For the treatment T_1 (flood irrigation), pump discharge was deficit only in February about 53.3 mm, 66.6 mm, and 62.2 mm than the irrigation requirement in 2015, 2016 and 2017

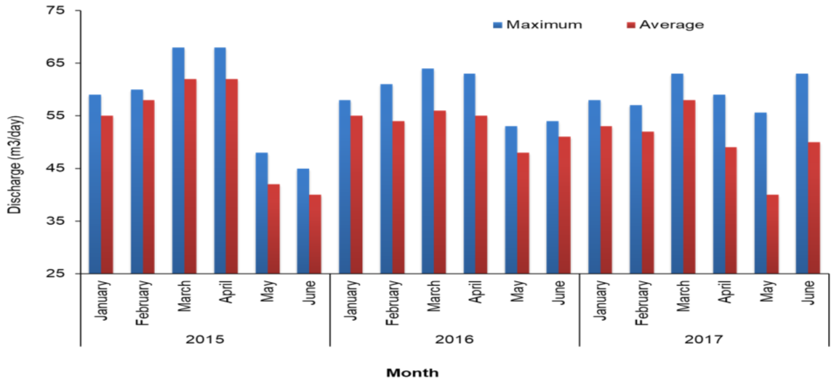

Fig. 4. Monthly average and maximum discharge of solar pump during 2015-2017.

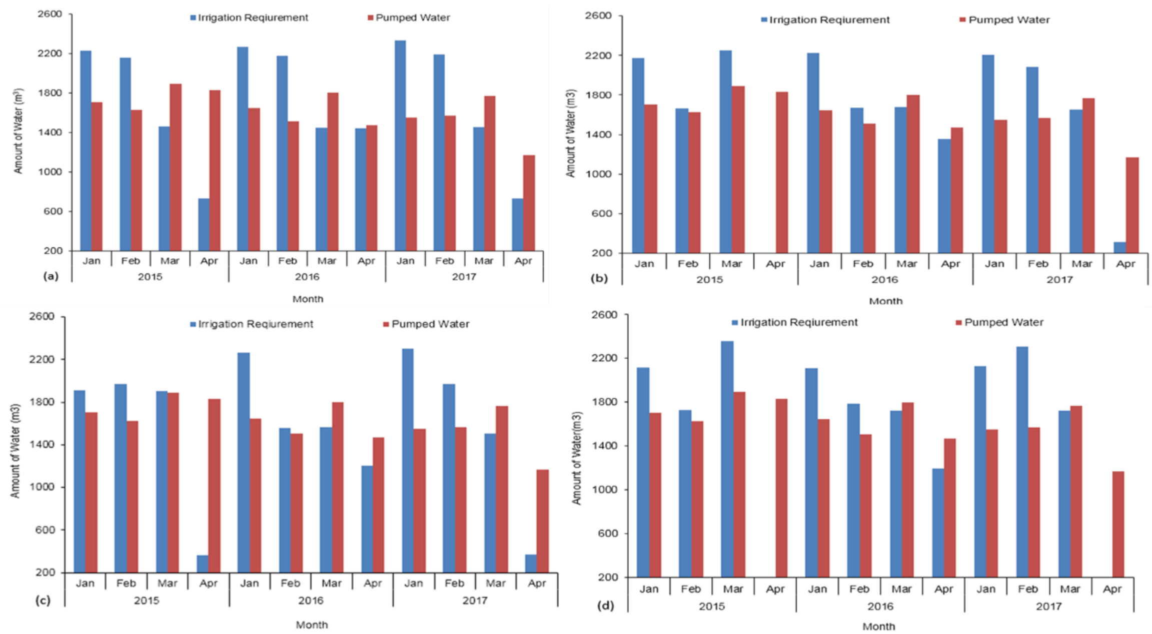

Fig. 5. Monthly irrigation requirement and solar pump discharge at different treatments (a) flood irrigation, (b) irrigation at saturation level (3 cm) (c) irrigation in AWD (3 cm) and (d) irrigation in AWD (5 cm) for Boro rice in 2015-2017.

respectively, considering one hectare of cultivable area. However, pump discharge was surplus for March and April. Similarly, for the treatment T_2 (3 cm irrigation at saturation) irrigation requirement (IR) did not meet up by about 36 mm in March, 16 mm in February, and 51.3 mm in Feb in 2015, 2016 and 2017 respectively. Water pumping in February and March was slightly lower than the required irrigation. Irrigation water deficit was same in February for the treatment T_3 (3 cm AWD) and T_4 (5 cm AWD). Therefore, by practicing flood irrigation and irrigation at 3 cm at saturation level, the total cultivable land was less than one hectare because of the insufficient irrigation water by 1.5 hp solar pump (1600 solar energy). But for the AWD practices, water requirement was almost the same or lowered than the pumped water. In that case, a designed 1.5 hp solar pump could cultivate one hectare of land without any alternative source of pumping. It was observed that, January and February in each year was the critical time for the solar pump irrigation due to lower discharge compared to crop demand. However, during the reproductive and ripening phases (March and April) there was no or minimal water shortage for the irrigation requirement (Fig. 5).

Yield of rice in different irrigation treatments

Table 1 presents The mean yield of BRRI dhan63 under four irrigation treatments. Yield did not get any significant difference among the irrigation treatments. The maximum yield was 5.4 t/ha, 5.8 t/ha, and 5.9 t/ha in 2015, 2016 and 2017, respectively. The lowest yield was 4.9 t/ha, 5.3 t/ha, and 5.5 t/ha in 2015, 2016 and 2017 respectively. In 2015, the yield was comparatively lower than in 2016 and 2017 (the optimum yield was 6.5 t/ha), because the land was reclaimed just before the experiment setup. The water depletion up to 15 cm below the soil surface (T_3) saved the irrigation water and there was no yield reduction. Therefore, for increasing the irrigation area and maintained the yield potential, AWD practice (applied 3 cm water when water goes to 15 cm below the soil surface) could be practiced. Previous studies also showed that AWD practice reduced irrigation water and had similar yield with continuous standing water.

Economic analysis of the solar system

Table 2 shows the benefits of solar pump for rice cultivation as well as non-rice crops. The initial cost of the solar pump including

Table 1. Yield of BRRI dhan63 under four irrigation treatments in 2015-2017.

Treatment	Year		
	2015 Mean yield (t/ha)	2016 Mean yield (t/ha)	2017 Mean yield (t/ha)
T_1 = Flood irrigation (7 cm)	5.4	5.8	5.9
T_2 = 3 cm irrigation at saturation level	5.2	5.6	5.6
T_3 = 3 cm irrigation in AWD	5	5.5	5.8
T_4 = 5 cm irrigation in AWD	4.9	5.3	5.5
LSD	NS*	NS	NS

*NS indicates non-significant

Table 2. Economic analysis of solar pump for round the year (rice and non-rice crops).

Cost and return (Tk/ha)	Aman	Mustard	Boro
1. Variable cost			
I. Input cost (Seed, fertilizer, herbicide, insecticide, labour cost etc)	15500	23800	19300
II. Labor cost	35000	25000	42000
III. Repair	2000	1000	2000
IV. Depreciation	5830	4380	7290
V. Interest	8200	6125	10210
Total	66530	60305	80800
2. Fixed cost			
I. Land rent	40000	20000	40000
Total cost (Fixed + Variable)	106530	80305	120800
REY	5300	4500	5800
Price (Tk./kg)	20	20	20
Return from paddy (Tk./ha)	106000	90000	116000
Return from Straw (Tk./ha)	10500	5000	7500
Gross return (Tk./ha)	116500	95000	123500
BCR	1.09	1.18	1.02
Gross margin(Tk.)	49970	34695	42700

installation was BDT 3,50,000 and the expected service life was considered 20 years. Command areas of 1.5 hp solar pump for Boro rice cultivation was one hectare. After Boro season, solar pump can be used for Aman rice and Rabi crops (i.e., Mustard). So, the benefit-cost was calculated considering one-hectare command areas for Boro, Aman and Mustard. In this experiment, variable cost was measured by summarizing the items such as seed, fertilizer, herbicide, insecticide, labour cost and land preparation cost, depreciation cost of solar pump, interest on solar pump investment, repair, and maintenance. Land rent was considered as fixed cost throughout the season. After calculating gross return and total cost, the benefit cost ratio was found 1.09 for aman season, 1.18 for mustard and 1.02 for Boro season.

CONCLUSION

A 1.1 KW solar power irrigation system is suitable for Aman-Mustard-Boro cropping pattern. During Boro season, applying AWD practice increases the command area of solar pump. The input cost was higher for solar pump but maintenance cost was comparatively low. So, solar pump irrigation system could be an option to minimize the energy consumption and fuel cost for irrigation purpose in the long run. We need to modify the existing system so that we can use it to irrigate crop land in a mass scale by groundwater and surface water. Solar pump is technically and economically feasible to supply power for irrigation in crop production throughout the years. Government subsidy is initially required for installing solar power pump to the farmers' level for popularizing and utilizing solar power in agricultural production.

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Optimization of Irrigation Water to Maximize Transplanted Aman Rice Production in Selected Areas of Bangladesh

M S Yesmin[1*], M B Hossain[1], D Roy[1], M N H Mahmud[1], P L C Paul[1], P K Kundu[2] and M T Islam[3]

ABSTRACT

In rainfed and irrigated agriculture, optimization of irrigation scheduling is very essential to maximize the crop production using the limited of agricultural water resources. A study was conducted to estimate requirement of irrigation and its scheduling of T. Aman (wet season) rice in the Northwest and Southeast region of Bangladesh using CROPWAT model. This paper utilized the daily rainfall and reference evapotranspiration data sets, obtained from seven weather stations for the period of 1981 to 2015. Effective rainfall and reference crop evapotranspiration (ET_o) were calculated using the USDA Soil Conservation method and Penman-Monteith method, respectively. The simulation model of this explored the appropriate transplanting date to utilize maximum rainwater and to avoid supplemental irrigation. Four transplanting dates 15 July, 30 July, 15 August and 30 August were considered for transplanting T. Aman rice in the study areas. The optimization results showed that the water requirement was lower of the rice crop transplanting on 15 July in all locations due to higher effective rainfall. No supplemental irrigation was required for T. Aman cultivation transplanted on 30 July in Rangpur, Dinajpur, Bogura and Mymensingh regions since rainfall was sufficient to meet the demand of the crop. Therefore, this period was found for suitable and recommended for transplanting of T. Aman rice in these four locations. Transplanting after 30 July in these four locations needed supplemental irrigations. This study also revealed that 30 July transplanting required one supplemental irrigation in Jashore and Rajshahi regions due to insufficient rainfall. This period was also considered as the appropriate transplanting time in these two locations. However, in Pabna, one supplemental irrigation must be applied for T. Aman even transplanting on 15 July owing to in adequate rainfall. Irrigation requirement and number of irrigations were gradually increased with delaying the transplanting time. Early transplanting demanded less irrigation than late transplanting.

Key words: CROPWAT model, crop water requirement, effective rainfall, crop water requirement, irrigation scheduling, T. Aman, transplanting date

INTRODUCTION

Rice is cultivated in three seasons namely Aus, Aman, and Boro in Bangladesh. T. Aman rice is grown under rainfed condition in wet season. T. Aman rice is one of the major crops of Bangladesh and contributed about 48% of the total rice production (BBS, 2019). T. Aman rice is transplanted from July to August and harvested during October to December. The biggest consumer of the world's water resources is agriculture, as irrigated agriculture uses about 70% of the world's ground and surface fresh waters (Michelon *et al*., 2020). This water amount is insufficient to address actual irrigation needs and is expected to decline in the next decades in the arid and semi-arid regions

Both rain fed and irrigated agriculture require greater water use efficiency although deteriorating water resources and growing food requirements (FAO,1988). In hydrological cycle, rainfall and evapotranspiration are the most significant components which contributed food production (Smith, 1992).This threatened resource is recurrently wasted due to in efficient water management practices in agriculture and resulting low water productivity (Tarjuelo *et al*., 1996). Agricultural production in South Asia

[1]Senior Scientific Officer; [2]Scientific Officer; [3]Chief Scientific Officer; Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701.
*Corresponding author's E-mail: shetara.brri.bd@gmail.com (M S Yesmin)

may be reduced up to 30% by 2050s if appropriate utilization of water use is not taken under prime consideration (Calzadilla *et al.*, 2011). It is estimated that the freshwater supply in the agricultural sector is likely to decline 8–10% globally owing to increasing struggle in various sectors such as agriculture, urban and industrial sectors (Toung *et al.*, 1994). Additional, plethora of Asian countries, per capita water availability has dropped by 40–60% between 1955 and 1990 (Gleick *et al*., 1993).

The declining trends of annual rainfall with more frequent hazardous events affecting catastrophe in terms of production destruction, extreme droughts, flooding, death and other calamities have been reported by many researchers (FAO ,1995). Therefore, appropriate strategies are needed for crop growth improvement through effective irrigation along with proper cultivation practices. Hence, water-efficient agricultural practices have massive importance to enable increasing cultivated area. Therefore, appropriate strategies are needed for crop growth improvement; create irrigation more effective and sustainable along with preserve farmland by proper cultivation practices. In this context, it is essential to improve irrigation management as well as water productivity (WP) or water use efficiency (WUE) in irrigation systems. Hamdy *et al.*, (2003) realize great promises for improving irrigation namely supplemental irrigation, deficit irrigation (DI), rainwater harvesting, sprinkler irrigation, precision irrigation techniques and soil-water conservation practices. The desired irrigation management practices in irrigated or rainfed conditions are necessary for improving crop yields. However, limiting factor of water, effective use of land and water resources has great benefits of higher WP.

In Bangladesh, about 90% of the total rainfall occurs from April to October(Roy *et al.*, 2010). T. Aman rice experienced terminal drought during the late monsoon. Rainfall is not sufficient for the potential yield of rice and most of the T. Aman rice remains at the flowering and grain filling stages after October (Sattar *et al*., 2009). The supplemental irrigation is highly essential in October-November for T. Aman rice cultivation. Rice yield is drastically reduced if supplemental irrigation is not applied timely. If the total amount of rainfall through the T. Aman crop growing period exceeds the crop water requirement then there is a need for supplemental irrigation due to the erratic distribution of rainfall (Saleh, 1991).

Nevertheless, irrigation for crop production, which is the largest water demanding sector in Bangladesh, needs extraordinary attention to manage upcoming water demand management. Improved irrigation management and agricultural practices can play a vital role to deal with the threat of water shortage (Acharjee *et al*., 2019). Suitable date of transplanting might be a modest and effective way to cope with changes in climatic factors with seasonal variability in rice production (Yesmin *et al*., 2019).

CROPWAT model can play a beneficial role in developing hands-on recommendations for optimization of crop production beneath of limited water supply conditions. CROPWAT is a customary model for agronomists, agro meteorologists and irrigation engineers to carry out appropriate calculations for crop water use studies and evapotranspiration and give precisely design of irrigation schedule (Smith, 1992). It permits the development of recommendations for the planning of irrigation schedule under erratic water supply situations, enriched irrigation practices and the assessment of production under rainfed environments or deficit irrigation (Shreedhar *et al*., 2015).

The present study targeted to find the prospect of utilizing maximum rainfall coverage during the T. Aman by figuring out the appropriate transplanting window based on rainfall distribution pattern. One of the key approaches is that application of exact amount of water to the crops at the exact time. For these motives, this study was carried out to estimate the irrigation requirement, total number of irrigation and appropriate time of irrigation to T. Aman rice in the Northwest and Southeast region of Bangladesh (Hossain *et al*. 2017).

METHODOLOGY

Study area

Figure 1 shows Daily rainfall and reference evapotranspiration data collected from seven districts namely Jashore, Pabna, Rangpur, Dinajpur, Mymensingh, Rajshahi and Bogura in Northwest and Southeast regions of Bangladesh for the period of 1981-2015. The sites and their coordinates are as follows: Jashore (23.16° N and 89.213°E), Pabna (24.15°N and 89.0667°E) and Bogura (24.85°N and 89.37°E). These regions belong to the agro-ecological zone (AEZ)-11 (High Ganges River floodplain) and AEZ-12 (Low Ganges River floodplain). These two AEZs cover 13,21,062 hectare (ha) with 32% loamy, 43% silt loam, and 12% clayey soil and 7,97,139 ha with 13% silt loam, 29% silty clay, and 31% clayey soil respectively (FAO, 1988).

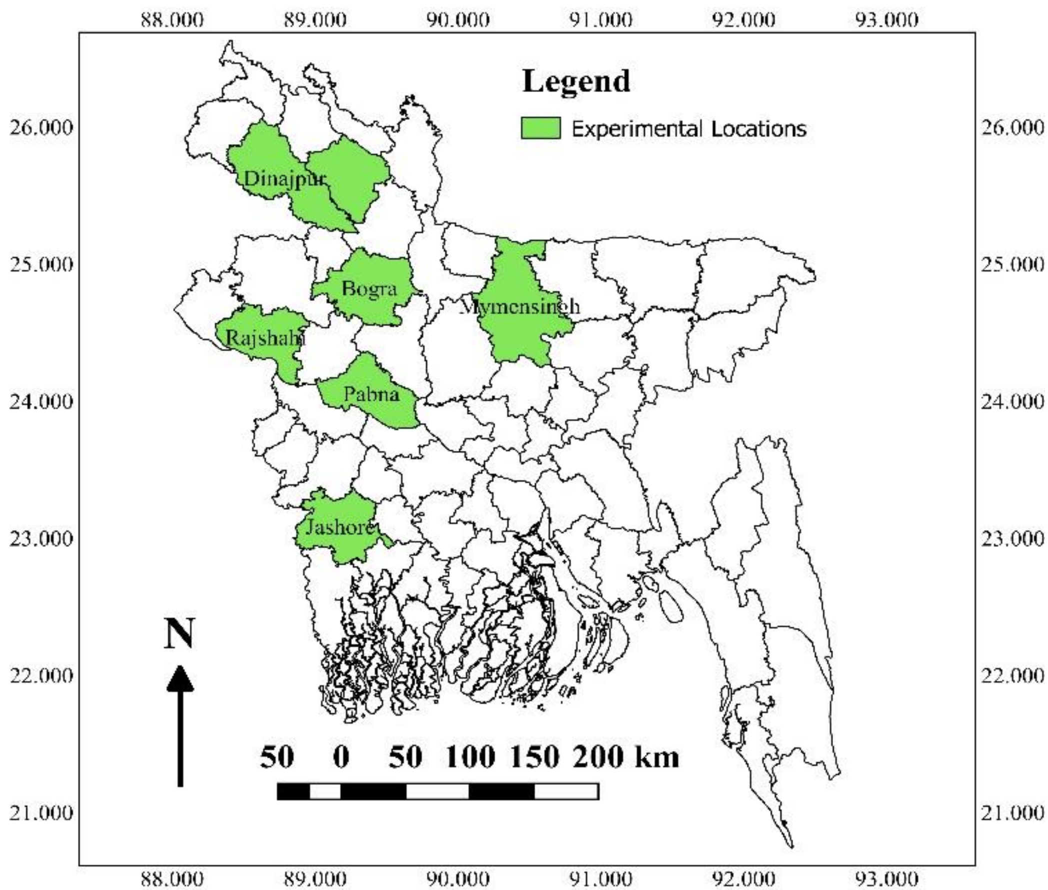


Fig 1: Experimental locations of the study area.

Input data requirement of the CROPWAT model

Land and Water Division of the FAO developed a practical decision support system called CROPWAT, is familiar to farmers for its easy calculation of crop water demands under diverse irrigation practices (Smith, 1992). The CROPWAT model uses climatic, crop and soil data for calculating the crop water requirement. The meteorological data contain: (1) maximum and minimum temperature (°C), (2) wind speed (ms^{-1}), (3) sunshine hours (h), (4) relative humidity (%) and (5) rainfall (mm).

All data of the study area are taken from Bangladesh Meteorological Department (BMD) from 1981-2015 for Jashore, Pabna (Ishwardi), and Bogura. In this study, T. Aman rice is considered for estimating crop water requirement. The CROPWAT model contains default data for T. Aman rice variety. The cropping pattern consists of date of planting, planted area (0–100% of the total area) and crop parameters (together with Kc value, root depth, depletion fraction, stage days).

In this study, irrigation scheduling was done for popular T. Aman variety BRRI dhan49 (135 days duration) and four transplanting dates (15 July, 30 July, 15 August, and 30th August). Growing period of rice was divided as follows:

(i) 30 days in seedling stage (nursery/land preparation)
(ii) Usually 10 days in initial stage (transplanting to seedling establishment)
(iii) Usually, 35 days in crop development stage (tillering to panicle initiation)
(iv) 30 days in mid stage (panicle initiation to 100%flowering) and
(v) 30 days in late stage (flowering to maturity).

The model considered Kc dry value as 0.7 for nursery, 1.05 for development and 0.7 for late stage. On the other hand, Kc wet value as 1.2 fornursery, 1.2 for development and 1.05 for late stage.

The CROPWAT model necessitates soil water status such as: initial available moisture, readily available moisture, and total available moisture. In this study the CROPWAT model comprehends default data for loamy soil. Default maximum percolation rate was 3.4 mm day^{-1} for silt loam soil in the model. The rice rooting depth was considered up to 40 cm.

Calculation of reference or potential Evapotranspiration (ET_o)

The CROPWAT software was used to determine ETo in mm $day^{-1}$and the radiation in $MJm^{-2}d^{-1}$ using relative humidity (%), wind speed (m s^{-1}), sunshine hours (h) and the average maximum and minimum temperatures (°C). All data were collected from Bangladesh Meteorological Department.

ET_o was calculated according to Penman-Monteith method using CROPWAT 8.0 model. The Penman–Monteith equation (FAO, 1998) incorporated in the CROPWAT model. Potential: CROPWAT model, crop water requirement, effective rainfall, crop water requirement, irrigation scheduling, T. Aman, transplanting date

Evapotranspiration is expressed by using following equation:

$$ET_0 = \frac{0.0408\,\Delta\,(R_n - G) + \gamma \frac{900}{T+273} U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34\,u_2)} \qquad (1)$$

Where, ET_0 is reference or potential crop evapotranspiration (mm d^{-1}); G is soil heat flux (MJ $m^{-2}d^{-1}$); T is average air temperature (°C); Rn is net radiation at the crop surface (MJ $m^{-2}d^{-1}$); γ is psychrometric constant (kPa $°C^{-1}$); U2 is wind speed measured at 2 m height (ms^{-1}); ($e_s - e_a$) is vapor pressure deficit (kPa); Δ is slope of the vapor pressure curve (kPa$°C^{-1}$); and 900 is a conversion factor.

Calculation of effective rainfall

Effective rainfall was calculated by giving decadal rainfall in CROPWAT and the average rainfall was calculated for a 34-year period. The amount of precipitation which effectively

USDA Soil Conservation method was used to calculate effective rainfall (Smith, 1991). In USDA Soil Conservation method assumes crops can use usually 60–80% of precipitation up to 250 mm per month. The crops will be benefited only 10% if the total precipitation exceed 250 mm per month. In other words, if precipitation increased, its efficiency decreased. The effective rainfall is calculated by empirical equation:

$$P_{effective} = P * \frac{(125-0.2\,P)}{125} \text{ For P<250 mm} \quad (2)$$

$$P_{effective} = 125 + 0.1\,P \text{ For P>250 mm} \quad (3)$$

Where, $P_{effective}$ is effective rainfall (mm), and P is monthly rainfall (mm)

Estimation of crop water requirement and time of application

The amount of water, plant uptake by the help of its rooting system is called crop water requirement (CWR) which is essential for plant growth and development (Michael, 1974). According to (FAO, 2005) CWR equals crop evapotranspiration under standard conditions, and it is expressed as:

$$\text{CWR} = \sum(\text{ET}_o \times \text{k}_c) \quad (4)$$

Where Kc is the crop coefficient of the given crop during the growth stage and T is the final growth stage.

RESULTS AND DISCUSSION

Distribution of potential crop evapotranspiration and rainfall

Figure 2 illustrates the annual potential evapotranspiration (ET_0) and annual rainfall in the study locations. It showed that the highest annual rainfall 2,243 mm in Rangpur followed by 2,220 mm, 1,812 mm, 1,759 mm in Mymensingh, Dinajpur and Bogura, respectively.

The lowest rainfall was 1,372 mm in Rajshahi. Among the study locations, the highest ET_0 was 1,450 mm in Jashore, whereas the lowest 1,228 mm accounted in Mymensingh. Annual rainfall exceeded the ET_0 in Jashore, Bogura, Rangpur, Dinajpur and Mymensingh locations. In the other locations, rainfall and ET_0 were similar.

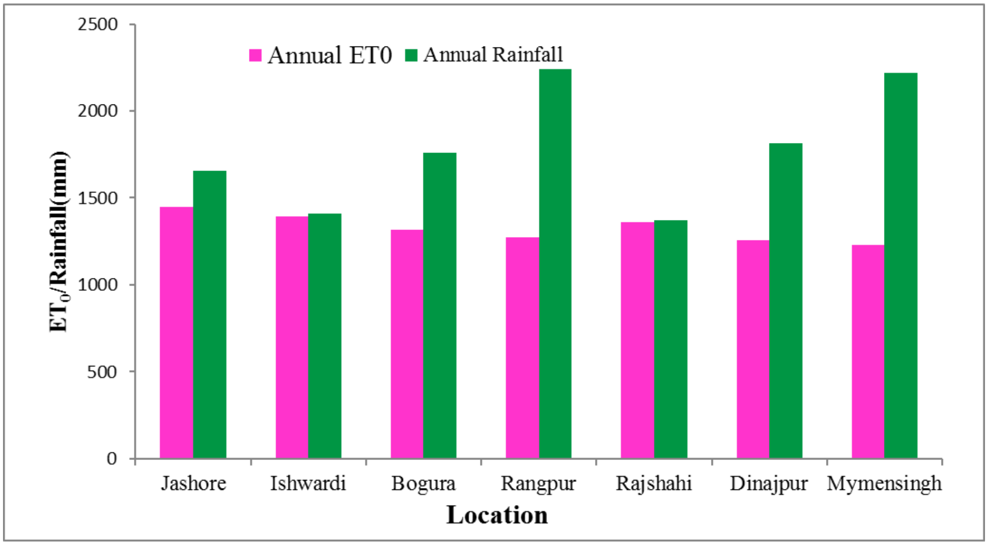
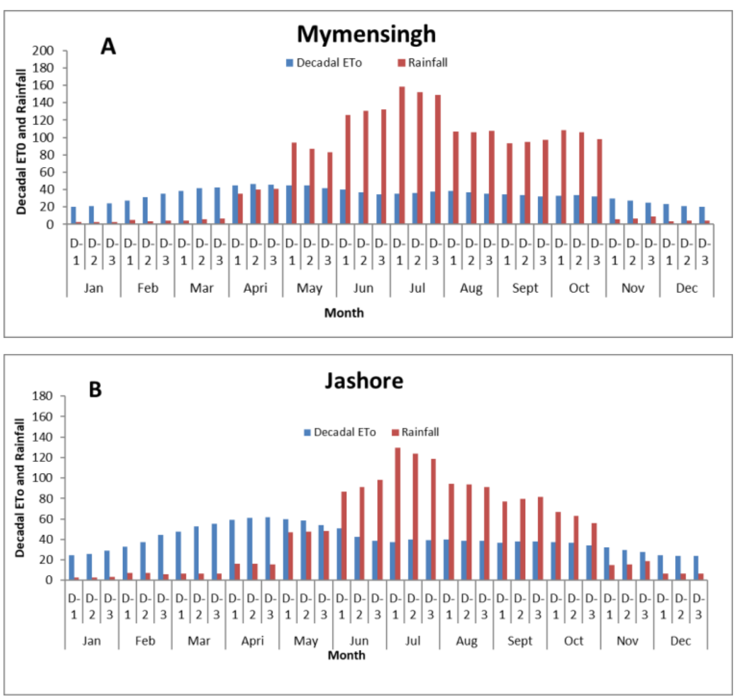


Fig 2. Spatial distribution of annual normal rainfall and potential evapotranspiration.

Spatiotemporal variation of crop water requirement and rainfall

Spatiotemporal distribution of decadal normal crop water requirement (ET_0) and rainfall in the study region were analyzed (Fig. 3). In Rangpur, from the first decade of May to last decade of October rainfall was found higher than ETo. It indicated that no irrigation was required to meet the consumptive use of crop due to enough rainfall. In the other period of the year, rainfall was deficit than ET_o and thus needed irrigation. In Jashore, between the first decade of June to the last decade of October rainfall was higher than ETo but between November to May ETo was higher than rainfall. The observed decadal ETo values compared to rainfall were higher from May to October and lower from November to April in Mymensingh. The highest decadal ETo was found in the second decade of April and the lowest in the first decade of January in Rajshahi. For the location of Bogura, the first decade of June to the last decade of October rainfall was higher than ETo and November to May ETo was higher than rainfall. In Dinajpur, it was observed that rainfall was higher than ETo from June to October, whereas from November to May, ETo was higher than rainfall. In another study, Hossain *et al*., (2017) found that during June to October rainfall was sufficient to meet the ETo in Western region of Bangladesh. Other than these months, ETo exceeded effective rainfall.

The temporal variation of ETo showed that the lowest ETo was found in January in almost all locations. It showed the rising trend after January and reached its peak in April. From March to June evapotranspiration increased due to low relative humidity and high temperatures. In contrast, in winter (November to February) evapotranspiration reduced due to high humidity along with low sunshine hours and temperature. Similarly, Hossain *et al*., (2017) found that potential ET value reduced with the lower values of wind speed, sunshine hours and temperature.



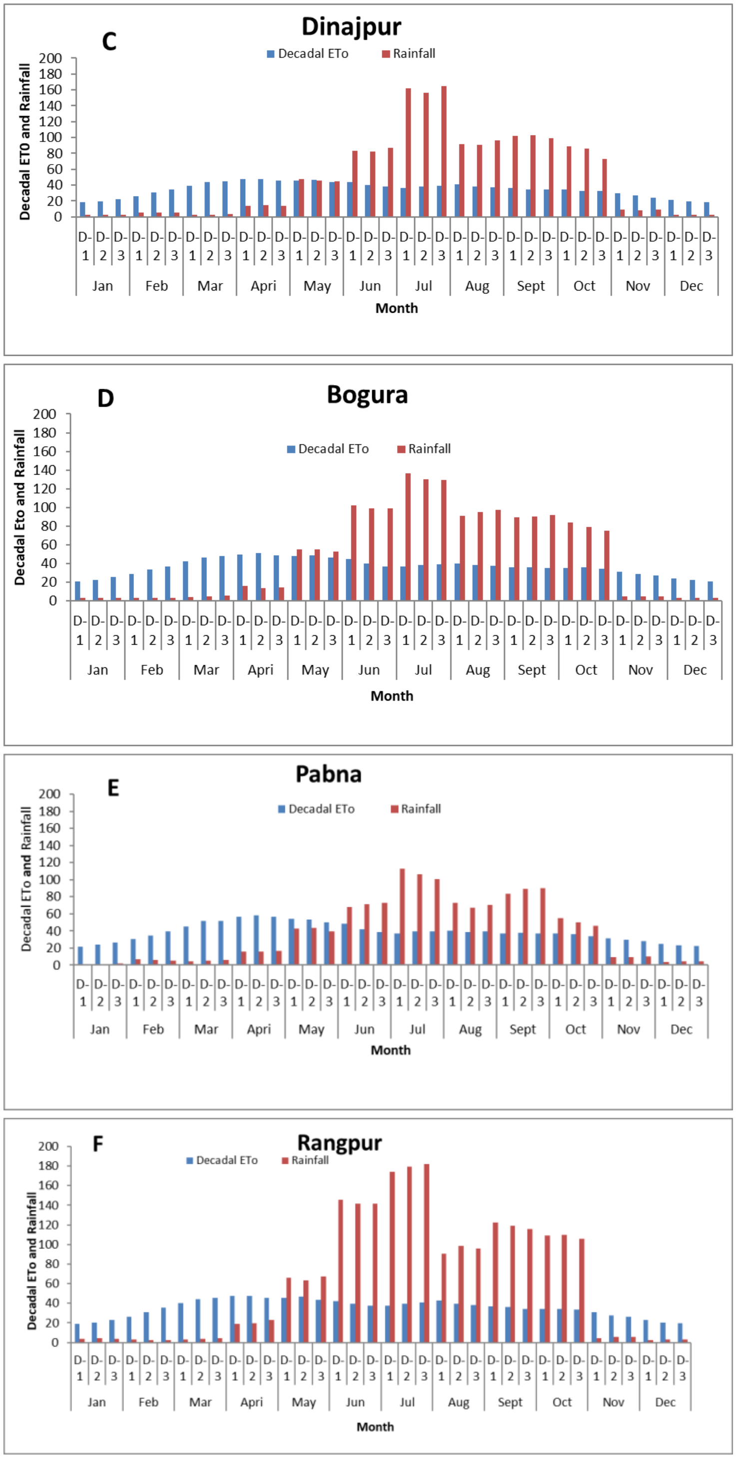


Fig 3. Spatiotemporal distribution of decadal normal ETo and rainfall in selected locations in Bangladesh (A-Mymensingh; B-Jashore; C-Dinajpur; D-Bogura; E-Pabna and F- Rangpur).

Crop water requirement, Effective Rainfall (ER) and net Irrigation Requirement (NIR) considering different transplanting dates:

Figure 4 shows rice crop water requirement (ETc) and effective rainfall for different transplanting dates which were analyzed. It depicts that the total effective rainfall was higher than ETc in transplanting dates for all locations. Among the tested transplanting dates, transplanting on 15 July showed rice would receive the highest rainfall amount during its growing span and produce highest ETc in all locations. Both rainfall and ETc followed a decreasing trend for delay transplanting. The maximum rainfall coverage was observed in Rangpur (720 mm), followed by Mymensingh (705 mm), Dinajpur (693 mm), Bogura (682 mm) for 15 July transplanting. However, the minimum rainfall was found in Pabna (416 mm) and Rajshahi (423 mm) for 30 August transplanting. Although, seasonal effective rainfall was higher than ETc, its uneven distribution caused drought in the crop growing period.

Table 1 shows the irrigation requirement and net irrigation requirement of T. Aman rice which were analyzed. It depicts that no supplemental irrigation was needed for transplanting on 15 July in all locations except Pabna. CROPWAT model estimated one supplemental irrigation (65 mm) for Pabna rice is transplanted on 15 July. Both the number of irrigation and NIR showed increasing trend for the delay transplanting. T. Aman rice transplanted on 30 July demanded one supplemental irrigation for Jashore (63 mm) and Rajshahi (65 mm) and two supplemental irrigations for Pabna (130 mm). However, no supplemental irrigation was predicted for Rangpur, Bogura, Dinajpur and Mymensingh.

The analysis suggests that transplanting on 15 August required supplemental irrigation of varying number for all locations. The highest three irrigations of 200 mm were estimated for Pabna region. Two irrigations were required for Jashore (133 mm) and Rajshahi (130 mm). Only one irrigation was estimated for Bogura, Rangpur, Dinajpur and Mymensingh regions. The effective rainfall after 15 August decreased steeply and crop growing period went to mid-November to December which is the dry month of the year. Thus, crop transplanted after 15 August faced terminal drought and accounted for supplemental irrigation. The highest five supplemental irrigations of 337 mm in total were estimated for Pabna, whereas the lowest three supplemental irrigations were accounted for Rangpur, Dinajpur and Rajshahi locations.

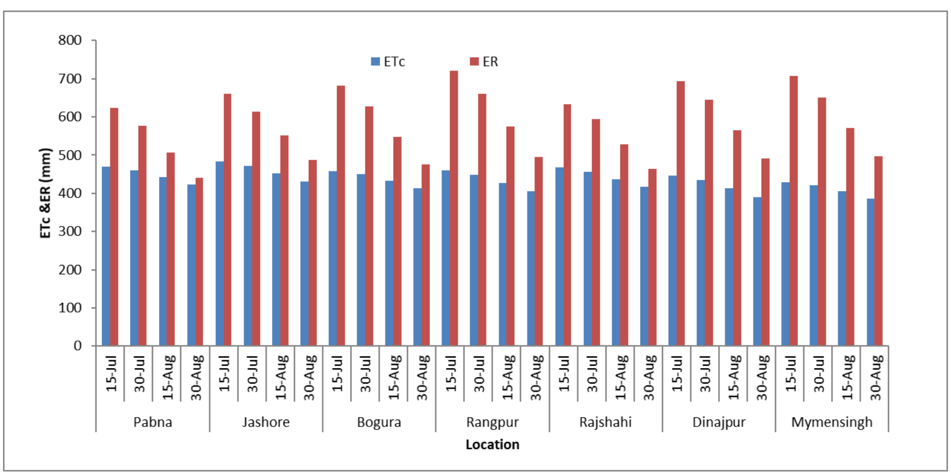


Fig 4. Spatial variation of rice crop water requirement (ETc) and effective rainfall

Table 1. Seasonal net irrigation requirement of T. Aman rice for different transplanting time in the study location.

Location	D/T	IR	NIR	No. of Irrigation
Pabna	15 July	1.9	65.3	1
	30 July	35.6	130	2
	15 August	69.8	199.7	3
	30 August	112.7	336.7	5
Jashore	15 July	0	0	0
	30 July	19.6	63	1
	15 August	45.3	132.6	2
	30 August	84.9	265.9	4
Bogura	15 July	0	0	0
	30 July	0	0	0
	15 August	70.7	61	1
	30 August	110.8	246	4
Rangpur	15 July	0	0	0
	30 July	0	0	0
	15 August	67.1	60.1	1
	30 August	106.5	185.3	3
Rajshahi	15 July	0	0	0
	30 July	25.4	65	1
	15 August	55	129.7	2
	30 August	94.8	260.2	3
Dinajpur	15 July	0	0	0
	30 July	0	0	0
	15 August	52.4	62	1
	30 August	89	186.4	3
Mymensingh	15 July	0	0	0
	30 July	0	0	0
	15 August	58.2	62	1
	30 August	95.4	222	4

CONCLUSION

Irrigation scheduling of T. Aman rice based on normal rainfall distribution was analyzed for Northwest and Southeast regions of Bangladesh using CROPWAT model. The estimated crop water requirement of T. Aman rice found lower when it was transplanted on 15 July in all locations due to higher effective rainfall. Both irrigation requirement and its split application gradually increased with delay transplanting over 15 July. No supplemental irrigation was required for T. Aman rice for 30 July transplanting in Rangpur, Dinajpur, Bogura and Mymensingh regions. Transplanting on 30 July in Jashore and Rajshahi, required one supplemental irrigation to meet the crop water demand. Supplemental irrigation must be applied in Pabna for T. Aman rice cultivation transplanting on 15 July to 30 August. Early transplanting demanded less irrigation than late transplanting. Transplanting of T. Aman rice within 30 July found the most appropriate time for utilizing maximum rainfall irrespective of all locations. Delay transplanting of T. Aman rice experienced terminal drought which may encounter yield reduction. Timely transplanting of rice could be saved ground water for irrigation as well as cost of production.

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Grain Yield and Water Productivity of Irrigated Rice Affected by Transplanting Dates in Bangladesh

M B Hossain[1*], D Roy[1], M N H Mahmud[1], P L C Paul[1], M S Yesmin[1], P K Kundu[2], M T Islam[3] and A A Rim[4]

ABSTRACT

Selection of suitable transplanting window is essential for getting desired crop yield and optimizing irrigation water. This study was conducted in four different locations of Bangladesh (Gazipur, Mymensingh, Cumilla and Bogura districts) to investigate the effect of transplanting period on irrigation water productivity during irrigated rice (Boro) cultivation. Ceres-rice model incorporated in DSSAT was used to estimate rice grain yield and agronomic parameters for Boro 2016-17. Daily weather data and soil data were collected from Bangladesh Meteorological Department (BMD) and Soil Resource Development Institute (SRDI). The estimated irrigation scheduling using CROPWAT-8.0 model was used as input to the DSSAT model. Rainfall distribution showed only about 22% (2% in winter and 20% in pre-monsoon) of annual rainfall occurred in irrigated rice growing period. Delay transplanting after 15 December, the cultivar BRRI dhan28 faced higher mean daily temperature resulted shorter life span. The increased seasonal mean temperature by 2.8ºC in Gazipur and Bogura and 2.6ºC in Mymensingh and Cumilla from 15 December to 01 March reduced growth duration by 24 days in Gazipur, Mymensingh and Bogura and by 26 days in Cumilla district. Cumilla received the maximum rainfall, however Gazipur experienced the lowest among the four study locations. The received rainfall amount increased with the advancement of transplanting date from 15 December. The increased rainfall reduced the irrigation demand of the cultivar. On the contrary, reduced growth duration due to delay transplanting decreased the grain yield. Transplanting up to 1 February produced almost similar grain yield, while irrigation demand decreased from 15 December transplanting. Water productivity showed increasing trend for late transplanting. Considering grain yield and irrigation water productivity, 15 January to 1 February transplanting were found suitable transplanting period for the study locations. Rice crop establishment within the recommended period could be optimized the grain yield and irrigation water productivity in the selected study locations. Thus, maximum coverage of rainfall can be reduced the irrigation demand. Consequently, it may help to optimize groundwater use and to arrest the groundwater mining.

Key words: Irrigation, rainfall, transplanting date, Boro rice, water productivity

INTRODUCTION

Increasing irrigation water productivity is one of the main factors for water utilization during irrigated rice (Boro) cultivation. Rice (*Oryza sativa L.*) is the staple cereal in Bangladesh and Boro rice contributes 49.12% of total annual rice production (BBS, 2017). Low air temperature during winter branded Boro rice as long duration crop. Due to less rainfall in winter, Boro rice requires huge amount of irrigation water and other inputs compared to other seasons (Roy *et al.*, 2019). However, Bangladeshi farmers are habituated to grow Boro rice for its high yielding capacity. Modern varieties are highly reactive to water management, fertilizer doses and responsive to temperature during growth period.

According to IPCC (2007) projection, climate change may cause temperature rise as well as erratic rainfall pattern which will impact Bangladesh agriculture in the long run. Hence, crop evapotranspiration rate increases due to high temperature (Chaouche *et al.*, 2010), rice plant would need extra irrigation water to meet up the excess crop water requirement. However, increased temperature would reduce the rice growth duration.

[1]Senior Scientific Officer; [2]Scientific Officer; [3]Chief Scientific Officer, Irrigation and Water Management Division, Bangladesh Rice Research Institute (BRRI), Gazipur-1701, Bangladesh; [4]Soil Science Division, Bangladesh Rice Research Institute (BRRI), Gazipur 1701, Bangladesh.
*Corresponding author's E-mail: belal.iwm@gmail.com (M B Hossain)

Maniruzzaman *et al.*, (2018) noticed that elevated temperature in Bangladesh resulted yield loss and shorter growth duration of irrigated rice (Boro). Acharjee *et al.*, (2017) indicated that shorter growth duration reduced potential crop water requirement of Boro rice. Due to changing climate and intensive crop cultivation, water resources in Bangladesh are getting scared (Roy *et al.*, 2014). Rainfall shortage and increasing extreme rainfall event causing less surface water storage resulting less groundwater recharge. Thus, declining trend of groundwater is observed in most of the locations of Bangladesh (Hossain *et al.*, 2021). Ahmed *et al.*, (2004) reported rapid increase of arsenic contamination in the rice growing areas due to excess withdrawal of groundwater during Boro season. To feed the over increasing population of Bangladesh, contribution of Boro rice needs to be sustained. Thus, Boro rice production should be ensured with decreasing water use for irrigation. It could be expected that delay in Boro rice transplanting would reduce field duration of crop as well as crop water requirement. The rice water demand in later part of the growing period due to late transplanting would be fulfilled by pre-monsoon rainfall. Delayed transplanting of Boro rice up to a certain time limit may not cause significant yield loss. With this view, the study was undertaken with the following objectives as: i) to identify the effect of late transplanting on grain yield of irrigated rice and, ii) to determine the irrigation requirement and water productivity of Boro rice for shifting transplanting period.

METHODOLOGY

Study locations

The study locations consisted of four different districts Gazipur, Mymensingh, Cumilla and Bogura in Bangladesh. Each location situated in different agro-ecological zone (AEZ) with varying climate and soil. Figure 1 shows the study areas of Bangladesh. The minimum temperature showed increasing trend from January and reached its maximum in June after that it begins to decrease trend. Among the study areas Mymensingh experienced the lowest mean temperature, whereas the highest temperature was found in Gazipur and Bogura. The maximum rainfall occurred in July for all the locations.

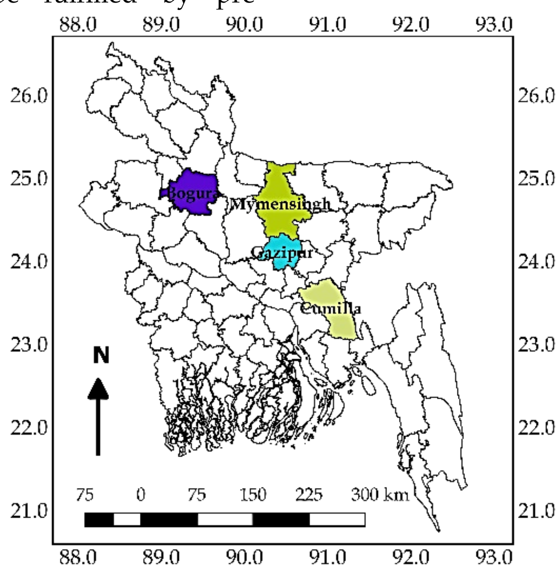

Fig. 1. Study area

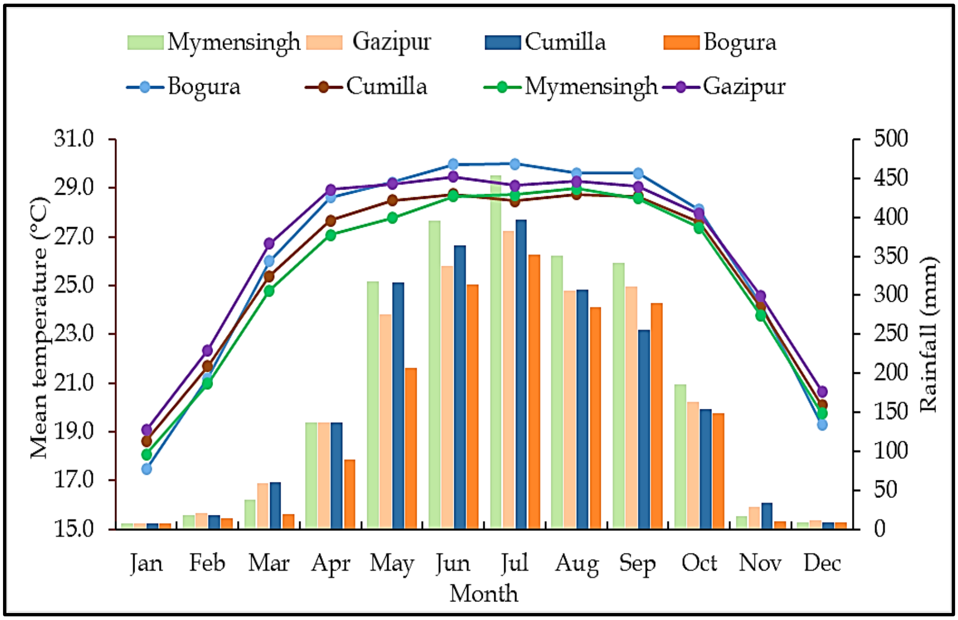

Fig. 2. Normal monthly mean temperature and rainfall (1981-2018) of the study areas.

Data Collection Model Parameterization

Weather and soil data

Historical daily weather data of maximum and minimum temperature, relative humidity, wind speed, bright sunshine hour and rainfall were collected from Bangladesh Meteorological Department (BMD). Required soil data of texture and particle size distribution, organic carbon, pH and nitrogen were collected from Soil Resource Development Institute (SRDI), Bangladesh. Ceres-rice model incorporated in Decision support system for agrotechnology transfer (DSSAT) model were adopted in this study. Weather and soil file for each study locations were made using the model as the input.

Cultivar selection

Bangladesh Rice Research Institute (BRRI) developed popular rice variety BRRI dhan28 were tested in four study locations. Average growth duration of BRRI dhan28 is 145 days with mean yield of 6.5 t ha^{-1} (Anonymous, 2020). Maniruzzaman *et al.*, (2017) identified the cultivar coefficient and we adopted it in our study. The cultivar coefficient was calibrated with the nitrogen fertilizer management experiment and validated with the genotype × environment interaction experiment. Table 1 shows the parameters of cultivar coefficient.

Table 1. Genetic coefficient of BRRI dhan28 for Bangladesh condition.

Cultivar	P1	P2O	P2R	P5	G1	G2	G3	G4	PHINT
BRRI dhan28	825	12.6	150	425	50	0.022	1.0	1.0	83

Where, P is time period in GDD (growing degree days) in °C above a base temperature from seedling emergence during which the rice plant is not responsive to changes in photoperiod. This period is also referred to as basic vegetative phase of the plant. P2O indicated critical photoperiod or the longest day length (in hours) at which the development occurs at a maximum rate, P2R was extent to which phasic development leading to panicle initiation is delayed (expressed as GDD in °C) for each hour increase in photoperiod above P2O, P5 indicated time period in GDD °C from beginning of grain filling to physiological maturity, G1 represented potential spikelet number coefficient as estimated from the number of spikelet per g of main culm dry weight, G2 is single grain weight (g) under ideal growing conditions, G3 is tillering coefficient (scaler value) relative to IR64 cultivar, G4 was temperature tolerance coefficient.

Model calibration and validation

For the model calibration, the observed grain yield and growth duration for varying transplanting time from 6 January to 22 February in 2016-17 and 2017-18 were compared with model simulated results. The field experiment was conducted at BRRI farm, Gazipur during Boro season. The model also validated by comparing simulated results with the observed grain yield of BRRI dhan28 from a multi-location trials conducted in the same year. The model performance was evaluated using normalized root mean square error (nRMSE), prediction error (P_e), coefficient of determination (R^2), degree of agreement (d). The equations for above mentioned statistical performance indicators are given below:

$$nRMSE = \frac{1}{\bar{O}}\sqrt{\frac{\sum_1^n (P_i - O_i)^2}{N}} \times 100 \quad (1)$$

$$P_e = \frac{(P_i - O_i)}{O_i} \times 100 \quad (2)$$

$$R^2 = \left[\frac{\sum(O_i - \bar{O})(P_i - \bar{P})}{\sqrt{\sum(O_i - \bar{O})^2 \sum(P_i - \bar{P})^2}}\right]^2 \quad (3)$$

$$d = 1 - \frac{\sum_{i=1}^N (P_i - O_i)^2}{\sum_{i=1}^N (|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (4)$$

The coefficient of determination (R^2) value ranges from 0 to 1. The value close to 1 represents a good agreement while only the value greater than 0.5 is the acceptable limit for watershed simulations (Moriasi *et al.*, 2007). For nRMSE, excellent model simulation is found if the value is smaller than 10%, good between 10 and 20%, fair between 20 and 30% and poor if larger than 30% (Raes *et al.*, 2012). The degree of agreement values (*d*) ranges between 0 and 1, where 0 indicates no agreement and 1 indicates a perfect agreement between predicted and observed data (Willmott, 1984).

Simulation of grain yield and growth duration

Rice grain yield and growth duration were estimated during Boro 2016-17 and 2017-18 for different transplanting periods. Four transplanting dates such as 6 January, 22 January, 6 February and 22 February were considered in this study. Forty-day-old rice seedlings were transplanted at a rate of 2-3 seedlings per hill. BRRI recommended urea fertilizer was applied @120 Kg-N in three equal splits.

Irrigation scheduling of rice

Irrigation was applied following alternate wetting and drying (AWD) irrigation practices. To do so, we utilized Food and Agriculture Organization (FAO) developed CROPWAT 8.0 model to determine the irrigation schedule of BRRI dhan28 for different transplanting dates. The model utilized maximum and minimum temperature, humidity, wind speed, sunshine hours, and rainfall to produce irrigation scheduling for rice crops. Then the estimated irrigation schedule for each transplanting date was used as input to the Ceres-rice model.

Growth duration, grain yield and water productivity

The seasonal mean temperature for each transplanting date was calculated for transplanting date and its relationship was developed to the crop growth duration. The amount of rainfall received by the crop and applied irrigation for each transplanting date were accounted. Finally, water productivity of rice was calculated from grain yield, rainfall and irrigation as shown in equation (i):

$$Irrigation\ water\ productivity\ (kg\ m^{-3}) = \frac{Grain\ yield\ (t\ ha^{-1}) \times 100}{Applied\ irrigation\ (mm)} \quad (i)$$

RESULTS AND DISCUSSION

Model calibration

Model simulated and field observed growth duration for different transplanting dates was analyzed (Table 2). For growth duration analysis, coefficient of determination (R^2) value was 0.79, normalize root mean square error (nRMSE) was below 10% and index of agreement value 0.83 indicated excellent model performance between simulated and observed field data of BRRI dhan28. Similar agreement was found for yield performance analysis (Table 3) where model simulated grain yield and field observed yield showed good agreement with R^2 value 0.65, nRMSE value 7.7 and d value 0.84.

Model validation

The validation of Ceres rice model was done with simulated and observed grain yield data during Boro, 2016-17 (Fig. 3) from a multi-location trial. Good model validation was found with nRMSE value 15.1, R^2 value 0.7 and 0.8 and d value 0.5 for grain yield of BRRI dhan28.

Rainfall distribution pattern

Figure 4 presents Annual rainfall of Gazipur, Cumilla, Mymensingh and Bogura which has been analysed. Among the study locations, the highest annual normal (37-year average) rainfall 2,270 mm was found in Mymensingh followed by 2,059 mm in Cumilla and 2,023 in Gazipur. However, the lowest 17,44 mm was observed in Bogura. All the study locations received comparatively higher rainfall than national average of 15,00-2,000 mm (Roy and Sattar, 2009). Seasonal rainfall distribution showed that rainfall occurrence is mostly season based and more than 60% of annual rainfall (66, 64%, 67% and 70% in Gazipur, Cumilla, Mymensingh and Bogura, respectively) was observed during monsoon (June to September) season (Figure 5). Biswas *et al.,* (2015) showed 92.7% total rainfall occurred during May to October in the northwest region of Bangladesh. Other than monsoon the second highest rainfall observed during pre-monsoon season followed by post monsoon season. Only 2% of total annual rainfall was observed in winter in all study locations.

Table 2. Simulated and observed grain yield and growth duration of BRRI dhan28 at Gazipur during Boro 2016-17 and 2017-18.

	Treatment	Growth duration (day)		nRMSE	R^2	d
		Simulated	Observed			
2016-17	06-Jan	137	138	5.66	0.79	0.83
	22-Jan	133	133			
	06-Feb	128	130			
	22-Feb	122	126			
2017-18	06-Jan	140	146			
	22-Jan	135	144			
	06-Feb	131	138			
	22-Feb	123	130			

Table 3. Simulated and observed grain yield and growth duration of BRRI dhan28 at Gazipur during Boro 2016-17 and 2017-18.

Year	Treatment	Grain yield (t ha^{-1})		nRMSE	R^2	d
		Simulated	Observed			
2016-17	06-Jan	5.53	5.74	7.7	0.65	0.84
	22-Jan	5.70	5.52			
	06-Feb	5.40	5.17			
	22-Feb	4.93	4.97			
2017-18	06-Jan	5.49	5.95			
	22-Jan	5.35	5.84			
	06-Feb	5.18	5.38			
	22-Feb	4.74	4.49			

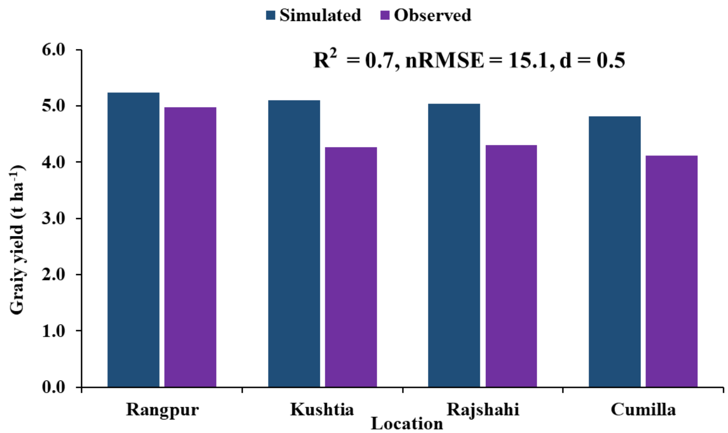

Fig. 3. Model simulated and observed grain yield of BRRI dhan28 in Rangpur, Kushtia, Rajshahi and Cumilla during Boro, 2016-17.

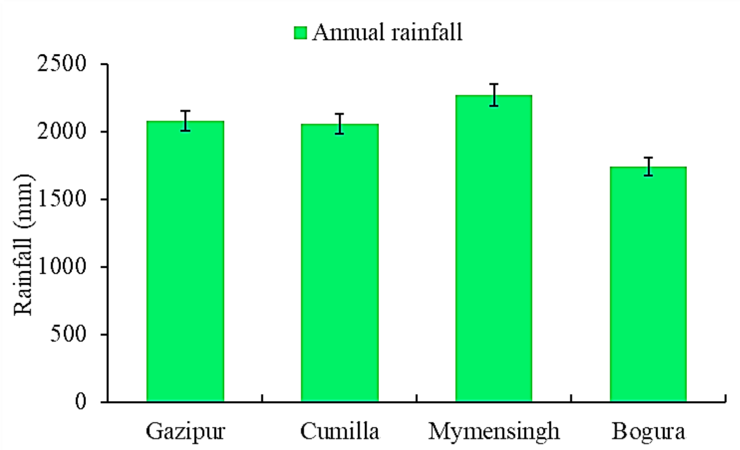

Fig. 4. Annual normal rainfall (mm) distribution of Gazipur, Cumilla, Mymensingh and Bogura (error bar indicates standard error).

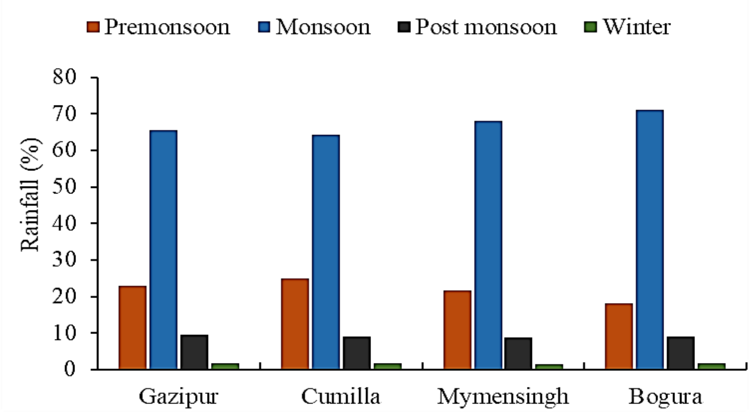

Fig. 5. Distribution of annual seasonal normal rainfall in the study locations.

Temperature effect on growth duration

Effect of seasonal mean temperature on growth duration of BRRI dhan28 on different locations was analysed (Fig. 6). Results showed that Gazipur faced the highest seasonal mean temperature followed by Cumilla and Bogura. Mymensingh received the lowest mean temperature for all the transplanting dates. Seasonal mean temperature showed the rising trend over delay transplanting than 15 December. Growth duration of BRRI dhan28 showed a decreasing trend over transplanting dates. The highest 152 days and the lowest 142 days growth duration of BRRI dhan28 was observed in Mymensingh and Gazipur, respectively for 15 December transplanting. This was the effect of the highest mean temperature 22.8°C observed in Gazipur and the lowest 21.8°C in Mymensingh. Delay transplanting of BRRI dhan28 from 15 December to 1 March increased temperature by 2.8°C in Gazipur and Bogura and by 2.6°C in Mymensingh and Cumilla. This increased temperature reduced the life span of the variety BRRI dhan28 by 24 days in Gazipur, Mymensingh and Bogura, and by 26 days in Cumilla district. This result was identical to Ahmed *et al.*, (2015) who found physiological maturity of BRRI dhan28 reduced by 14 to 16 days for delay sowing from 1 to 30 November in Jashore district. Maniruzzaman *et al.*, (2018) observed that growth duration of BRRI dhan28 reduced by 8, 7 and 10 days in Gazipur, Cumilla and Rajshahi respectively, for rising temperature by 1 °C.

Rainfall coverage and rice irrigation water requirement for Boro rice

Boro rice cultivation starts in winter and matured in pre-monsoon season resulting high irrigation demand in its growing period. However, all the locations received considerable amount of rainfall during pre-monsoon. BRRI dhan28 experienced the lowest amount of rainfall water when it transplanted on 15 December. The received rainfall amount increased with the delay transplanting from 15 December. The spatial rainfall variation showed that Cumilla got the highest rainfall among the locations in all transplanting date except 1 March (Fig. 7). On the contrary, Gazipur received the lowest rainfall among the locations for all transplanting dates. The higher received rainfall reduced the irrigation demand as

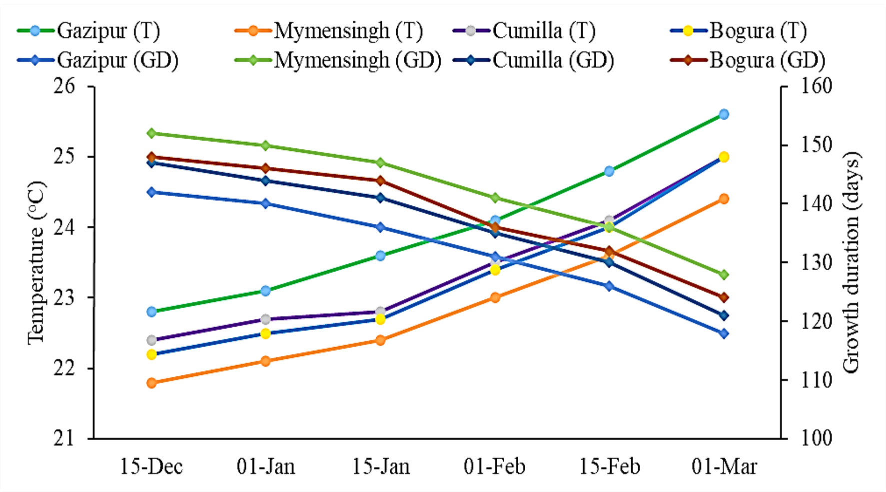

Fig. 6. Seasonal mean temperature effect on growth duration of BRRI dhan28 during Boro, 2016-17 in Gazipur, Mymensingh, Cumilla and Bogura. T indicates seasonal mean temperature and GD for growth duration.

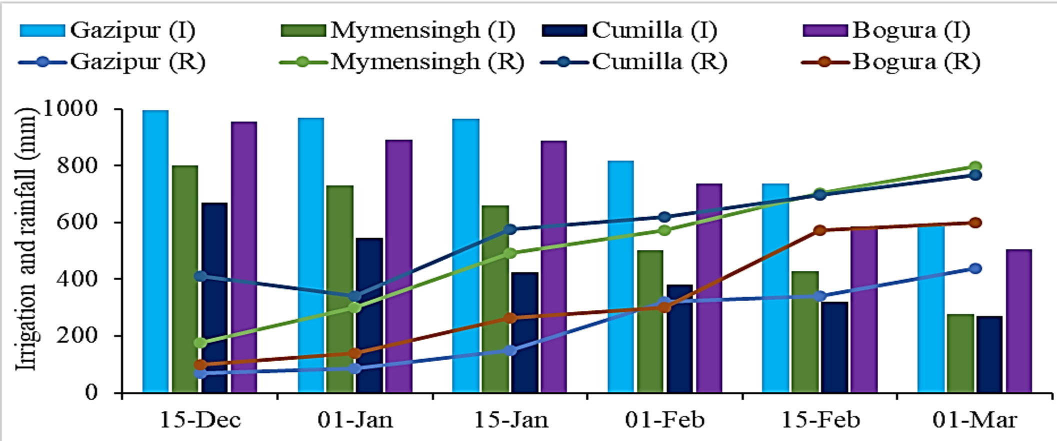

Fig. 7. Spatio-temporal variation of rainfall coverage and irrigation water requirement of BRRI dhan28 under different transplanting dates during Boro, 2016-17

rainfall met the consumptive use of rice. Hence, irrigation demand reduced with the delay transplanting in every location. The highest irrigation water (995 mm, 800 mm, 670 mm and 956 mm in Gazipur, Mymensingh, Cumilla and Bogura respectively) was applied for 15 December transplanting whereas 1 March transplanting required the lowest irrigation water (585 mm, 277, 272 and 507 mm in in Gazipur, Mymensingh, Cumilla and Bogura respectively).

Grain Yield performance and water productivity

Table 3 shows the spatio-temporal variation of grain yield of BRRI dhan28 under varying transplanting dates. It explained that yield potentiality of the cultivar decreased with the delay transplanting in all over the locations. This was due to the increased seasonal mean temperature reduced the growth duration as well as enhanced maturity of the variety. Among the locations, the highest grain yield was found in Mymensingh in all transplanting dates. In Mymensingh, 15 December to 15 January transplanting showed parallel grain yield performance (6.73 to 7.01 t ha^{-1}) and after that period yield reduction occurred. Similar yield was monitored both in Cumilla and Bogura for 15 December to 1 February transplanting. In Gazipur, the maximum grain yield was observed 5.25 t ha^{-1} for 1 January transplanting; however, similar yield was recorded for 15 December (5.23 t ha^{-1}) 15 January (5.02 t ha^{-1}) and 1 February (5.1 t ha^{-1}) transplanting. These results were found identical to Roy *et al.*, (2019) who found the decreasing yield over delay transplanting of BRRI dhan28. Yesmin *et al.*, (2019) noticed 15 November to 15 December the best sowing window for BRRI dhan28 at Amtali, Barguna area considering grain yield.

Delay transplanting increased the irrigation water productivity of Boro rice. This is due to the more rainfall accumulation in the late planting condition reduced the irrigation water demand. In Gazipur, the maximum irrigation water productivity was found on 1 February transplanting and that was minimum in 15 December transplanting. In the other locations, 1 March transplanting showed the maximum irrigation water productivity (1.98, 1.55 and 0.83 kg m^{-3} in Mymensingh, Cumilla and Bogura, respectively). The lowest 0.84, 0.82 and 0.58 kg m^{-3} irrigation water productivity was monitored in Mymensingh, Cumilla and Bogura, respectively for 15 December transplanting.

Table 4. Grain yield and water productivity of BRRI dhan28 in the study locations during Boro 2016-17.

Transplanting date	Grain yield (t ha^{-1})				WP (kg m^{-3})			
	Gazipur	Mymensingh	Cumilla	Bogura	Gazipur	Mymensingh	Cumilla	Bogura
15-Dec	5.25	6.73	5.49	5.53	0.53	0.84	0.82	0.58
01-Jan	5.23	7.01	5.62	6.07	0.54	0.96	1.03	0.68
15-Jan	5.02	6.84	5.58	5.99	0.52	1.04	1.31	0.67
01-Feb	5.10	6.20	5.11	5.55	0.62	1.23	1.34	0.75
15-Feb	4.19	6.18	4.94	4.24	0.57	1.45	1.54	0.72
01-Mar	3.16	5.49	4.22	4.20	0.54	1.98	1.55	0.83

CONCLUSION

Rainfall occurrence in Gazipur, Mymensingh, Cumilla and Bogura district of Bangladesh is mostly seasonal and more than 60% of total rainfall occurred during monsoon (June to September). Around 20% of annual rainfall received during pre-monsoon, however only 2% found in Winter. This resulted high irrigation demand in Boro rice cultivation. Delay transplanting of BRRI dhan28 from 15 December to 1 March faced increased temperature by 2.8ºC in Gazipur and Bogura and by 2.6ºC in Mymensingh and Cumilla. Consequently, this increased temperature reduced the life span of the variety by 24 days in Gazipur, Mymensingh and Bogura and by 26 days in Cumilla district. Besides, higher rainfall incidence reduced the irrigation demand in late transplanting condition. Mymensingh region showed the best yield performance among the locations where grain yield declined after 15 January transplanting. Similar trend was noticed in Cumilla and Bogura. The maximum grain yield was observed on 1 January transplanting; however, similar yield was recorded for 15 December to 1 February transplanting in Gazipur. Considering temperature, rainfall and irrigation water availability, 15 January to 1 February transplanting was found suitable transplanting period for the study locations.

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Rice-based Cropping System Intensification in the Coastal Saline area of Bangladesh: Problems and Prospects

P L C Paul[1*], D Roy[1], M N H Mahmud[1], M B Hossain[1], M S Yesmin[1], P K Kundu[2] and M T Islam[3]

ABSTRACT

The coastal zone environment of Bangladesh is characterised geographically by river deltas and estuaries, where tidal and riverine flooding and varying salinity levels affect agriculture and livelihoods. In this area, the land and agricultural productivity is very low because of several constraints, particularly waterlogging, high salinity of soil and water, freshwater scarcity for crop irrigation and natural disaster. In this review, the objectives are to focus on the limiting factors for crop intensifying and highlighting the opportunities to increase coastal agriculture while enhancing farmer's livelihoods. Some recent studies demonstrated many opportunities for increasing cropping systems that have not yet been exploited extensively. Rainwater or low saline river water storing in the internal canal can fulfil the water requirement for dry season rice and non-rice crops, thereby increasing growth and yield. Early establishment of "Rabi" crops (non-rice) can utilize maximum low-saline soil water and escape high salinity/drought or heat/storms at later period of the growing stages, but this early sown Rabi crops needs early harvest of Aman rice around 15-30 days earlier than farmer practices. Moreover, early sowing by zero tilled dibbling (such as sunflower, maize, wheat, and potato) in wet soils results in higher yield potential. Using rice straw mulch ~5 t ha^{-1} has been shown to be highly beneficial for ameliorating soil constraints. A recent study revealed that straw mulch application on soil surface increased soil water and soil solute potential in the upper root zone, reduced soil salinity, soil strength, and cracking which attributed to higher yield. Considering the successful dry season crop establishment and yield potential requires early drainage to remove excess soil water and a drainage system that mitigates waterlogging from heavy rainfall events during the growing season. We expect this review will facilitate the future research planning and execution in this vulnerable coastal environment.

Key words: Waterlogging, salinity, drainage, tillage, mulching, rabi crop establishment

INTRODUCTION

Bangladesh coastal area is in the lower floodplain of the Ganges delta. This area is extremely vulnerable to increasing sea level as the elevation of the area is ~2-3 metres above mean sea level (Paul *et al.,* 2020b). Besides sea level rise, this area is most prone to cyclones, storm surges, and flooding (Paul *et al.,* 2016). The coastal zone comprises ~32 % of the net cultivable land of Bangladesh and is home to over 30 million people (BBS, 2018). Around 1.1 million hectare of coastal land is impacted by various salinity level (Paul, 2020). In this area, cropping intensity is low less than 150% as farmers only grow low-yielding traditional rice ('Aman') in the monsoon season, and huge area stand uncultivated during the dry season (Paul, 2020). Since 2007, this area has been faced by several super cyclones such as "Sidr" in 2007, "Aila," in 2009, "Mahasen" in 2013, and "Amphan" in 2020. These environmental vulnerabilities limit agricultural production, food security, and livelihood improvement in this area. Over the last 10-15 years, several research projects have been implemented especially for cropping system intensification through adoption of high yielding rice and non-rice cultivars, escaping salinity and waterlogging risk, improving soil physicochemical properties, practicing a range of tillage operation, conjunctive use of fresh

[1]Senior Scientific Officer; [2]Scientific Officer; [3]Chief Scientific Officer; Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701.
*Corresponding author's Email: plcpauliwm@yahoo.com (P L C Paul)

and saline water and assessment of salt and water balance (Kabir *et al.,* 2019; Mainuddin *et al.,* 2020; Mondal *et al.,* 2015b; *Paul et al.,* 2021a; Sarangi *et al.,* 2020; Yesmin *et al.,* 2019).

Even though there were some improved technologies for crop establishment, growth, and yield, some negative findings were also recorded from these studies. For example, Paul *et al.* (2021b) demonstrated that early establishment of sunflower has the risk for waterlogging from sudden heavy rainfall while late sowing of sunflower suffers salinity and heat stress later stage of the growing season. On the other hand, mechanized zero tillage in clay-textured soil creates soil smearing, compaction, and cracking, thereby depressing crop growth and development (Paul *et al.,* 2020a).

Furthermore, the land shape and topography and lack of available agricultural tools limit the crop intensification in this area (Mandal *et al.,* 2019). Moreover, a new global pandemic of novel coronavirus (COVID-19) has started to disrupt agricultural farming and could affect food availability in the future. So, it would be challenging to continue the food supply to the entire nation. There is a scope to use underutilized or fallow land during the dry season estimated around 800,000 ha land in the coastal zone, contributing to adding the nation's food basket (Mainuddin *et al.,* 2013). However, a range of constraints needs to be addressed to explore the coastal area for increasing the cropping intensity and productivity.

COASTAL ZONE HYDROLOGY

Land topography

Hydrologically, Bangladesh's coastal zone is influenced by three river basins: the Ganges, Brahmaputra, and Meghna (GBM), which landmass holds 19 districts (Fig. 1). Agricultural land in the coastal area is generally protected by earthen embankments called polders. In the 1960s, 139 polders were constructed to protect agricultural land and livelihoods from tidal inundation and seawater intrusion (Paul, 2020). Figure 2 shows a typical polder view in the coastal zone of Bangladesh. Polders are generally surrounded by river water, which may vary from fresh water in the upper zone (Northern coastal zone) to saline water in a lower zone (close to the Bay of Bengal).

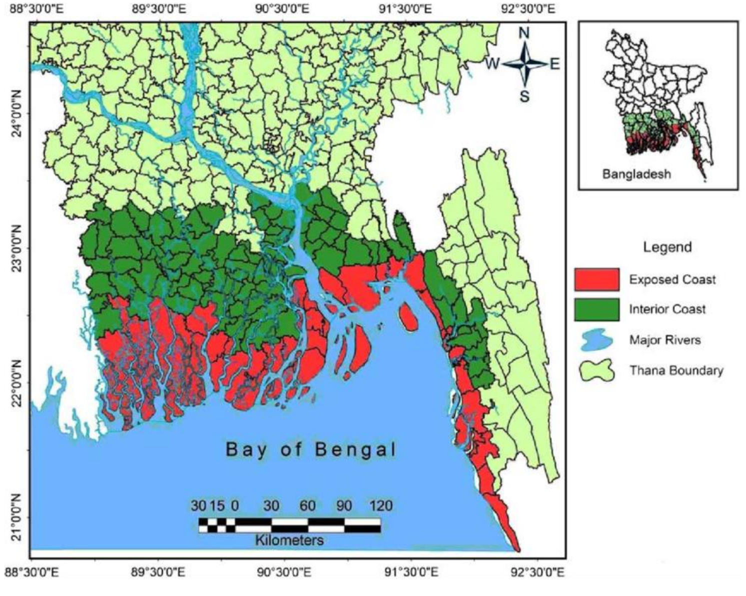

Fig. 1. Coastal zone of Bangladesh green colour (interior coast) and red colour (exposed coast)

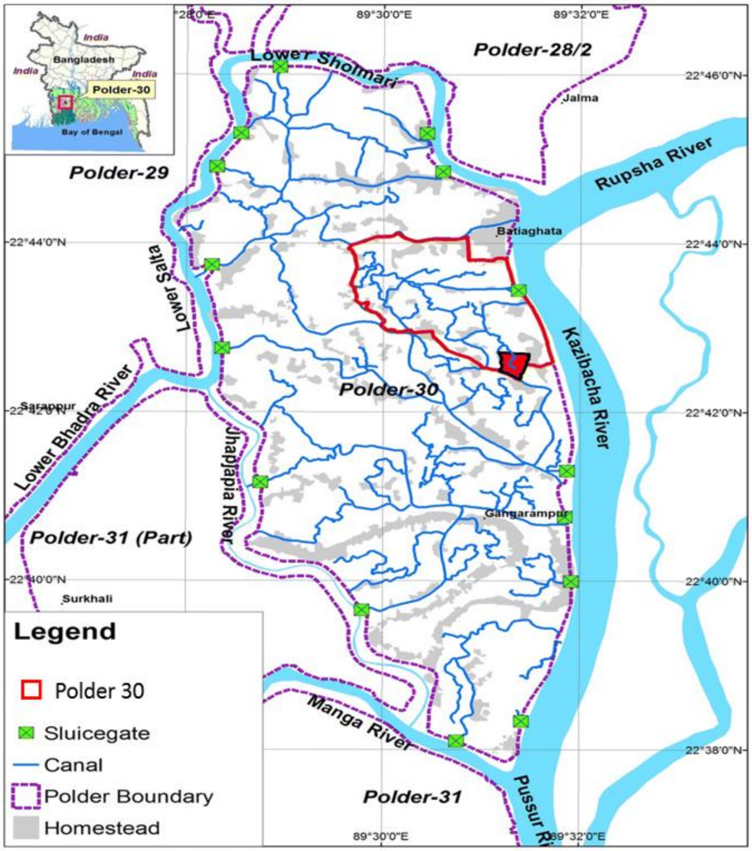

Fig. 2. Plan view of a typical polder in the coastal zone of Khulna district (Yadav *et al.*, 2011)

Variation of water salinity

The water and soil salinity within low-lying polders show both seasonal and spatial variation. Salinity remains low during the monsoon season (July-November) and high in the dry season (December-June). Fig. 3 shows the variation in the EC_w (electrical conductivity of water) of river water at a specific location in the area of Khulna district over five years (2016-17 to 2020-21) and its average. As in the figure, the surface water salinity is very low < 1 dS m^{-1} during August to November, but it exceeds 4 dS m^{-1} in January, reaching a maximum of about 20-30 dS m^{-1} in April-May (ACIAR annual report, 2021). Another report has sown the increasing trend of river water salinity in the coastal area which was 26 dS m^{-1} during April in 2017 and 30 dS m^{-1} during May in 2028 (Belal *et al.*, 2019). The water salinity from different sources during the growing season in 2016-17 is shown in Figure 4. River water salinity increased from mid-December and peaked at 25 dS m^{-1} in April and May (Fig. 4). River water salinity during low tide was slightly lower than high tide. Canal water salinity varied 1 to 3.5 dS m^{-1} entire the season. The pond water salinity was lower than the canal, however, water salinity was almost similar in the two sources in May. Groundwater salinity in this area varies with aquifer depth. The shallow aquifer (~30-50 m deep) has EC_w values ranging from 2.5 to 3.5 dS m^{-1} in March to May, while the deeper aquifer (~150 m deep) has EC_w values greater than 4 dS m^{-1} (Bell et al., 2019).

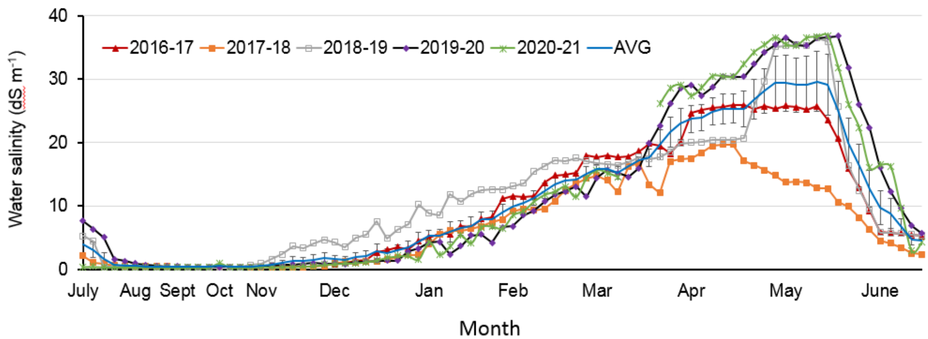

Fig. 3. River water salinity throughout the year in Khulna, Bangladesh.

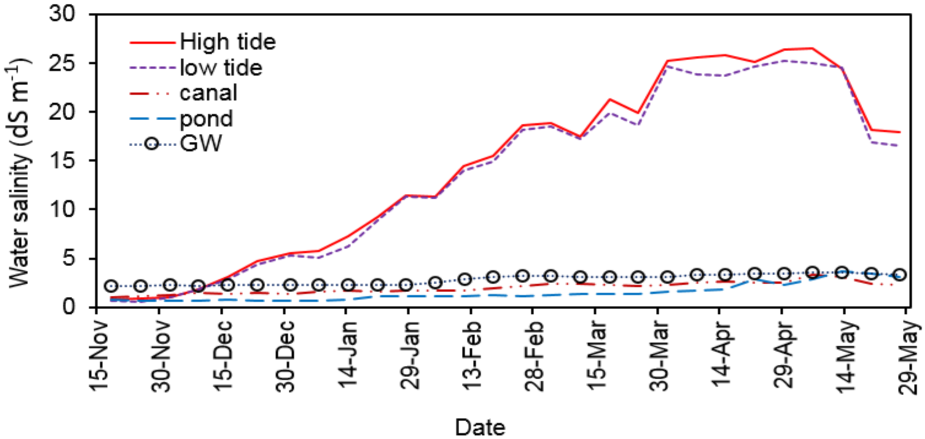

Fig. 4. Variation of water salinity from different sources during the dry season in 2016-17 in Dacope upazila under Khulna district.

Climate and seasonal risk

This area has a subtropical monsoonal climate. The annual rainfall is ~1,800 mm, and ~ 80 % of this occurs in the monsoon season (July to October). Although conditions are generally more humid with higher temperatures in the summer (March-June) and drier with cooler temperatures in the winter (December-February), long-term weather data also show significant variation across the coastal zone (Yu et al., 2019). The temperature in the coastal zone has shown an increasing trend (0.04 ^{0}C year^{-1}) over the last 40 years (Yu *et al.*, 2019), although the west region tends to be warmer than the east (Mondal *et al.*, 2015a). Long-term temperature data showed that the maximum and minimum temperature in the west region (e.g., Khulna) varied from 25 and 35 ^{0}C, and 12 and 26 ^{0}C, respectively, and in the east area (e.g., Patuakhali) varied from 25 and 33 ^{0}C and 13 and 26 ^{0}C, respectively. A recent study has shown that increased temperature was negatively correlated with sunflower yield, and the temperature was the most dominating factor in the variation of sunflower yield than soil salinity (Paul, 2020).

There is a decreasing trend in rainfall from the eastern region to the western region, and from north side to south side. More than 200 mm rainfall (monthly average) occurred in May to October, and the amount was always higher in the east (e.g., Patuakhali) than that in the west (e.g., Khulna) (Bell *et al.,* 2019). Since the 1960s, maximum rainfall over a 5-day period has increased (Yu *et al.,* 2019). This rainfall is beneficial for overall crop production (Bell *et al.*, 2019) as heavy rainfall in the monsoon season dilutes and washes out the available salt in the soil, decreases water salinity (below 1.0 dS m^{-1}), and improves the favorability of the wet season for rice cultivation. In the dry season, increased rainfall is useful to crop production by mitigating salt and drought stress. However, recent studies have shown that a few heavy events of rain often occur in the dry season (November to April), which can interfere with early crop establishment or cause crop damage (Bell *et al.,* 2019). In the same report, they also reported that in November, there could be greater than 20 mm rainfall events in fifty percent of years and greater than 50 mm in 25 % of years, but in December and January, rainfall > 20 mm is unlikely. Similarly, the probability of heavy rain may increase by 25-65 % and 5-30 % for > 20 mm and > 50 mm events, respectively from February to April. These heavy rainfall events in the dry season can create waterlogging, which interacts with salinity in the root-zone to jeopardise crop growth and survival (Barrett-Lennard, 2003). Another study conducted by Paul *et al.* (2020c) found that post-monsoon rain in December damaged sunflower seedlings and decreased yield by about 50% (Fig. 5).

Fig. 5. Sunflower seedling waterlogged by post-monsoon rain in Dacope, Khulna in 2018

ABIOTIC CONSTRAINTS FOR DRY SEASON CROP ESTABLISHMENT

Waterlogging

Large land areas in the coastal zones are seasonally flooded due to the combined effects of monsoon rainfall and tidal influence. These effects usually lead to prolonged waterlogging (saturation of the soil) and water stagnation because of siltation in the river, low infiltration rate, shallow water tables, and poorly structured soils (Ghassemi *et al*., 1995; Ismail and Tuong, 2009). About one million ha of land are annually affected by waterlogging in the coastal zone (Ismail and Tuong, 2009). Waterlogging of soils is crucial abiotic stress that affects plant growth and development (Jackson and Colmer, 2005). Waterlogged soils develop hypoxia (low concentration of oxygen) due to the lower oxygen solubility in water (0.28 mol m-3 at 20 0C) (Qureshi and Barrett-Lennard, 1998), lower rates of oxygen diffusivity in water-filled soil pores (Grable, 1966), and a quick depletion of dissolved oxygen by the respiration of soil bacteria and plant roots (Armstrong and Drew, 2002).

Many winter crops such as vegetables, pulses, and oilseed species cannot tolerate prolonged waterlogging and consequently suffer from plant cell injury over this period because oxygen deficiency strongly restricts ion uptake by roots and ion transport to the shoot. Wilting, chlorosis, and leaf senescence are common plant symptoms in flooded soils (Drew, 1990).

Studies showed that waterlogging under saline conditions can have more damaging impacts on crop growth and yield than waterlogging alone (Singh, 2015). Barrett-Lennard (2003) reviewed the waterlogging and salinity interaction in relation to ion movement and transport, and plant survival status. He showed that plant growth is hindered by the combined effect of waterlogging and salinity because of higher concentration of Na+ and Cl- in the shoot. An experiment conducted by

Paul et al. (2021c) in the south-west coastal region of Bangladesh demonstrated that short term waterlogging more than 24 hours diminished early growth of sunflower.

Soil salinity

The salinity of agricultural land is a severe issue for crop production globally as well as in the coastal zone of Bangladesh. Most tropical coastal zone soils are identified as saline and sodic soils. The main causes of salt build-up in soils are the intrusion of seawater or brackish water flow, irrigation with saline water, salt accumulation on the soil surface through capillary rise from shallow groundwater, poor drainage, and changing climate (Michael, 1978). Fig. 6 shows the process of salinization through seawater intrusion.

Saline soil is defined when the electrical conductivity of soil saturated paste extract (ECe) is > 4 dS m^{-1} at 25 ^{0}C, and exchangeable sodium percentage (ESP) <15 and sodium adsorption ratio (SAR) <13-15 (Richards, 1954). Most plant species are adversely affected when EC_e is higher than 4 dS m^{-1} (George *et al.*, 2012). However, many factors including soil texture, soil moisture, formation of salts, climatic conditions and groundwater table can influence soil salinization.

Salinity problems affect plant growth and deteriorate soil physicochemical properties, resulting in soil degradation and lower crop production. In salt problematic soils, crop growth is mainly impeded by three main reasons. These are water deficit (because of the lower osmotic potential of soil water), ion toxicity due to excess salt availability (Na^+, Cl^- and SO_4^{2-}), and nutrient imbalance in the internal mechanism of plants (George et al., 2012). In saline soils, the main cations are Na^+, K^+, Ca^+, and Mg^+ and the most anions are Cl^-, SO_4^{2-}, HCO_3^-, CO_3^{2-} and $NO^{3,}$ which are highly variable concentrations and proportions (Tanji, 2002).

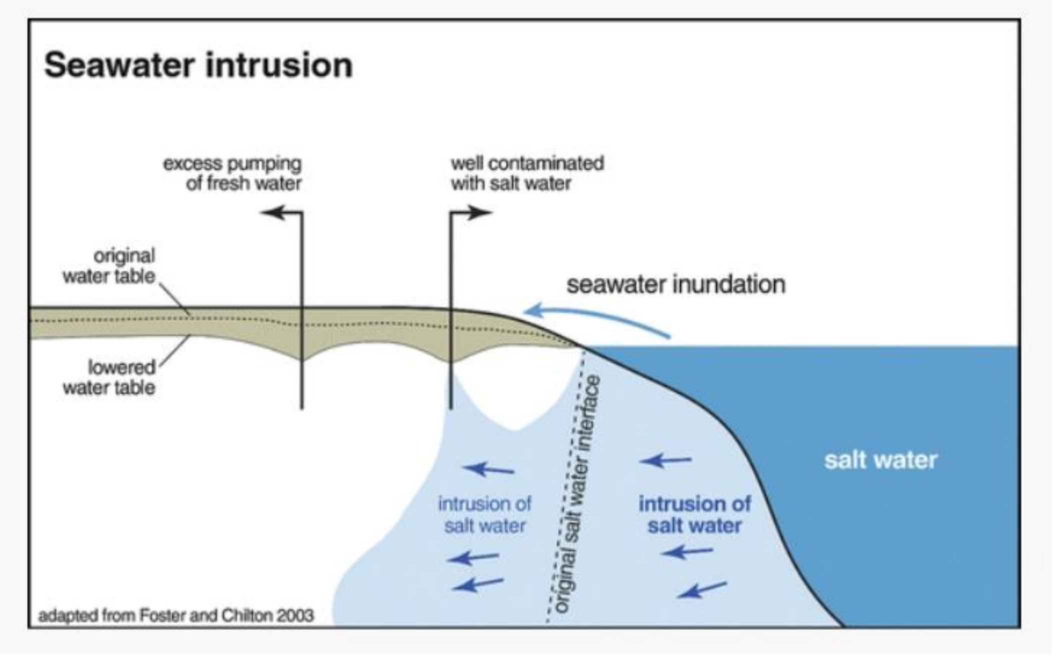

Fig. 6. Salinization of coastal soil and aquifers due to saltwater intrusion from the sea (Greene *et al.*, 2016)

Sodicity is another barrier to crop and soil management. Sodicity problems occur in soil when dissolved salts are leached out into the soil, but exchangeable sodium (Na^+) is retained on soil cation exchange sites (Rengasamy, 2002). An excessive proportion of Na^+ in soil relative to calcium and magnesium may cause soil structural collapse (George *et al.,* 2012; Horneck *et al.,* 2007).

Effects of salts on soil properties

Irrigation water can improve or damage soil properties as a certain amount of soluble salts are presented in irrigation water. However, the effects depend on the salts type and quantity of salts and their management, soil texture, and hydrology (Warrence *et al.,* 2002). Both concentrations of soluble salts and exchangeable cations of soils can affect soil properties simultaneously. For example, an excess of exchangeable Na^+ affects the soil physical properties more than the chemical properties (Mondal, 1997). The increased ESP often caused soil swelling and dispersion, resulting in soil clogging, reduction of soil permeability and hydraulic conductivity, and surface crusting (Frenkel *et al.,* 1978; Pearson and Bauder, 2006). Occasionally, increased salt concentration in the soil solution can have a flocculating effect on soil, which enhances clay particle aggregation (Warrence *et al.,* 2002). The benefits of soil aggregation are more permeability, higher infiltration, better soil aeration, root penetration, and growth (Hanson *et al.,* 1999; McNeal, 1968).

Constraints for Non-Rice Crop Establishment

The use of late-maturing traditional rice varieties and the lack of timely drainage together result in the late establishment of traditional rabi crops such as sesame and mungbean because the soil is too wet to cultivate until February. Late rabi crop establishment, in turn, results in crop damage or complete failure because of high soil and water salinity and soil inundation from pre-monsoon rain prior to harvest. Practicing minimum tillage such as zero and strip tillage can facilitate the early sowing of non-rice crops into the wet soil juts after the rice harvest. However, a recent study has demonstrated that mechanized minimum tillage in clay-wet soil created soil smearing and compaction, resulted in poor sunflower root growth and development and yield (Paul *et al.,* 2020a). Moreover, minimum tillage increased soil surface dryness and salt accumulation on the soil surface hence decreased soil solute potential. The same study also pointed out that increased soil surface disturbance (reduced tillage like single pass and bed planting) increased soil water storage and decreased soil salinity, thereby increased yield. Another study conducted by Paul *et al.* (2021a) for the same area has reported that no-tillage in clay textured soil increased soil resistance and surface cracking, which reduced root biomass and plant growth, hence decreased yield.

SCOPE OF CROPPING SYSTEM INTENSIFICATION

Storing of non-saline/low-saline surface water

Irrigation water availability is a prerequisite for crop intensifying in the coastal area. There is an opportunity to store surface water in the surface water bodies (canals or ponds) for enhancing the supply of irrigation water during the rabi season (Fig. 7). After the rainy season, river water remains non-saline until mid-December. Therefore, before river water become saline and unsuitable for irrigation, water stored in the internal canals and ponds can be used throughout the dry season. However, the volume of fresh water is limited and not enough for irrigated rice and expansion of Rabi crop cultivation (Mila *et al.,* 2021). Re-excavation of existing canals can increase the volume of irrigation water, hence increasing Boro/Rabi crop cultivation.

Fig. 7. Water storage in the internal canal in Dacope Upazilla under Khulna district for Rabi crop cultivation.

Surface drainage to mitigate waterlogging

For the timely establishment of rabi crops, drainage is essential to remove excess water from the field as well as from the surface soil (Fig. 8). Moreover, drainage is effective to cope up the risk of crop failures from the heavy rainfall events throughout the crop season. Paul *et al.* (2020a) have conducted an experiment on the early establishment of sunflower and showed that a surface drainage (15-20 cm deep and 20-25 cm wide) after crop harvesting of wet season rice is effective for mechanized Rabi crop establishment while escaping salinity and heat stresses at later stages of crop. Another study showed that surface drainage saved early sowing crop failure from waterlogging (Paul *et al.*, 2021a and Islam *et al.*, 2022)

Fig. 8. Pictorial view of a surface drainage system to remove excess soil water from the field in Khulna district.

Early establishment of rabi season crops

Growing medium duration of high yielding Aman rice at 15-20 days earlier than farmer's practices and rapid drainage of excess soil surface water can facilitate early sowing of rabi crops. Wheat planting between 25 November and 1 December had a yield of 4.2 -4.4 t ha^{-1} and delayed in sowing decreased yield (Kabir *et al.*, 2019). Similarly, no-tilled sunflower dibbling in wet soil between 20 November and 15 December produced a maximum yield of 3.5 - 4 t ha^{-1} (Paul *et al.*, 2021b). The early establishment of sunflower (23 November 2016) by dibbling in the wet soil in Dacope, Khulna, is shown in Figure 9. The benefit of early sowing is the maximum utilization of residual soil moisture and lower salinity, resulting in higher soil solute potential and grain yield.

Fig. 9. Early sowing of sunflower by no-tilled dibbled in the wet soil in Dacope, Khulna in 2016-17.

Soil water and salinity management by novel tillage and mulching practices

Early rabi crop establishment in the low-lying area of the coastal area is challenging due to excess wetness of soils. Some studies have found that rabi crops such as sunflower, maize, and potato can be dibbled into the wet soil and produced satisfactory yield (Paul *et al.*, 2021b; Kabir *et al.*, 2019, Paul *et al.*, 2022). However, for the delayed establishment, no-tilled dibbled and the mechanized minimum soil disturbance (zero and strip tillage) is less effective in clay-textured soil than intensive soil disturbance (Paul *et al.*, 2020a). Mechanized minimum tillage was related to increased soil bulk density, soil compaction, increased soil surface dryness and salinity, hence decreased yield. While more soil disturbance (bed planting and single pass) reduced the salt deposition on the upper soil and increased soil moisture storage, which maintained higher solute potential in the upper root zone, thereby improving yield. Figure 10 shows the soil condition after the operation of minimum tillage (zero tillage) and reduced tillage (bed planting).

In the coastal saline area, the rapid loss of surface soil moisture in clay-textured soil increased soil strength and crack formation in the dry season, which was related to the reduction of yield loss. The application of rice straw mulch on the soil surface significantly increases crop yield during the rabi season (Sarangi *et al.*, 2018, Paul *et al.*, 2020b). There is plenty of straw mulch in the coastal area, during the dry season despite it competes with cattle feeding. Paul *et al.* (2020b) have shown that using straw mulch on soil surface at 5 t ha^{-1} enhanced sunflower yield by 16-26% which was related to improved soil water content, reduced soil salinity, and increased solute potential of soil solutions in the 0-15 cm soil layer. Also, rice straw mulch ~ 5 t ha^{-1} is effective in lowering the soil resistance and surface cracking (Fig. 11) (Paul *et al.*, 2021a). The benefits of soil surface mulch on sunflower yield, soil water content, soil salinity, soil resistance and cracking in the coastal saline area of Bangladesh in 2019 are presented in Table 1.

Fig. 10. The surface condition of soil under zero tillage (left) and bed planting (right) in Dacope, Khulna.

Table 1. Effects of different mulch treatments on sunflower yield, soil water content, soil salinity, soil resistance and soil cracking in Dacope, Khulna in 2019 (Paul *et al.*, 2020b and Paul *et al.*, 2021a)

Mulch treatments	Sunflower yield (t/ha)	Soil water content (%, w/w)	Soil Salinity (EC1:5)	Soil resistance (MPa)	Soil cracking (m^3/m^2)
No-Mulch	2.6	32	0.79	1.7	0.025
Rice straw (5 t/ha)	3.1	35	0.65	0.4	0.005
Rice straw (10 t/ha)	3.2	36	0.60	0.4	0.003
Rice residue	2.2	-	-	-	-

Fig. 11. Soil and crop condition under no-mulch (left) and rice straw mulch (right) in Dacope, Khulna

Cultivation of Boro and Aus rice for cropping system intensification

Though available freshwater is limited during the dry season in the coastal saline area, farmers still have a strong choice to grow Boro rice. Although Boro rice needs a high-water requirement, it can be grown if freshwater is abundant for irrigation. A recent study showed that in the medium saline area like Dacope upazila in Khulna district, some salt-tolerant cultivars such as BRRI dhan67 and BINA dhan10 were grown by using stored non-saline water in the existing canal. The optimal time for preparing seedling nurseries for Boro rice was the second week of November to the second week of December, which produced average 6 t ha^{-1} of yield. Figure 12 shows the Boro cultivation (BRRI dhan67) using stored less saline water. Therefore, where fresh irrigation water is available in the low-lying coastal area, Boro rice can be grown on a smaller scale because the volume of fresh water is not enough to grow rice in wider scale.

On the other hand, if freshwater is scarce, Aus rice is an alternative option to grow in this area as it needs less irrigation water. Some studies demonstrated that transplanting Aus rice in April-May can save irrigation water because of pre-monsoon rainfall (Bell *et al.*, 2019). Using freshwater from a pond or canal for rice seedling nursery and rainfall water for the later part of the season can produce a 3.5-4 t ha^{-1} yield.

Fig. 10. Boro rice cultivation using stored canal water in Dacope, Khulna in 2018.

Strategies for Water management

In the coastal region, freshwater availability during the dry season is limited because of the high river and groundwater salinity. Therefore, some strategies are necessary to diminish the salinity stress on crop growth. Saline water irrigation can increase plant root zone salt concentration, which results in lower crop yield than the non-saline condition. Moreover, irrigation water containing high in carbonates and bi-carbonates (alkali water) accounts for precipitation of Ca and Mg and thereby influence to increase soil pH and sodium concentration (Minhas et al., 1998; Sharma and Minhas, 2005). One strategy to control root zone salinity is the combined utilization of saline and freshwater (Murad *et al.*, 2018). The blending and cyclic modes are commonly used for different quality of irrigation water in many areas (Gawad *et al.,* 2005; Oster, 1994; Qadir and Oster, 2004). The blending method can be used by mixing two different sources of water to obtain a certain level of salinity for a specific crop. However, the effectiveness of this method depends on crop species, degree of salinity, soil texture, and the volumes of the two water supplies (Grattan *et al.,* 2009; Minhas *et al.,* 2020; Sharma and Minhas, 2005). Some studies have suggested that using cyclic modes (fresh and saline water) provided better crop and soil management for higher yield (Minhas *et al.,* 1998). In the cyclic method, low saline irrigation water (<1.0 dS m^{-1}) can be applied at the early period (germination to seedling stage) because most crops are sensitive at these stages, and water with high salinity can be used at later growth stages when crops usually tolerate higher salinity (Naresh *et al.,* 1993; Rhoades, 1992). Chauhan *et al.* (2007) advocated that the practical way to alleviate the effect of saline water irrigation is cyclic use. For example, if two water sources are available, the preferred option is to use fresh water at the early and sensitive stage and the using of saline water should be applied at the later stages of growth when the plants are often more tolerance to salt.

CONCLUSION

The salt-affected coastal region of Bangladesh is highly vulnerable to salinity, waterlogging and natural disasters. However, recent studies conducted in the coastal region of Bangladesh have demonstrated many opportunities for cropping systems intensification. The main scope involves: (i) storing the surface water in the internal canal from the monsoon season to use for the dry season crops when solute potential is low, and (ii) early establishment of rabi crops to use maximum soil residual moisture and avoid crop stress from increasing salinity and drought, heat stress and storms at latter part of the growing season. One of the most effective ways to establish rabi crop early on wet soil is zero tilled sunflowers, potato, maize, and wheat. Straw mulch is highly beneficial for increasing soil water storage, reducing salinity, and reducing soil compaction and cracking. Boro rice can be grown if enough water is available for irrigation, whereas pond water can be used to prepare Aus seedling and the available rainfall at the rest of the growing season. To achieve the sustainable coastal agricultural development, it is essential to ensure that access to the benefits of available technologies is socially inclusive.

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Natural Groundwater Recharge: A Review on the Estimation Methods

M N H Mahmud[1*], D Roy[1], P L C Paul[1], M B Hossain[1], M S Yesmin[1], P K Kundu[2] and M T Islam[3]

ABSTRACT

Groundwater recharge study is essential because it provides information on the groundwater flow and availability, and its sustainable management over many years. Groundwater recharge estimation also helps evaluating the characteristics of aquifer, such as its bearing capacity and susceptibility to contamination. Many studies so far have focused on several techniques and methods of estimation of groundwater recharge. These methods were very simple, such as seepage meter or tracer techniques, and even complex numerical modelling. However, picking up the right techniques from multiple require essential considerations such as physiography and climatic condition of the location, reliability of the technique, cost and resource availability, and other unavoidable factors that may put limitations in the applicability of a particular method. Furthermore, the reliability of a recharge estimation method also depends on the recharge rates of a particular site. Therefore, an appropriate technique of recharge estimation should be taken such that the estimation resolution of that technique is matched with the average recharge rates of that site. This paper discusses various recharge methods to select a suitable approach appropriate for the climatic condition of Bangladesh. Estimating groundwater recharge by only one method may result in several errors and draw a wrong conclusion. Applying multiple approaches can minimize these errors and enhance the acceptability of the recharge estimates.

Key words: Water balance, water table, aquifer, tracer, lysimeter

INTRODUCTION

Groundwater recharge is the downward movement of water through the unsaturated zone in the subsurface to the saturated zone beneath the water table (Acharya *et al*., 2018). There are some other terminologies regarding the groundwater recharge. 'Net infiltration', 'drainage', 'percolation', and 'residual flux' are often used to indicate the groundwater recharge (Scanlon *et al*., 2002). Assessment of groundwater recharge is an essential requirement for managing groundwater resource sustainably and efficiently. Attention has been given to this assessment, particularly in regions where groundwater supplies are in high demand, such as the North-west region of Bangladesh, where such resources are the key to crop production, industrial and household use, and hence economic development. Quantity of groundwater recharge also estimates the sustainable yield of an aquifer. The sustainable yield indicates a consistent water withdrawal rate, which can cause no adverse effects of an aquifer (Sophocleous, 1992). Such effects could be decline in aquifer water levels. The negative effects of over withdrawal of water also include declines in water flows of streams that are hydraulically connected to the aquifer. In addition, water quality may deteriorate due to over withdrawal of water from an aquifer. However, the rate at which the aquifer is recharged is an essential factor in assessing groundwater resources.

The location and timing of recharge, and thus the choice of recharge estimating technique, is influenced by the climate (mainly the rainfall), geomorphological characters such as soil type, nature of the topography, amount of surface vegetation, and geological condition of a site (Scanlon *et al*., 2002). For example, humid and arid regions represent two different

[1]Senior Scientific Officer; [2]Scientific Officer; [3]Chief Scientific Officer; Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701.
[*]Corresponding author's E-mail: hasan11bau@yahoo.com (M N H Mahmud)

climates, the recharge quantification of which requires different approaches. The groundwater tables of humid regions are generally shallow (Takounjou *et al*., 2011). This region receives a large amount of rainfall and has a low influence of high temperature, which results in high infiltration. Eventually, the recharge in the humid region is usually high (Reese and Risser, 2010). In contrast, in the arid climate, water table depth is high. Furthermore, the precipitation in the arid region is less than 700 mm/year (Allison *et al*., 1994). Therefore, the potential evapotranspiration of the region equals the precipitation or sometimes exceeds it. As a result, the recharge amounts in an arid region usually are small compared to the resolution of the recharge estimation technique (Allison *et al*., 1984).

More than 35 % of irrigation water is lost in the irrigated rice through percolation below the root zone collectively at land preparation and during the growing season under conventional puddled transplanted rice (Mahmud *et al*., 2017) . This amount of percolation loss is even greater under strip planting (45% of irrigation water). A weak plough pan due to practising strip planting over a seven years period has increased the infiltration rate (Mahmud *et al*., 2017). However, deep percolations are not real water losses in the landscape since that water is not contaminated and would return to the groundwater creating new sources of diffuse recharge and increasing groundwater storage that is potentially available for reuse (Humphreys *et al*., 2008). Therefore, it is needed to know a suitable method that can estimate the groundwater recharge from both irrigated and rain-fed rice hydrology on a seasonal or yearly basis.

This paper aims to outline different aspects of numerous techniques used for quantification of the groundwater recharge and the reliability of the recharge estimations. This paper also discusses the important factors that the researchers should consider in choosing the method and the restrictions of using a specific technique. Since the review of techniques used in a wide range of climatic conditions (arid, semi-arid, sub-humid, and humid) is beyond the scope of this report, this paper confines the review of the recharge estimation techniques used only in the sub-humid areas such as Bangladesh.

GROUNDWATER USE WORLDWIDE

Ninety-nine percent of the earth's liquid freshwater is groundwater, which is the source of fresh drinking water to more than two billion people. Moreover, 38 % of irrigation water for the global croplands comes from groundwater (Association, 2016; Siebert *et al.*, 2010). The estimated total volume of groundwater in the world is about 22.6 million km^3, which is mainly occupied in the upper two kilometres of the continental crust (Gleeson *et al*., 2016). Table 1 shows groundwater extraction by ten major countries for irrigation, domestic use, and industrial purposes. Most of the countries use more than 50 % of the groundwater resources for the irrigation, and more than 20 % for domestic purposes. When groundwater withdrawal rate is greater than the natural recharge rate, groundwater mining occurs, which causes aquifer depletion in different countries of the world (Siebert *et al*., 2010). For example, total groundwater depletion in subhumid to arid regions was 126 km^3 year^{-1} in 1960 which was increased to 283 km^3 year^{-1} in 2000 (Wada *et al*., 2010). Dey *et al*. (2017) carried out a study on the groundwater table fluctuation in the north-west districts of Bangladesh (Rajshahi, Pabna, Bogura, Dinajpur, and Rangpur) over 33 years (1981-2014). The findings revealed a declining trend of groundwater level in Rajshahi district from 4 to 12 meter from the surface over the study period (Fig. 1), which mainly attributed to over withdrawal of groundwater than recharging aquifer.

Table 1. Ten nations with the greatest withdrawal of groundwater. Data taken from National Groundwater Association (Association, 2016).

County	Population in 2010 (thousand)	Groundwater use in 2010 (km^3 year^{-1})	Groundwater use by sectors		
			Irrigation (%)	Domestic use (%)	Industrial use (%)
India	1224614	251.00	89	9	2
China	1341335	111.95	54	20	26
United States	310284	111.70	71	23	6
Pakistan	173593	64.82	94	6	0
Bangladesh	148692	30.21	86	13	1
Mexico	113423	29.45	72	22	6
Saudi Arabia	27448	24.24	92	5	3
Indonesia	239871	14.93	2	93	5
Japan	126536	10.94	23	29	48
Thailand	69122	10.74	14	60	26

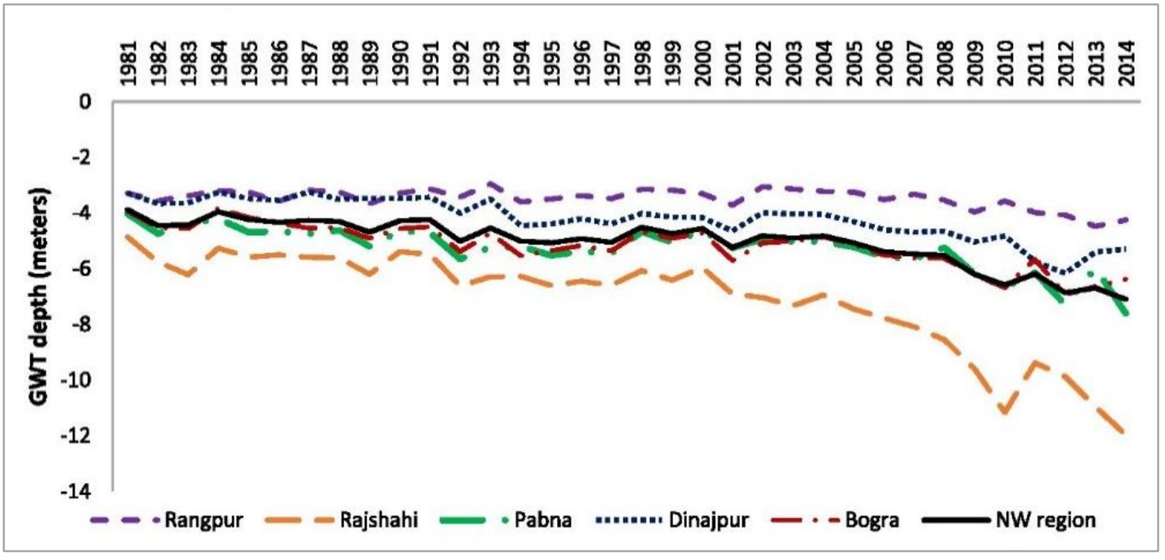

Fig. 1. Changes in groundwater table depths (January to May) from 1981 to 2014. Measurements are the average of maximum and minimum of groundwater depths of the corresponding districts. The figureis adopted from Dey *et al*. (2017).

GROUNDWATER RECHARGE

Processes and mechanisms

Precise understanding of the fundamental mechanism of recharge for a particular area is required at the beginning to estimate the groundwater recharge more accurately. De Vries and Simmers (2002) gave an overview of the processes and mechanisms of groundwater recharge. According to their description, groundwater recharge is the amount of water that flows downward through the unsaturated zone beyond the rooting depth reaches the water table, making contribution to the groundwater reservoir. When rain occurs or irrigation water is applied, a part of the water is used to fulfill the soil water deficit, goes to the atmosphere through evapotranspiration. More than these two uses, water percolates downward (infiltration) to the water table and recharge takes place. From this definition it is considered that groundwater recharge over an area is equal to the infiltration for the same area. However, not necessarily all infiltration water reaches the groundwater table. The infiltration might be restricted by the impermeable or semipermeable layer that has a low water conductivity. The water then moves horizontally and flows to a nearby local depression, such as a pond, where it runs off and evaporates and not contributes to the groundwater reservoir. In an area with a shallow aquifer compared to the landscape, the recharged aquifer with a shallow water table may create a groundwater system where horizontal water flow or an associated seepage might take place within the area. In a high water table aquifer, when time scale is considered, water might be extracted by evapotranspiration immediately after reaching the water table.

Carreira *et al.* (2010) explains how amount of rainfall effects whether there is recharge or not. In areas ranging from humid to sub-humid, yearly precipitation is greater than the potential evapotranspiration, which results in continuous recharge. In contrast, in low rainfall areas, such as arid and semi-arid, rainfall does not exceed the evapotranspiration that contributes to the yearly groundwater recharge. But, over many years the precipitation and the preferential flow of groundwater flow can be the source of recharge.

Groundwater recharge types

According to the water sources, groundwater recharge can be classified into three types: direct or diffuse recharge, localized recharge, and indirect or non-diffuse recharge (Acharya *et al.*, 2018; De Vries and Simmers, 2002; Sibanda *et al.*, 2009) (Fig. 2). Direct recharge is the water contributed to the groundwater reservoir from rain or irrigation by direct percolation through the unsaturated zone after separating from the other water balance components (soil water deficits, surface runoff and evapotranspiration). Localized recharge is the amount of water percolation that is resulted from horizontal surface concentration or depression of water (such as ponding in the rice field). Indirect recharge refers to the amount of water added to the groundwater reservoir by percolation through the beds of rivers and canals or other waterbodies.

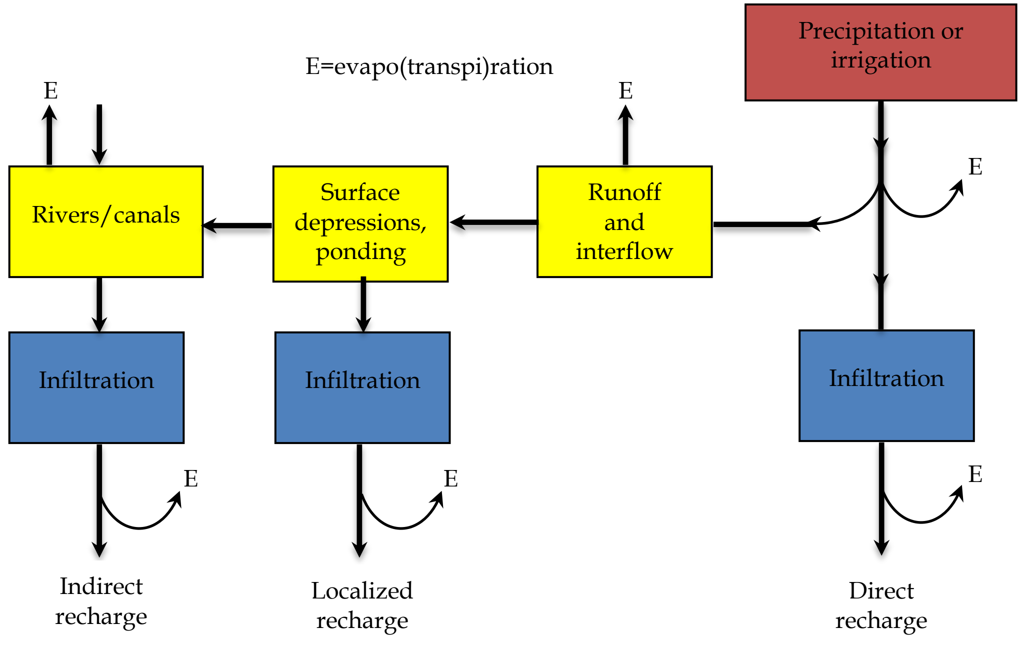

Fig. 2. A flow diagram of different mechanisms of groundwater recharge in a semi-arid area (Lerner, 1997).

Groundwater recharge estimation

Groundwater recharge estimation is primarily classified as direct and indirect methods. Examples of direct physical methods are the Lysimeter method, and direct chemical methods are tracer techniques, either applied or historical. Whereas indirect physical methods are soil water balance, water budget method, groundwater table fluctuation method etc.

Groundwater recharge estimation techniques can also be classified according to regions where arid, semi-arid and humid climates are present. For arid and semi-arid climates, water budget method, isotopic tracers, lysimeters, Darcy's law, and other numerical models are applicable. For humid climates soil water balance, water budgets, lysimeters, Darcy's law, applied tracers, water table fluctuations, and numerical models are appropriate (Scanlon *et al*., 2002).

Factors affecting groundwater recharge

Factors that influence groundwater recharge include climate, land use, land cover or vegetation, geology, topography, soil texture, soil structure or strength, irrigation water use (Acharya *et al*., 2018), depth of water table (Brini and Zammouri, 2016), soil moisture, properties of the geological materials, and the existence of nearby waterbodies (Ali and Mubarak, 2017). These factors work individually or as a combined effort interacting with each other affecting the recharge. However, climate, soil texture, surface cover has been put forward, among other factors affecting groundwater recharge. Climatic factors include precipitation and evapotranspiration since these two variables influence the abundance of water at the soil surface, which eventually controls the groundwater recharge (Scanlon *et al*., 2002).

Soil textural parameters such as porosity and pore size distribution affect water holding capacity, infiltration and transpiration, eventually affecting groundwater recharge (Jobbágy and Jackson, 2004). For instance, sandy soils have more pore spaces and greater hydraulic conductivity; thus, groundwater recharge is higher. In contrast, clayey soils also have tiny pores and greater surface tension that slows down the vertical movement, inhibiting lower infiltration and recharge. In addition, plant available water is higher in clayey soil because of greater micropores than coarse-textured soil; therefore, the evapotranspiration is higher, and groundwater recharge is lower in clayey soil.

Table 2. Summary of the recharge estimated in some humid regions using different estimation methods.

Country/region	Yearly average rainfall	Recharge estimation methods	Recharge mm/year	Coefficient of recharge	Source
USA, Pennsylvania	1069 mm	Lysimeter	311	29 %	Risser *et al*. (2009)
		Water budget	308	29 %	
		WTF*	252	24 %	
USA, North Carolina	1170 mm	WTF	140	12 %	Coes *et al*. (2007)
		Darcy's law	110	9 %	
North-east Bangladesh	1050 mm	Chloride tracer	49	4.7 %	Ali (2010)
		Water balance	59	5.6 %	Ali *et al*. (2019)
Western Australia	775 mm	Environmental chloride	116	15 %	Sharma and Hughes (1985)
USA, Minnesota	500-900 mm	WTF		16-26 %	Delin *et al*. (2007)
USA, Wisconsin	750-900 mm	Numerical Model	110		Cherkauer (2004)
Argentina, Pampa plain	1064 mm	WTF, S_y=0.09	210	18 %	Varni *et al*. (2013)
		WTF, S_y=0.07	164	14 %	

*WTF= water table fluctuation

The density and type of surface cover or vegetation largely influences groundwater recharge (Ali and Mubarak, 2017). The runoff component of the rain or irrigation, and soil evaporation are largely governed by the soil cover and the plant leaf canopy, and thus groundwater recharge may be variable. Generally, the recharge is more remarkable in an area with less vegetation than in a surface with good vegetation of annual crops or grasslands. Mathenge *et al*. (2020) observed the groundwater recharge of Stony Athi sub-catchment of Kenya. They reported 197 mm/year recharge on sandy loam soil with forest cover compared to 36 mm/year recharge on clay soils with impervious layers. Higher recharge on the forest cover was attributed to vegetation interrupting the surface runoff and enhancing water infiltration through the sandy soil.

GROUNDWATER RECHARGE ESTIMATION METHODS

Lysimeter method

The lysimeter method is a popular and repeatedly used groundwater recharge estimating method where all the water balance components (precipitation, irrigation, evapotranspiration, and the change in soil water storage) in the lysimeter zone are measured (Ali and Mubarak, 2017). The remaining component, i.e., the deep percolation, which is the recharge, is then calculated as the residual of the following water balance equation.

$$R = P + I - ET \text{ or } E \pm \Delta S \quad (1)$$

Where R = recharge, P = precipitation; I = irrigation, ET = evapotranspiration, E = evaporation, if there is no crop or vegetation only evaporation should be considered instead of evapotranspiration. $\pm\Delta S$ = changes in soil water storage (calculated from the differences in initial to the final soil water content in the lysimeter zone).

The water balance method of estimating groundwater recharge is direct and depends on reliable and precise data of the water flux in the lysimeter. Hence, the data from lysimeter methods can be used as typical, referring to which data generated from other estimating methods can be verified and calibrated (Rosenberg *et al*., 1983). Furthermore, mini lysimeters can provide direct measurements of percolation at the root zone. In comparison, deep drainage-type lysimeters provide measurements of percolation below the root zone (Kitching *et al*., 1980).

The problems associated with this method are the high expense of constructing and maintaining the lysimeter. Since the soil and vegetation are disturbed during sampling, soil profiling and density are not identical to the natural soil. In addition, the drainage conditions confine to the lysimeter zone, and the bottom of the lysimeter is considered the lower boundary (Gee and Hillel, 1988). There is also a possibility of the flow through the sidewalls of the lysimeter that can overestimate the actual recharge (Ali and Mubarak, 2017).

Water balance methods

The water balance method of estimating groundwater recharge is a residual approach of water balance equation similar to the lysimeter method except for the soil water storage component, where the changes in water storage are determined for the entire unsaturated or vadose zone. This method also considers the runoff component. The simple water balance equation for a basin is as follows:

$$R = P + I - ET \text{ or } E - R_o \pm \Delta S \quad (2)$$

Where R = recharge, P = precipitation; I = irrigation, i.e., the amount of water added, ET = evapotranspiration, E = evaporation when there is no crop or vegetation on the surface, R_o= runoff $\pm\Delta S$ = changes in soil water storage (calculated from the differences in initial to the final soil water content in the unsaturated or vadose zone).

Measurements of the components at the right side of the water balance equation are subject to significant errors that may lead to errors in determining the component at the left side, i.e., the recharge. Therefore, the reliability of the water balance method largely depends on how accurately water balance components in the equation is measured or estimated (Sophocleous, 1991).

The unsaturated zone or the vadose zone of a soil profile is the crucial zone. In humid climates, the unsaturated zone allows a favourable condition for infiltration of the adequate rainfall, and thus water flows effortlessly to the water table. In contrast, in the arid region, ET is >90% of the precipitation, and hence there is little water left for recharging the groundwater (Acharya *et al.*, 2018). Thus, the arid region requires a more precise measurement of the recharge. Therefore, the water balance methods of estimating groundwater recharge are suitable more in humid regions than in arid climates (Knutsson, 1988).

Water budget method

The water budget method of estimating groundwater recharge is the most common, indirect, and residual approach. This method uses a conceptual hydrologic model, where all of the components in the water budget equation are measured or estimated, and calculation of the residual determines the residual (Scanlon *et al.*, 2002). The following equation is the water budget equation for a basin or site:

$$P + Q_{on} = ET + Q_{off} + \Delta S \qquad (3)$$

Where P= precipitation (and/or irrigation); Q_{on} = water flow onto the basin or site and Q_{off} = off the basin or site; ET = evapotranspiration, and ΔS = change in water storage. Unit of all components is as mm/day or mm/year. Some of the individual components of the equation consist of subcomponents. Q_{on} is written as the surface water flow (Q_{on}^{sw}), plus the groundwater flow (Q_{on}^{gw}). Q_{off} is written as the surface water flow off the site (Q_{off}^{sw}) which is equal to the R_o (runoff), plus the groundwater flow off the site (Q_{off}^{gw}). ET is classified according to the source of evaporated water such as surface water evapotranspiration (ET^{sw}), evapotranspiration from the unsaturated zone (ET^{uz}), and/or evapotranspiration from the saturated zone, i.e., the groundwater (ET^{gw}). Water storage is also classified as surface-water storage (ΔS^{sw}), storage in the unsaturated zone (ΔS^{uz}) and storage in the saturated zone i. e., the groundwater (ΔS^{gw}). Rewriting the water budget equation incorporating the abovementioned subcomponents results in:

$$P + Q_{on}^{sw} + Q_{on}^{gw} = ET^{sw} + ET^{uz} + ET^{gw} + R_o + Q_{off}^{gw} + Q^{bf} + \Delta S^{sw} + \Delta S^{uz} + \Delta S^{gw} \qquad (4)$$

Where Q^{bf} = baseflow (i.e., groundwater flow to nearby streams, rivers, or springs).

The above equation gives the following equation form which, groundwater recharge, R, can be calculated (Schicht and Walton, 1961):

$$R = Q_{off}^{gw} - Q_{on}^{gw} + Q^{bf} + ET^{gw} + \Delta S^{gw} \qquad (5)$$

This equation states that all water flowing into the water table (Q_{on}^{gw}) either flows out of the reservoir as groundwater flow (Q_{off}^{gw}), is discharged as streams or rivers to the surface (Q^{bf}), is evapotranspirated (ET^{gw}), or is reserved in storage (ΔS^{gw}). Substituting this equation into Eq. (4), the water budget equation becomes as follows:

$$R = P + Q_{on}^{sw} - R_o - ET^{sw} - ET^{uz} - \Delta S^{sw} - \Delta S^{uz} \qquad (6)$$

For a given location or site, some parts in Eq. (6) are negligible and may be ignored.

The water budget method is preferable due to its flexibility and the assumptions are inherent for the terms in the water budget equation. Hence, this method is useful for a wide range of space and time. For example, using in lysimeters, the recharge could be cm/seconds, extending to kilometers /centuries in a global climatic model.

The limitation of this method is like other residual approaches of estimating groundwater recharge. The accuracy of the estimated recharge depends on how precisely other components in the water budget equation are measured. This limitation is problematic when the amount of recharge rate is relatively smaller than that of the ET. Therefore, the usefulness of water budget methods in arid and semi-arid regions is a big concern (Gee and Hillel, 1988).

Water table fluctuation methods

Healy and Cook (2002); Nonner (2006); Scanlon *et al*. (2002) suggested an approach of Groundwater recharge by the analysis of water table fluctuation (WTF) in an unconfined aquifer. Hydrographs of water table in observation wells and the concept of the specific yield of an aquifer are used in WTF methods. The underlying hypothesis is that a water level rise in an unconfined aquifer is resulted from recharge water coming to the water table (Acharya *et al*., 2018; Sophocleous, 2004). In this hypothesis groundwater plumage, evapotranspiration, and net horizontal flow are considered negligible (Scanlon *et al*., 2005), and the specific yield is unitless constant (Yin *et al*., 2011). The WTF method of groundwater recharge estimation has been practiced since the 1920s (Healy and Cook, 2002).

Recharge is calculated as:

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \qquad (7)$$

Where, R = recharge rate in m/day, S_y= specific yield (unitless), Δh = water table height measured in m, and Δt = time (day).

Freeze and Cherry (1979) defined specific yield as the volume of water discharged from an aquifer storage by gravity flow per unit area of that aquifer per unit drop in the water table. Specific yield can be determined by performing a pumping test and can be estimated using the following equation (Neuman, 1987)

$$S_y = \frac{V_w}{V_c} \qquad (8)$$

Where: V_w = cumulative volume of discharge from the pumping well and

V_c = volume of cone of depression from a water table.

Δh in the recharge equation is measured as the difference between the peak of the water table in response to the rainfall and the low point in the extrapolated recession curve (Lutz *et al*., 2015) as shown in Figure 4.

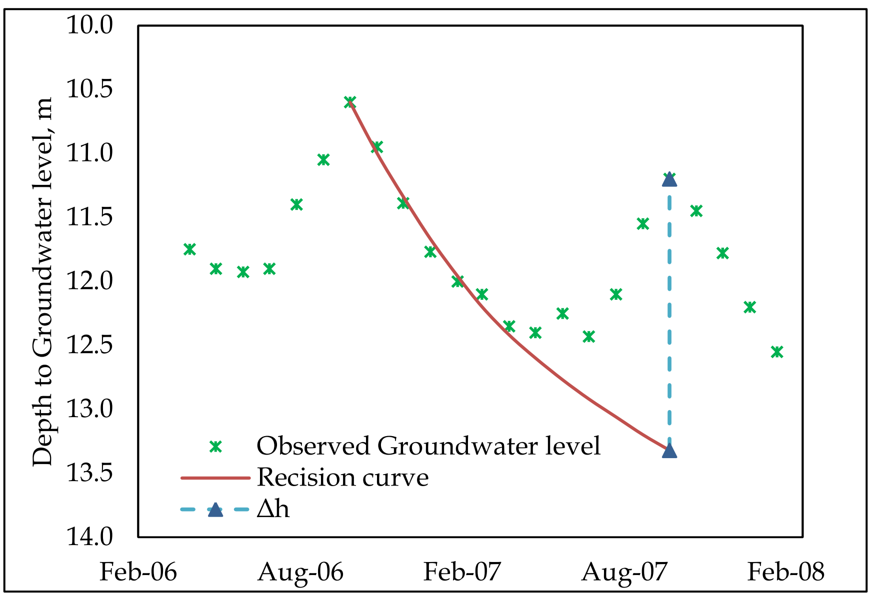

Fig. 3. The peak point of the water table and the low point drawn from the extrapolated recession curve used to determine Δh for recharge estimations. Figure taken from Lutz *et al*. (2015).

Applied tracer technique

This method of estimating groundwater recharge involves the application of tracer materials at a certain point or over an area representing a small region. The estimated value represents the groundwater recharge over the time between tracer application and soil sampling. The time scale is generally a cropping season, few months, or years.

The tracer material could be built in historical chemical composition in the soil profile or applied tracer technique. A popular approach of tracer technique is to use KCl of a given concentration (1 normal), where it is injected as a pulse at 20 cm depth of the soil profile in the field. Water infiltration from the rain or irrigation transports the tracer down to the unsaturated zone. The soil samples mixed with the tracer material from the subsurface are collected after a certain period by digging a trench or performing a core sampling. The Cl ion concentration is then determined by the Mohr method, using a micro-burette with 0.01 mm resolution.

The vertical distribution of the Cl ion is used to determine the velocity (v). The recharge rate (R, mm/year) is estimated using equation 9 as Scanlon *et al*. (2002) described.

$$R = v\theta = \frac{\Delta z}{\Delta t}\theta \quad (9)$$

Where Δz = depth of the peak of the Cl ion concentration, cm, Δt = time between tracer application and soil sampling, year, and θ = average volumetric soil water content, cm^3/cm^3.

Numerous studies estimated groundwater recharge using tracer techniques. For example, Wu *et al*. (2016) estimated the mean value of recharge 124.3 and 18.0 mm/year at two sites of north China plain. Ali *et al*. (2019) reported an average recharge rate of 53.7 mm/year at Ishwardi, Bangladesh.

Use of Darcy's equation

The most straight way of assessing recharge is to estimate the water flow rate over a unit of time (water flux) through the unsaturated zone (Allison *et al*., 1983; Stephens and Knowlton Jr, 1986). Since there is no practical instrument for directly determining the flux, of hydraulic conductivity of a soil profile and the unsaturated hydraulic gradient is measured separately. According to Darcy's equation, groundwater flux (q) is the hydraulic conductivity times the hydraulic gradient.

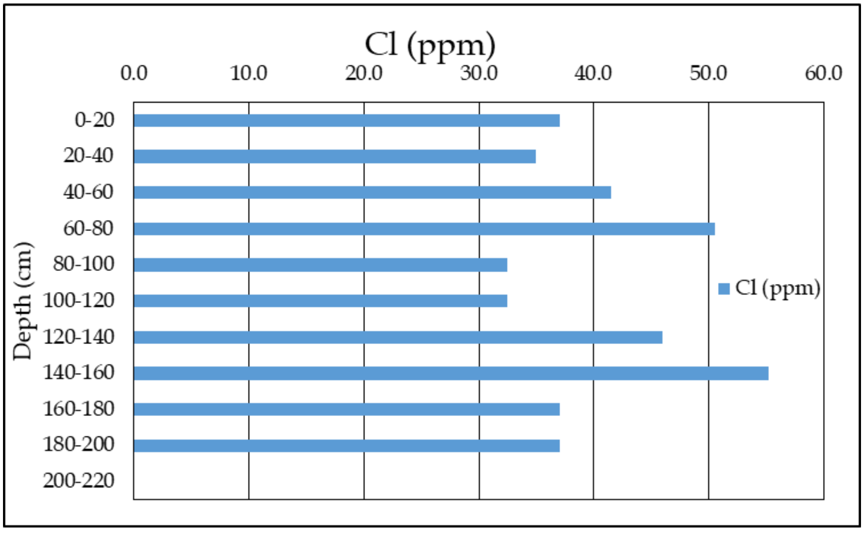

Fig. 4. Tracer concentration (Chloride Ion, parts per million) profile at 0-200 cm depth. Figure showing depth of tracer peak (Δz) at 140-160 cm. The figure is taken from Ali *et al*. (2019).

According to Darcy's law, rate of groundwater flow in volume (q) through the vertical cross section of an aquifer (A) equals the groundwater recharge rate (R) multiplied by the surface area that contributes to the flow (S) (Ali and Mubarak, 2017; Scanlon *et al.*, 2002).

$$qA = RS$$

$$\text{or } R = \frac{qA}{S} = [K(\theta) \times dH/dz \times A]/S \quad (10)$$

where, $K(\theta)$ = hydraulic conductivity at the soil volumetric water content, dH/dz = hydraulic gradient.

The hydraulic gradient in a uniform soil structure is generally near 1. In such a condition, the flux equals the hydraulic conductivity.

Darcy's method can be used for different areas ranging from an arid region where recharge rate is about 35 mm/year (Stephens and Knowlton Jr, 1986) to an irrigated region with a thin unsaturated zone where recharge rate could be 500 mm/year (Kengni *et al.*, 1994). Moreover, this method can be performed on broad spatial scales (1 to ≥ 10,000 km^2) (Ali and Mubarak, 2017). This method assumes steady-state groundwater flow is horizontal in aquifers and vertical in aquitards, and there is no groundwater extraction. Since this method is highly dependent on the hydraulic conductivity and hydraulic gradient, this technique is not useful for regions where these two parameters vary broadly with space (Yin *et al.*, 2011). Moreover, an accurate determination of the thickness and the length of the aquifer needs close consideration.

CONCLUSION

In this review, only a few methods of estimating groundwater recharge for humid climates and their advantages and disadvantages have been discussed. Recharge estimated from the residual of water balance models or water budget models may overestimate or underestimate the real magnitude. Similar errors can take place when hydraulic conductivities and the hydraulic gradients in Darcy's equation are estimated or measured. Considering the simplicity, availability of the chemicals used, and the cost of estimation, the tracer technique offers the best options for determining the recharge rate in subhumid areas. Moreover, since plenty of precipitation allows continuous recharge in the subhumid region like Bangladesh, the physical methods of estimating recharge, which relies on the direct measurement of water flux (lysimeter method and tracer technique), is more applicable than the indirect methods (WTF method). The significant challenges in the WTF estimation method is the lack of necessary data, for example, the S_y. The estimated value of S_y with errors may lead to a non-confident estimation of the groundwater recharge. However, since each approach of estimating groundwater recharge invites uncertainties, the use of multiple approaches (including tracer techniques) is recommended to overcome the constraints associated with using a single recharge estimation technique. Nonetheless, considering the advantages, limitations, and cost of each method, suitable techniques of groundwater recharge estimation in Bangladesh can be preferred.

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Paddy Field Water Movement Through Soil Profiles Under Different Water Management Practices: A HYDRUS 1D Model Study

D Roy[1]*, M N H Mahmud[1], P L C Paul[1], M B Hossain[1], M S Yesmin[1], P K Kundu[2], A Debnath[2], M R B H Pranto[2] and M T Islam[3]

ABSTRACT

Physical measurement of hydrological processes through soil profile is very complicated and time-consuming. Complex and coupled physical processes like water movement with soil matric potential in puddled paddy field can be simulated using physical process-based model HYDRUS 1D. The model simulation was setup for the multilayered (different soil materials at 0-15 and 15-30 cm depth) paddy fields having continuous flooded irrigation (CFI) practice and water saving Alternate Wetting and Drying (AWD) practice. Measured soil physical properties of three Bangladesh Rice Research Institute (BRRI) regional station farms (Kushtia, Sirajganj, and Rangpur) were used as model input, initial and boundary conditions configuration. The model was calibrated and validated using the water data of a dry season field experiment in Kushtia. The calibrated (RMSE of 0.54 cm, d of 0.94, NSE of 0.89) water level data validated successfully with observed water level data of AWD practiced paddy field (d of 0.95, NSE of 0.92). Soil water content reached the threshold/critical level in AWD practice (-101 cm of water soil matric potential at 15 cm soil depth) earlier in light textured soil (loam or sandy loam) compared to heavy textured soil (clay). The physical properties of the layered soils (i.e., soil particle size distribution and soil water release curve, SWRC) did not affect much on water movement in CFI practice, but it had substantial impact on field water movement under AWD practice. The change in soil water storage followed the general trend for respective soil water holding and releasing capacity, clay soil was heavier and released water slowly than that of loam or sandy loam soils. The positive water flux above 15 cm of soil profile mainly drove the water flow due to evapotranspiration and soil water and pressure distribution along the soil profile while the negative fluxes below 15 cm of soil depth due to infiltration or percolation contributed as a secondary force. A basic understanding of HYDRUS simulated results would lead to realize the total physio-hydrological environment in the paddy field.

Key words: HYDRUS 1D, AWD, continuous flooded irrigation, soil physical properties, paddy field

INTRODUCTION

Rice is the largest water consuming stakeholder in irrigated agriculture although water for rice cultivation is going to be scared soon. Water is turning to a costly input for rice production due to increasing demand of other users like industry and urbanization (Bouman and Tuong, 2001; Loeve *et al.*, 2007). In Asia, where rice dominates 40-46 percentage of crop net irrigated area (Li and Barker, 2004; Bouman *et al.*, 2007a), water saving practices are popularizing in recent times as available water resource is reaching its limit in this region. The water saving irrigation technologies for rice cultivation, includes alternate wetting and drying (AWD) practice, saturated soil culture, direct seeding rice, aerobic rice, are now being widely adopted in rice growing areas. Continuous ponding condition in paddy fields leads to huge water misuse during Boro season in the irrigation projects as well in farmer's management (Sattar *et al.*, 2009). Compared to continuous flooding irrigation practice, farmers do not need to irrigate the paddy field frequently in AWD practice. When soil water depletes below a critical or threshold level, farmers need to irrigate the field. Many researchers have reported that AWD practice

[1]Senior Scientific Officer; [2]Scientific Officer; [3]Chief Scientific Officer, Irrigation and Water Management Division, Bangladesh Rice Research Institute (BRRI), Gazipur 1701.
*Corresponding authors' E-mail: debjit.roy@gmail.com; debjit.iwm@brri.gov.bd (D Roy)

saves irrigation water over the continuously flooded irrigation practice, and it does not have any impact on rice yield (Bouman *et al.*, 2007a; Cabangon *et al.*, 2004; Zhang *et al.*, 2009; Kukal *et al.*, 2005; Mishra *et al.*, 1990; Liu *et al.*, 2005; Sharma *et al.*, 2002; Singh *et al.*, 2002; Tabbal *et al.*, 2002). The AWD fields had the same yield as continuous flooding and beneficially saved 16-24% in water costs and 20-25% production costs, and thus water productivity is always higher for AWD practice over conventional irrigation practice (Roy and Sattar, 2009).

Water flow through the cultivated paddy field is the result of highly complex and coupled hydrological and physical processes. The processes are often very complicated and ambiguous. The understanding, explaining, and evaluating those complicated processes with respect to field observation is really time consuming and sometimes very costly. Considering the adverse situations for practical field measurement, using computer models to interpret the soil processes are becoming very common. Water movement through the multilayer soil profile has been investigated by using conceptual models both in continuous flooded paddy field and AWD practiced paddy field (Bouman *et al.*, 2007b; Inthavong *et al.*, 2011; Khepar *et al.*, 2000, Luo *et al.*, 2009; ten Berge *et al.*, 1995; Chen and Liu, 2002; Chen *et al.*, 2002; Garg *et al.*, 2009; Janssen and Lennartz, 2009). HYDRUS is a physical process model that deals with soil water and solute movement processes both horizontally and vertically using numerical simulations. HYDRUS 1D and HYDRUS (2D/3D) have been used by many investigators around the world to simulate water movement in agricultural fields under different irrigation scheme for different crops including transplanted rice (Ramos *et al.*, 2012; Phogat *et al.*, 2010; Sutanto *et al.*, 2012). HYDRUS model (Šimůnek *et al.*, 2008, 2012) is a very effective and useful model option for heat and water flow simulation. HYDRUS models can predict and simulate different hydrological processes like rainfall, snowfall, evaporation, transpiration, infiltration, root zone water accumulation, soil water holding capacity, capillary movement of water in the soil, drainage, irrigation, groundwater movement and storage and all directional movement of flow within any homogeneous or layered soil profile (Šimůnek *et al.*, 1998, 2012; Šimůnek and Bradford 2008; van Genuchten *et al.,* 1980).

In recent past, some studies for puddled paddy fields water flow indicated that Richard equation could be capable of solving field-scale water flow variation (Wopereis *et al.*, 1992, 1994; Tuong *et al.*, 1994; Liu *et al.*, 2001; Chen and Liu, 2002; Chen *et al.*, 2002; Tournebize *et al.*, 2006). HYDRUS model (Šimůnek *et al.,* 1998) uses Richard equation to solve numerical simulations in combination with van Genuchten model (1991). The convenience of the model is that it can simulate the processes for water movement from measured soil physical and hydraulic properties, which can be achieved from field or laboratory tests, in addition to the appropriate boundary and initial conditions (Warrick, 2003). In this study, we set our objective to simulate and explain irrigation water movement in multi-layered paddy field soil profile at different locations of Bangladesh both in continuously flooded irrigation (CFI) practice and AWD practice based on the measured soil physical properties and field observed experimental data.

METHODOLOGY

The HYDRUS 1D model simulations were setup for Kushtia (23°54′51″ N, 89°05′56″ E), Sirajganj (24°24′9.9″ N, 89°38′43.44″ E) and Rangpur (25°41′42″ N, 89°16′03″ E) region. The model was run for two water management practices: (a) Continuously flooded irrigation (CFI) and (b) Alternate wetting and drying (AWD). The depth of the soil profile for the simulation was taken 30 cm considering the root zone of the rice plant. In each location, measured soil physical properties information of soil samples from two soil depths (0-15 cm and 15-30 cm) were taken as input to simulate water movement along the paddy field soil profile. The soil samples were collected from three research farms of BRRI regional station Kushtia, Sirajganj and Rangpur, respectively. The soil physical properties were measured for each location by collecting soil samples from soil profile (up to 30 cm) of different spots at 0-15 cm, and 15-30 cm depths using standard protocols (Dane and Topp, 2002). Two different soil samples were collected from each depth: one core sample for bulk density determination and soil textural analysis; another for soil water retention curve construction by pressure plate apparatus. Soil samples for bulk density measurement were collected with a core sampler. Each core was made of stainless-steel having 5 cm height and 5 cm diameter. Bulk density of soil samples was determined after oven drying the core soil samples at 105°C for 72 hours (Black and Hartge, 1986). The soil textural analysis of the collected samples was conducted by hydrometric method (Bouyoucos, 1951). The soil samples were soaked overnight in a mixture of 100 ml Calgon solution (5% NaOH Meta Phosphate solution) and 100 ml distilled water. Then sand, silt and clay percentages were calculated from hydrometer measurements. USDA soil texture triangle was used to identify the soil textural class of respective soil sample (USDA 1975). Table 1 presents the textural class and particle distribution of all soil materials used for simulation.

The soil water retention curve (SWRC) was determined for each soil layer in 0.05 bar, 0.1 bar, 0.33 bar, 1 bar, 3 bar, 5 bar and 15 bar by using pressure plate apparatus (Soil Moisture Equipment Corp., USA). Field capacity (1/3 bar or 0.33 bar) and wilting point (15 bar) are the upper and lower limits of available moisture. Later, the soil pressure units were converted from kPa to cm of water (1 kPa = 10.1972 cm of water) for convenient modeling. The soil samples were saturated in water for 24 hours before placing on the apparatus. The individual wet weight of soil samples was measured after extracting the soil moisture with different bars. After completing all moisture extraction in different bars, the soil samples were oven dried at 105°C for 72 hours (Dane and Hopmans, 2002, Roy *et al.*, 2018). Figure 1 shows the SWRC of each soil layer in each location. All other soil hydraulic parameters were predicted using van Genuchten-Mualem soil hydraulic property model (van Genuchten, 1980). Input values in HYDRUS model of soil hydraulic properties (saturated water content, residual water content, hydraulic conductivity etc.) for all soils were considered for simulation (Table 2).

Table 1. Soil texture and bulk density of different soils used for model simulation.

Location	Soil layer (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class	Bulk density (gm/cm^3)
Kushtia	0-15	22	16	62	Clay	1.45
	15-30	21	19	60	Clay	1.48
Sirajganj	0-15	32	48	20	Loam	1.13
	15-30	36	44	20	Loam	1.49
Rangpur	0-15	46	40	14	Loam	1.22
	15-30	58	30	12	Sandy loam	1.14

During the model simulation, atmospheric boundary condition with surface runoff was selected as upper boundary condition and free drainage was selected as lower boundary condition. Moisture content at field capacity of each soil layer was setup as initial conditions for simulation. Observation node was setup at 15 cm depth in the soil profile. Figure 2 presents the initial condition setting before running the HYDRUS 1D model. The time duration was considered 15 days for each simulation with respect to the water level data obtained from an experiment conducted in dry season of 2019-2020 in BRRI Kushtia regional station farm (BRRI, 2019). The variety was BRRI dhan58, growth duration was 150 days and 40 days of seedlings were transplanted in this experiment. The actual field duration, considered for modeling purpose, was 21 DAT (Day after transplanting) to 35 DAT.

Table 2. Hydraulic properties of soils from different locations used in HYDRUS 1D model.

Location	Soil layer	Residual water content, θr cm³/cm³	Saturated water content, θs cm³/cm³	Alpha, α 1/cm	n	Saturated hydraulic conductivity, K cm/hr
Kushtia	0-15 cm	0.10	0.46	0.02	1.23	0.42
	15-30 cm	0.10	0.46	0.02	1.24	0.40
Sirajganj	0-15 cm	0.07	0.47	0.01	1.63	2.37
	15-30 cm	0.06	0.38	0.01	1.52	0.39
Rangpur	0-15 cm	0.05	0.43	0.01	1.55	1.94
	15-30 cm	0.05	0.46	0.02	1.46	4.45

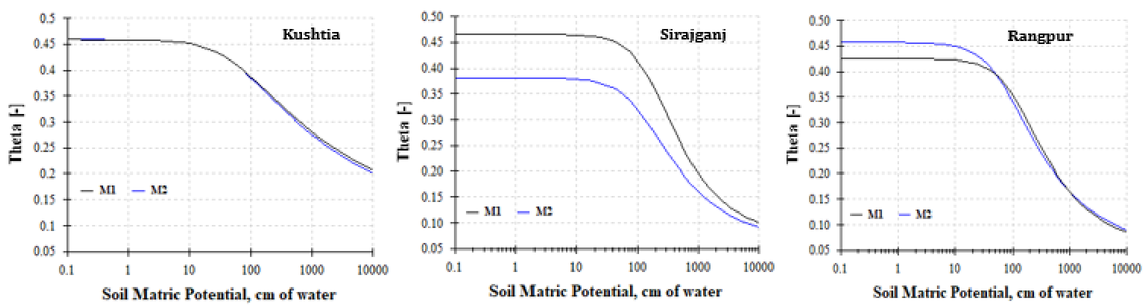

Fig. 1. Soil water retention curves (SWRC) of Kushtia, Sirajganj and Rangpur soils. The y axis is volumetric water content (Theta) in cm³/cm³. M1 and M2 are the soil materials of 0-15 cm depth and 15-30 cm depth, respectively at each location.

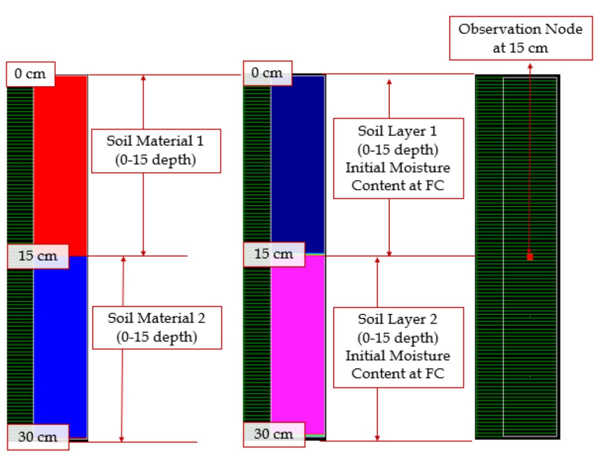

Fig. 2. Initial conditions setup along the multi-layered soil profile in HYDRUS 1D model.

In this study, the model was calibrated and validated with respect to actual field observed water level data of the experiment (BRRI, 2020). The simulated water level calculated from soil matric potential data of CFI practice and corresponding observed water level data were used for model calibration. Model validation was done in AWD practice using calibrated data of CFI practice. The observed evapotranspiration (ET) data and actual irrigation application amount in both CFI and AWD practice were applied in model simulation (Table 3). An amount of 6 cm irrigation was given in three times at Day 1, Day 7, and Day 13 in CFI practice. In AWD practice, only one irrigation (6 cm) was supplied at Day 1.

Table 3. Date wise irrigation amount and Evapotranspiration (ET) during the simulation period.

Day	Irrigation in CFI, cm	Irrigation in AWD, cm	Evapotranspiration, ET cm
1	6	6	0.2
2	0	0	0.1
3	0	0	0.2
4	0	0	0.1
5	0	0	0.2
6	0	0	0.2
7	6	0	0.2
8	0	0	0.3
9	0	0	0.1
10	0	0	0.4
11	0	0	0.1
12	0	0	0.1
13	6	0	0.2
14	0	0	0.5
15	0	0	0.1

The model performance was evaluated by (i) the root mean square error (RMSE), (ii) index of agreement (d) (Willmott, 1982), and (iii) Nash-Sutcliffe modeling efficiency (NSE) (Nash and Sutcliffe, 1970).

$$(i)\ RMSE = \sqrt{\frac{\sum_{i=1}^{N}(P_i - O_i)^2}{N}} \quad (1)$$

where, O_i is the measured value and Pi is the predicted value.

$$(ii) d = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2} \quad (2)$$

where, $\bar{O}$ is the measured mean and $\bar{P}$ is the predicted mean.

$$(iii) NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - O)^2} \quad (3)$$

where, O is the observed average.

The simulation outputs from the model for Kushtia, Sirajganj and Rangpur regions were analyzed comprehensively and discussed based on water content distribution along the soil profile, soil matric potential distribution along the soil profile, soil water flux variation along the soil profile, and soil moisture storage along the soil profile during the simulation period in days for both CFI and AWD practice.

RESLUTS AND DISCUSSION

During the model calibration, water level data were calibrated with simulated soil matric potential for CFI practiced paddy field of Kushtia. Figure 3a presents the simulated volumetric water content variation with the duration of the simulation period. The simulation started from the initial soil water content at field capacity (0.35 cm^3/cm^3). After the irrigation application of 6 cm at Day 1, Day 7, and Day 13, soil water content hiked to saturated water content and then gradually decreased. Figure 3b is shows the corresponding soil matric potential variation with time in the CFI field of Kushtia. Soil matric potential reduces with increased soil water content and vise-versa (Hillel, 1998). The simulated results showed the same trend here. The observed water level of the experiment (BRRI, 2020) calibrated along with the soil matric potential variation. The simulated water level data after calibrating showed a satisfactory agreement (d = 0.94) with the observed field water level data. The model performed a very well prediction (NSE = 0.89) with a RMSE of 0.54 cm (Fig. 4a). The model was then conducted for AWD practiced paddy field for validation purpose. For the validation (Fig. 4b), simulated water level data of AWD practiced paddy field matched with field observed water level data reasonably (d = 0.95, NSE = 0.91).

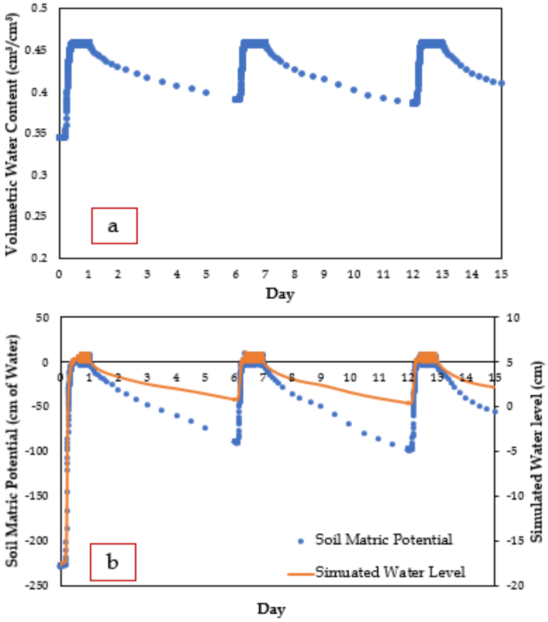

Fig. 3. Continuous flooded irrigation in paddy field of Kushtia (a) variation of simulated soil water content with time; (b) variation of simulated soil matric potential with time and calibrated water level with soil matric potential variation.

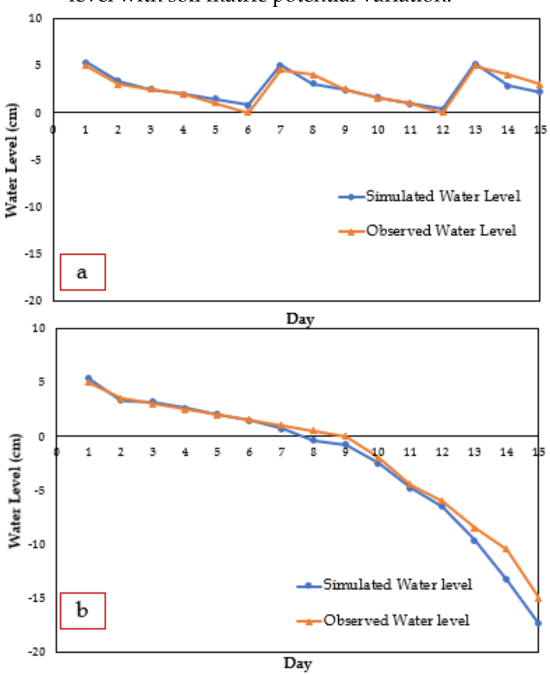

Fig. 4. (a) Simulated (after calibration) and observed water level in CFI field of Kushtia; (b) simulated water level validation with the observed water level in AWD field of Kushtia.

Figure 5 describes the soil water content variation along the soil profile during the simulation period. In all the simulations, the initial soil water content was at field capacity of the respective soil material. It was assumed according to field condition that after the initial crop settling (20 DAT), the fields of both water management reached at field capacity uniformly, which is denoted as T0 in the Fig. 5a-5f. Under AWD practice, paddy field soil water environment moves between being saturated to being saturated and unsaturated alternatively. So, the difference was huge between the water movement through the soil profile of continuously flooded field and AWD practiced field. Various studies reported different threshold levels for AWD practice. The level could be varied from the soil matric potential at 10 cm depth of soil of -20 kPa to -30 kPa for average root zone soil matric potential (Tuong *et al.*, 2005; Kukal *et al.*, 2005; Luo *et al.*, 2009). The threshold level differs because those critical values were derived based on different soil physical properties of a specific field experiment. To make the simulation precise, we followed -101 cm of water (-10 kPa) soil matric potential at 15 cm depth of soil profile (Tuong, 2008) as the threshold level when soil water content reached at field capacity. The simulation profiles clearly showed that the soil moisture never went to field capacity, or even closer to it in CFI practice. In AWD practice, it was obvious that soil moisture content reached field capacity before the next irrigation applied. However, the time for reaching field capacity differed among the soil texture. In clay soil of Kushtia (Fig. 5b), the 15-day soil water contents along the soil profile (T5) reached depth and exactly crossed the field capacity line at 15 cm depth. So, the total irrigation interval was 15 day with a safe yield. On the contrary, in the loam soils of Sirajganj and Rangpur (Fig. 5d and Fig. 5f), the 12-day soil water content line (T4) crossed the field capacity at 15 cm depth. It indicates that, for

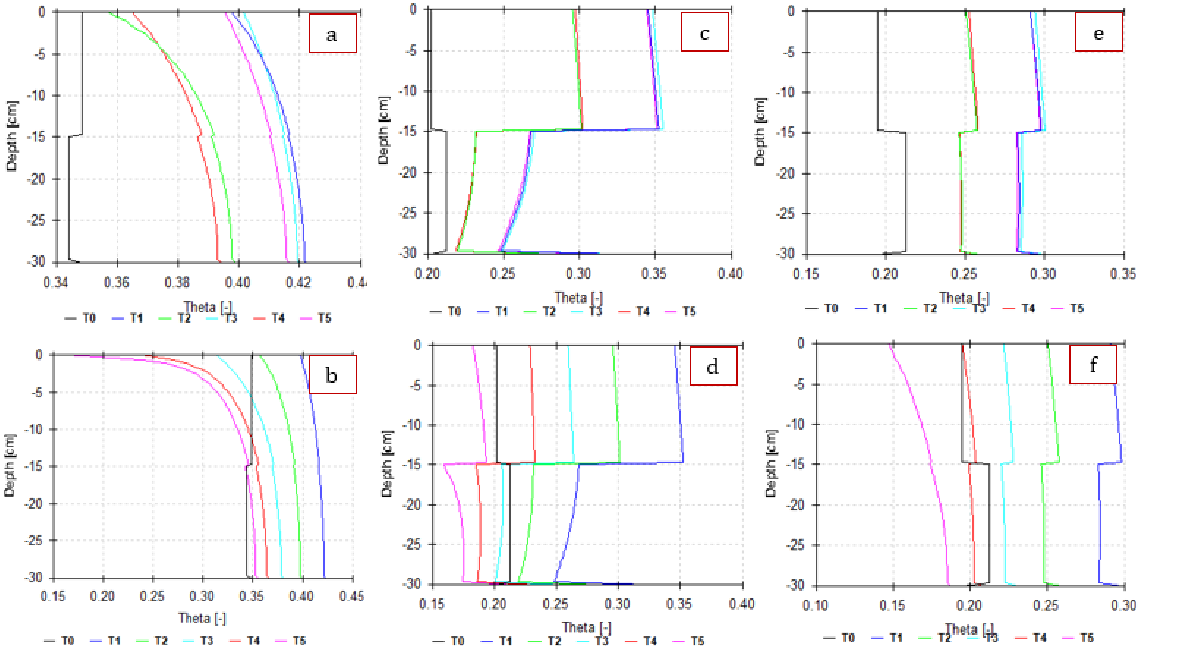

Fig. 5. Simulated soil water content variation along the soil profile for (a) CFI at Kushtia, (b) AWD at Kushtia, (c) CFI at Sirajganj, (d) AWD at Sirajganj, (e) CFI at Rangpur, and (f) AWD at Rangpur. The soil water content status presented at simulation starting (T0), at 3 days (T1), at 6 days (T2), at 9 days (T3), at 12 days (T4) and, at 15 days (T5).

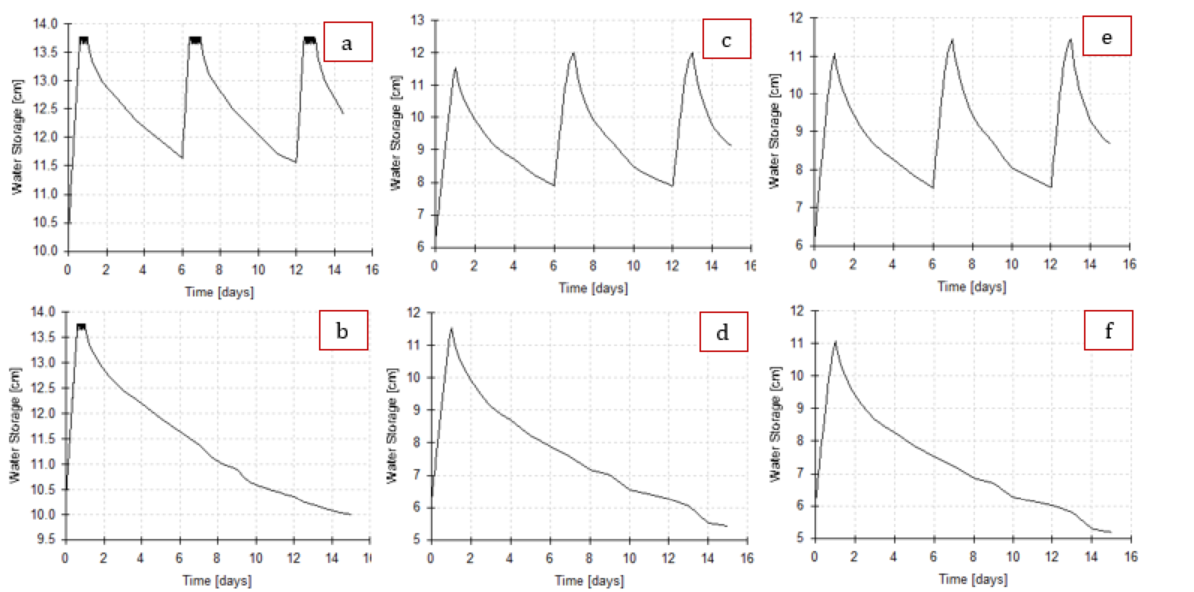

Fig. 6. HYDRUS simulated soil water storage variation with simulation period for (a) CFI at Kushtia, (b) AWD at Kushtia, (c) CFI at Sirajganj, (d) AWD at Sirajganj, (e) CFI at Rangpur, and (f) AWD at Rangpur.

loam soil or light-textured soil, 15 days irrigation interval would be a bit risky in terms of safe AWD practice. Thus, it would be better to apply irrigation before 12 days after the previous irrigation event. The soil water content distribution along the soil profile of Sirajganj (Fig. 5c and 5d) is remarkably different than other soil profiles. The SWRCs of the layered soils in Sirajganj, taken for simulation, were very much different (Fig. 1). Though both soil materials are similar in terms of soil textural analysis (Table 1), their bulk density values were greatly varied. Due to high bulk density at the second soil layer (15-30 cm), the soil water content reduced 0.35 cm^3/cm^3 to 0.25 cm^3/cm^3 (Fig. 5c and 5d) after 3 days (T1). As discussed earlier, soil moisture reached at field capacity at 15 cm depth after 14 days (T4), however, T5 is showing a slight increase in soil water content below 15 cm depth after 15 days. The soil might be tightly packed and was releasing water slowly compared to the first layer (0-15 cm). So, after 15 days, the first layer dried up, but second layer continued to emanate water. In case of Rangpur, the soil profile scenario was completely reversed compared to Sirajganj. In Rangpur, the second layer (15-30 cm) soil profile was sandy loam soil having less bulk density than that of the first layer soil (loam). The volumetric soil water content of the second layer, especially close to saturation, was higher compared to the first layer volumetric water content at near saturation (Fig. 1). Even after 15 days of irrigation in AWD practiced paddy field, the soil water content along the depth gradually varied with increasing trend, and the higher water content indicated better water holding capacity of second layer soil material, i.e., sandy loam soil.

Figure 6 presents the water storage variation, i.e., total water availability with respect to soil profile depth, along with the simulation period. After the irrigation event, soil water storage picked up to saturated level (13.8 cm, equal to saturated water content 0.46 cm^3/cm^3 of clay soil, Table 2) according to Figure 6a and 6b. In CFI paddy field, water storage variation followed the same trend throughout the simulation duration, i.e., the next irrigation was applied when water storage reached around 11.5 cm (0.38 cm^3/cm^3), practically when water was disappeared from soil surface and soil water content was far higher than field capacity even close to saturation (Fig. 5a). On the other hand, water storage fell from saturated condition to field capacity condition (13.8 cm to 10 cm) in AWD practiced paddy field after 15 days. In Sirajganj and Rangpur soils (loam soils), water storage was comparatively lower than the soils of Kushtia (clay soils). As shown in Figure 6c and 6e, soil water storage, after second and third irrigation events, had the added amount compared to water storage after the first irrigation amount. The reason is probably, the water amount received in soil profile after first irrigation was not sufficient to saturate the soil completely as the initial condition was at field capacity (around 0.22 cm^3/cm^3). According to Figure 6d and 6f, it is evident as Figure 5d and 5f shows that light textured soil in Sirajganj and Rangpur region should be irrigated after 10-12 days of an irrigation event in AWD practice.

A comparative understanding of the water flux variation between CFI practice and AWD practice can be obtained from Figure 7. The figure presents the water flux variation along the soil profile after simulation starting (T0), after 3 days (T1), after 6 days (T2), after 9 days (T3), after 12 days (T4) and after total simulation duration or, 15 days (T5) for the Kushtia fields. According to Figure 7a, in CFI practice field, the positive flux above 15 cm of soil and negative flux below 15 cm of soil indicated the same amount of evapotranspiration and infiltration after 3 days of an irrigation event (T1). After 6 days (T2), negative water flux below 15 cm of soil became smaller due to less infiltration; however, positive water flux above 15 cm of soil remained same as evapotranspiration was happening every day. After 9 days, the negative flux below 15 cm of soil again increased, because second irrigation was applied at Day 7,

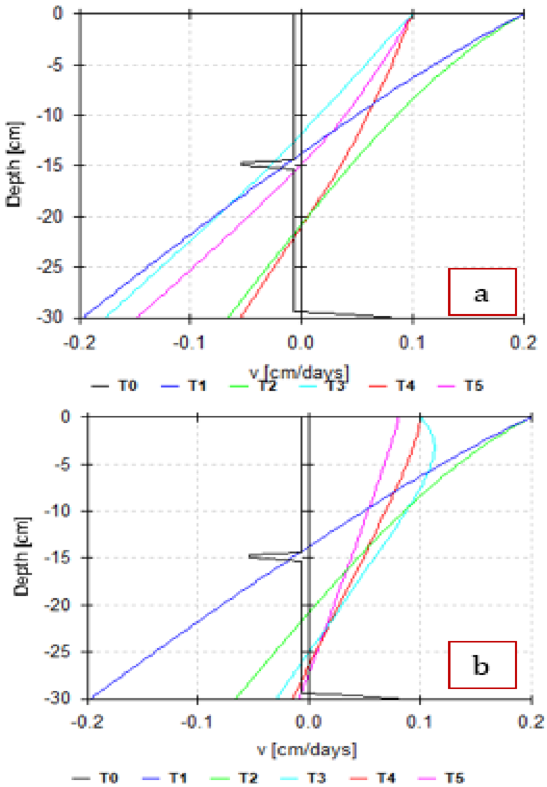

Fig. 7. Variation of water flux along the soil profile for (a) CFI at Kushtia and (b) AWD at Kushtia. The water flux (cm/days) denoted as before simulation (T0), 3 days (T1), 6 days (T2), 9 days (T3), 12 days (T4) and 15 days (T5).

which increased the infiltration through the soil profile. Water flux variation along the soil profile repeated as T4 after 12 days of the simulation period (after 5 days of second irrigation event). It also repeated as T3 after 15 days of the simulation period (after 2 days of third irrigation event). A representing water flux variation scenario after 3, 6, 9, 12 and 15 days, respectively, can be observed in AWD practiced paddy fields. Because the soil profile just received one initial irrigation event throughout the simulation period. After 3 days (T1), both the positive water flux above 15 cm of soil profile as well as negative water flux below 15 cm of soil profile were higher as both evapotranspiration and infiltration happened simultaneously. After six days (T2), negative flux below 15 cm of soil reduced as infiltration reduced, but positive flux above 15 cm of soil remained the same as evapotranspiration continued. Infiltration stopped after almost nine days of only irrigation event (T3), so negative flux below 15 cm of water disappeared. As evapotranspiration was being in progress, positive water flux was observed until the end of the simulation period of 15 days (T4 and T5).

CONCLUSION

The water movement through multilayered soil profile of the paddy field in CFI practice and in AWD practice was simulated using HYDRUS 1D physical process-based model. Measured soil physical and hydraulic properties of three BRRI regional station farms were used as model input and initial conditions. The relevant properties (i.e., soil particle size distribution and SWRC) of layered structure of soil profile governed the water movement through the soil profile. The simulated results indicates that irrigation interval could be shorter in light textured soil compared to the heavy textured soil depending on the water storage and water releasing capacity of the soil. The positive water flux like evapotranspiration primarily controls soil water content and soil matric potential balance and distribution when negative flux acts as a secondary force at deeper soil profile due to infiltration or percolation. This model simulation study would give a basic understanding of the water movement through different soil profile under different water management practices in Bangladesh, which might help to get an insight about the total crop-soil-water based physical and hydrological process environment in paddy field.

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Influence of Water Stress on Canopy Temperature and Yield Contributing Characteristics of Wet Seeded Rice

S Parveen[1*] and E Humphreys[2]

ABSTRACT

Canopy temperature (CT) is one of the indices for evaluating water stress. The study has been taken to correlate water stress with CT and to evaluate effect of water stress on crop and yield performance of wet seeded rice (WSR). The canopy temperature of rice at vegetative and flowering stages were investigated under different soil water stresses. The field experiment was conducted at IRRI (International Rice Research Institute) during dry season, 2011. Three levels of water stress (-10, -20 and -40 kPa) were applied at 3-leaf (3L) to panicle initiation (PI), PI to flowering (FL) and FL to physiological maturity (PM) stages. One non-stressed treatment, i.e., continuously flooded puddled transplanted rice (PTR-CF) was used as a control. Soil water tension was measured using a 30-cm long gauge tensiometer and a handheld infrared thermometer was used to measure CT. Canopy temperatures were recorded from 3L to PI and PI to FL stages. In both the stages, CT was within the range of marginal stress. Canopy temperature depression (CTD) was higher in the stressed condition than that of the non-stressed. At the PI stage, leaf area index (LAI) was significantly lower in WSR than PTR-CF. LAI was comparatively lower in WSR with -20 kPa and -40 kPa than WSR with -10 kPa and PTR-CF when water stress imposed during PI-FL. Decreasing grain yield was observed when irrigation threshold increased from -10 to -40 kPa during PI to FL and FL to PM, but the differences were not significant. Yield components of WSR with different stresses were not significantly different. But spikelet fertility (%) and grain weight (g) of WSR was significantly higher than that of PTR-CF. The yield of PTR-CF was similar to the yield of WSR. Panicle/m^2 correlated negatively with CT under a stressed condition. Yield and all yield components except spikelet per panicle were positively correlated with CT at 60 days after seeding (CT_{60}). Under stressed condition, CT correlated negatively with the grain yield. Results revealed that CT correlated positively with grain yield under non-stressed condition (CT_{35} and CT_{60}). Spikelet fertility percentage (SF%) correlated negatively with CT_{35} and CT_{46}. It has been concluded that CT and CTD may be used for water stress evaluation.

Key words: Wet seeded rice, canopy temperature, water stress, crop performance

INTRODUCTION

Plant growth and development (Boonjung and Fukai, 1996; Kato *et al.*, 2007) mainly depends on water. Rice plant is sensitive to water stress. Effect of water stress on one or all growing stages have considerable influence on plant growth and development. Declining leaf expansion rate and decreasing plant height, leaf area and biomass production reduced interception of photosynthetically active radiation (PAR) of rice when water stress imposed during vegetative phase (Inthapan and Fukai, 1988). Tiller abortion also increased due to water stress at vegetative phase. Kumar *et al*. (2006) reported that dry matter partitioning increased significantly from leaf and stem to grain due to water stress imposed at reproductive stage. Physiological activities of root, leaf photosynthesis, dry matter accumulation and transpiration rate of rice plant impeded by water stress at heading stage (Cai *et al.*, 2002; Tao *et al.* 2004; Wang *et al.*, 2006). Moderate water stress at the heading and filling stages significantly

[1]Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701, Bangladesh; [2]International Rice Research Institute, Los Banos, Philippines.
[*]Corresponding author's E-mail: parveenbrri98@yahoo.com (S Parveen)

increased spikelet fertility percentage and grain weight (Wang *et al*., 2004). After heading, water stress had negligible effect on the yield of rice (Zheng *et al*., 2006). Parveen *et al.* (2017) reported that grain weight decreases with water stress at -40 kPa imposed during the whole growing season.

Water stress effects on canopy temperature (CT). Therefore, CT may be used as an indicator for crop water stress (Jackson *et al*., 1981). Generally, CT is lower than the atmospheric temperature due to leaf cooling process by transpiration. Soil water availability in the root zone reduced by water stress limits transpiration rate. Thus, leaf cooling process hampered, and heat injury occurred. Mackill and Coffmam (1983) and Xu *et al.* (1999) described heat injury and resistance to heat injury by panicle temperature and canopy temperature. Slight heat injury occurred by lower panicle temperature while resistance to heat injury happened by lower canopy temperature. Burke (1996) categorized the range of CT as non-stressed ($CT_{mean}<27^oC$), marginally stressed ($27^oC<CT_{mean}<29^oC$) and highly stressed ($CT_{mean}>29^oC$) temperatures, respectively. Parvaze *et al.* (2019) reported significant correlation with grain yield and canopy temperature depression (CTD). CTD represents the reduction of CT to the ambient temperature.

Scientists are now using the canopy temperature measurement as a screening technique under water stress condition. However, the correlations of CT with LAI, biomass, grain yield and yield components of WSR are lacking. Therefore, the aim of this study to figure out correlation of water stress with CT and to determine the effect of water stress on crop and yield performance of wet seeded rice (WSR).

METHODOLOGY

The field research was conducted at the International Rice Research Institute (IRRI), Los Baños, Philippines ($14^011'$N, $121^015'$E), from January to May 2011. The climate is tropical with a dry season (starts in January and ends in May) followed by a wet season (continues until December). However, rainfall during the dry season (January to April) varies greatly from year to year, ranging from a total of 43 mm in 1993 to 630 mm in 2009. The long-term average annual rainfall is around 2000 mm, of which 92% occurs from May to December. Monthly mean potential evaporation greatly exceeds mean rainfall during January to April, while mean rainfall is well in excess of potential evaporation during June to December. Average monthly potential evaporation ranges from 103 mm in December to 190 mm in April. Solar radiation increases from a monthly mean of 13.8 $MJm^{-2}day^{-1}$ in January to a maximum of 20.9 $MJm^{-2}day^{-1}$ in April and then decreases to a monthly mean of 12.2 $MJm^{-2}day^{-1}$ in December. Mean monthly maximum temperature varies from 28.3^0C in January to 33.0^0C in May. Variation in mean monthly minimum temperature is even smaller, ranging from 22.8^0C in December to 24.1^0C in September. The relative humidity is high throughout the year, with monthly averages ranging from 82.1% in May to 87.6% in September. Average wind speed is low, ranging from 1.1 to 1.8 ms^{-1}, with the lowest values during the rainy season.

The topsoil (0 - 15 cm) is silty clay with 1.45% organic carbon and neutral pH (Table 1 and Table 2). The subsoil is silty clay to 30 cm, overlying clay, and clay loam. There is a hard pan starting at 18 - 20 cm depth which has lower hydraulic conductivity (Ksat, 35 $cmday^1$) and higher bulk density than the rest of the soil profile. Up to 75 cm soil depth Ksat ranged from 35-53 $cmday^{-1}$. Below 60 cm, Ksat was much higher (around 200 $cmday^{-1}$) due to the presence of gravel.

Table 1. Soil physical properties at the experimental site.

Depth (cm)	Texture			Textural Class	Bulk density[A] (gcm^{-3})	Ksat[A] ($cmday^{-1}$)
	Clay (%)	Sand (%)	Silt (%)			
0-15	53	12	35	Silty clay	0.93 (0.02)[B]	46 (6.3)
15-30	53	13	34	Silty clay	1.01 (0.1)	35 (5.3)
30-45	49	20	31	Clay	0.90 (0.09)	48 (2.5)
45-60	39	30	28	Clay loam	0.93 (0.02)	53 (7.9)
60-75	31	40	29	Clay loam	1.07 (0.12)	200 (14.7)
75-90	20	54	25	Sandy clay loam		

[A]Determined in the middle 5 cm of each soil layer i.e., at 5-10, 20-25, 35-40, 50-55, 65-70, 80-85 cm.
[B] standard error in parentheses.

Table 2. Chemical properties of topsoil at the experimental site prior to puddling in 2011.

Soil layer	pH (1:1in H_2O)	Organic C (%)	Olsen P (mg/kg)	Exch. Ca ($meq100g^{-1}$)	Exch. K ($meq100g^{-1}$)	Kjeldahl N (%)
0-15 cm	7.0	1.45	18	25.5	1.07	0.161

Wet seeded rice (WSR) was grown with three levels of soil water deficit stress (-10, -20 and 40 kPa) applied during three growth stages: 3-leaf to panicle initiation (3L-PI), panicle initiation to flowering (PI-FL) and flowering to physiological maturity (FL-PM) (Table 3). One treatment included continuously flooded puddled transplanted rice (PTR-CF) in the experiment. The experiment was laid out with four replications in a randomized complete block design and plot size was 10 m × 5 m. To minimize seepage flows between treatment plots, the bunds were lined with plastic sheet, which was installed up to the hard pan, to a depth of about 20 cm below the soil surface, and individual treatment plots were separated by buffer plots. The buffer plots were irrigated at the same time as the driest adjacent treatment plot.

For the establishment of the experiment, the soil was ploughed using an animal drawn mould-board plough followed by a hydrotiller/rotavator powered by a 2-wheel tractor with cage wheels (3 passes) and levelled by a manually drawn wooden plank. The soil was then left to settle for one day prior to basal fertilizer application and wet seeding. The rice variety NSIC Rc222 (seed to seed growth duration 120 days) was used. Seeding was done on 14 January 2011. Prior to seeding, the seed was soaked for 24 hrs, drained, then incubated for 24 hrs by storing in a hessian bag in a dark and warm (45-50^{0}C) room. For the WSR, the pre-germinated seed was sown at the rate of 60 kg dry seed ha^{-1} using a manually pulled drum seeder. This rate is equivalent to about 255 $seedsm^{-2}$.

Table 3. Treatments of the field experiments.

Treatment	Crop establishment method[1]	Irrigation threshold during each crop stage[4] (kPa)		
		3L-PI	PI-FL	FL -PM
10-10-10	WSR[1]	10	10	10
10-20-10	WSR	10	20	10
10-40-10	WSR	10	40	10
10-10-20	WSR	10	10	20
10-10-40	WSR	10	10	40
CF-CF-CF	PTR[2]	CF[3]	CF	CF

[1]WSR-wet seeded rice; [2]PTR- Puddled Transplanted rice; [3]CF-continuously flooded
[4]3L= 3-leaf stage, PI= panicle initiation, FL= flowering and PM= physiological maturity

For the puddled transplanted rice (PTR), the pre-germinated seeds were sown in a raised seedbed on the same day that the WSR was sown. Transplanting was done 17 days after sowing (DAS) when the plants had reached to the three-leaf stage. There were 2-3 seedlings per hill in rows 20 cm apart with hill-to-hill spacing within the row of 20 cm. At the time of transplanting, the soil surface was flooded with a shallow layer of water (1 to 2 cm deep). During the first week after transplanting, the soil surface was allowed to dry for molluscicide application and was re-irrigated for seven days after molluscicide application.

Fertilizer was applied at a rate of 160-41-80-5 kgha^{-1} of N-P_2O_5-K_2O-Zn, respectively, each year. Diammonium phosphate (DAP) was the source of P and some of the N, the remaining N was applied as urea. Muriate of potash (MOP) was the K source, and Zn was applied as zinc sulphate. The full doses of Zn and P_2O_5, 30 kgha^{-1} of the N, and half of the K were applied as basal by broadcasting 24 hr before wet seeding or transplanting. Nitrogen top dressing was split as 50-50-30 kgNha^{-1} at maximum tillering, PI, and heading, respectively. The other half of the K was applied at PI.

Soil tension was measured using 30-cm long tensiometers installed in all replications for each treatment. The tensiometers were installed in between two plant rows, and the middle of the ceramic cup was placed at 15 cm below the soil surface. A handheld infrared thermometer (Model TECPEL 513, TAIWAN), with a field view of 100 mm to 1000 mm, was used to measure CT. CT was measured at 35, 46, 50, 60, 67, 71, and 73 DAS. The data were taken from the four sides of each plot at 1 m distance from the edge and approximately 50 cm above the canopy at an angle of 30^{o} to the horizontal. Readings were taken between 1300 hr and 1500 hr on sunny days (Guendouz, 2012).

GenStat V.14.1 was used for data analysis. Data were analyzed for determination of analysis of variance (ANOVA). Treatment means were compared by 5% level of significance (LSD). Factorial analysis was done for interaction between water stress treatment and growth stages. Pearson's correlation coefficient was analyzed by Ssx stat programme at the 5% level of significance.

RESULTS AND DISCUSSIONS

Effect of water stress on canopy temperature of rice

Canopy temperature (CT) was increased with the increase in water stress (Fig. 1). At 3L to PI stage (35 DAS) canopy temperature ranges from 27.8 to 29.5^{0}C at -10 kPa stress due to prevailing high air temperature (32.3^{o}C). Due to removing stresses at 46 DAS, canopy temperature decreased and ranges from 22.7 to 23.6^{o}C. Water stress at PI to FL, the highest canopy temperature (28.3^{o}C) was recorded at -40 kPa which was followed by -20 kPa. Increased canopy temperature under water stress condition might have occurred due to increase in respiration and decrease in transpiration as a result of stomatal closure. Chuan *et al.* (2012) found that leaf temperature of rice was increased by water stress significantly under severe water stress. The minimum canopy temperature (24.9^{o}C) was recorded in flooding condition (PTR-CF). CT was found less than air temperature. The evaporative cooling involve in transpiration might cool the leaf below ambient air temperature.

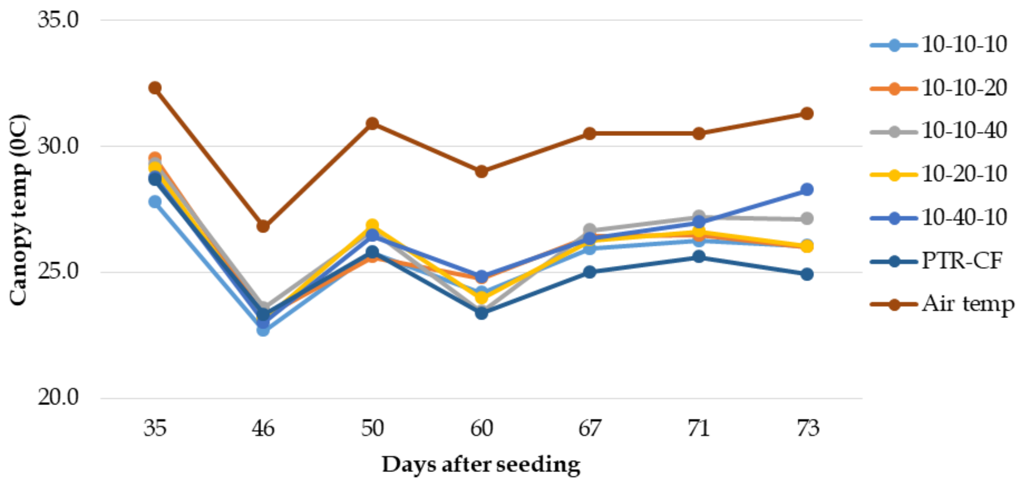

Fig. 1. Canopy temperature in different water stress treatment

CT has the positive relation with water stress (Table 4). Higher water stress increases the CT. Water stress (WSR 10-40-10) shows the higher (R^2 = 0.2168) relation with CT. Water stress index responded with CT and vapor pressure deficit. Turner *et al.* (1986) found that the temperature difference between the canopy and the air increased with the decline of soil moisture. Some researchers made it simple for farmers (Kacira *et al.*, 2002) that require only measures of CT.

Effect of water stress on growth and development of rice

Table 5 presents the LAI influenced by water stress. LAI was significantly lower in WSR than PTR-CF at PI. The higher LAI (4.65) was found in PTR-CF and lower (2.60) in WSR. At FL, LAI did not significantly differ with water stress, but comparatively higher in WSR with -10 kPa and PTR-CF than WSR with -20 kPa and -40 kPa. LAI had significant differences at PI, but no such trend was observed at PM.

Table 4. Relation of canopy temperature with water stress at vegetative and flowering stage.

Treatment	Relation of canopy temperature with water stress
WSR 10-10-10	Positive association (R^2 = 0.1335)
WSR 10-10-20	Positive association (R^2 = 0.0677)
WSR 10-10-40	Positive association (R^2 = 0.0124)
WSR 10-20-10	Positive association (R^2 = 0.0337)
WSR 10-40-10	Positive association (R^2 = 0.2168)

Table 5. Effect of water stress on leaf area index (LAI) at key stages.

Treatment	3 L	PI	FL	PM
WSR 10-10-10	0.09	3.27	3.35	0.78
WSR 10-20-10	0.07	3.03	3.12	0.44
WSR 10-40-10	0.08	2.83	2.92	0.61
WSR 10-10-20	0.10	2.60	3.31	0.53
WSR 10-10-40	0.07	3.59	3.81	0.58
PTR-CF	0.03	4.65	3.78	0.47
$LSD_{0.05}$	ns	1.25	ns	ns

3L= three leaf stage, PI= panicle initiation stage, FL= flowering stage, PM= physiological stage
WSR= wet seeded rice, TR-CF= transplanted rice with continuously flooded

Water stress had no significant effects on biomass (Table 6). But lower biomass was obtained in PTR than WSR. However, lower biomass (7.9 tha^{-1}) within WSR was obtained with -40 kPa water stress imposed during PI-FL.

Yield and yield components under water stress condition

Yield was not significantly different with water stress in both WSR and PTR-CF (Table 7). But there was a decreasing trend of grain yield with increasing water stress. Water stress imposed as -10, -20 and -40 kPa during PI-FL and FL-PM decreased the grain yield. The higher grain yield (5.9 tha^{-1}) was obtained from WSR-10-10-10. Whereas the lower grain yield (4.4 tha^{-1}) was found in WSR 10-40-10. Yield of PTR-CF was similar to WSR. This was due to compensate of significantly lower spikelet fertility and grain weight with non-significantly higher panicle density and more spikelet per panicle. Yield components between the WSR and water stress were not significantly different.

CT ranges from 22.8 to 29.1°C showed no significant correlation with spikelet fertility%. This result can be justified by the findings of Straussberger (2015) who reported that rice spikelet fertility significantly decreased with over 33°C threshold.

Parveen *et al*. (2017) reported the lowest average grain weight (20.1 mg) with a water stress of -40 kPa during FL-PM only. Grain filling stage determine the grain weight and the lower biomass at flowering determines the grain weight and yield (Zhang et al., 2016). Parveen *et al*. (2017) results of the lowest grain weight were similar to the findings of Yoshida (1981) and Castillo *et al*. (2006). However, the present study has no effect on grain weight with imposing -40 kPa water stress.

Table 6. Effect of water stress on biomass (t/ha) at key stages.

Treatment	3 L	PI	FL	PM
WSR 10-10-10	0.06	2.9	8.0	15.6
WSR 10-20-10	0.06	2.1	8.1	11.7
WSR 10-40-10	0.06	2.5	7.9	10.7
WSR 10-10-20	0.08	3.0	8.4	13.7
WSR 10-10-40	0.06	2.5	9.0	13.3
TR-CF	0.04	2.4	7.4	11.5
$LSD_{0.05}$	ns	ns	ns	ns

[A]3L= 3-leaf stage, PI= panicle initiation stage, FL= flowering stage, PM= physiological stage
WSR= wet seeded rice, TR-CF= transplanted rice with continuously flooded

Table 7. Effect of water stress on yield and yield components of WSR.

Treatment	$Panm^{-2}$	$spikeletpan^{-1}$	spikelet fertility%	1000 grain weight (g)	Straw yield (tha^{-1})	HI	GY (tha^{-1})
WSR 10-10-10	379	81.5	88.5	23.7	5.3	0.49	5.9
WSR 10-20-10	428	60.3	84.3	23.9	4.8	0.48	5.3
WSR 10-40-10	319	66.2	89.3	23.3	5.0	0.44	4.4
WSR 10-10-20	340	86.3	89.3	24.5	5.1	0.49	5.6
WSR 10-10-40	389	82.4	85.8	23.4	5.1	0.48	5.5
PTR-CF*	422	91.9	78.4	22.0	4.3	0.49	5.1
$LSD_{0.05}$	ns	ns	6.5	1.3	ns	ns	ns

* WSR= wet seeded rice, PTR - CF= Puddled transplanted rice with continuously flooded, HI=Harvest index

Correlations between CT, LAI, and BM

LAI was negatively correlated with CT at PI and FL except CT_{60} at FL (Table 8). There was no consistent trend of LAI correlation with CT at PM. Correlation of BM with CT showed no consistent trend at PI, but there was a strong negative correlation of CT_{46} with BM at PM stage.

Correlations between CT, grain yield and yield components

Paniclem^{-2} correlated negatively with CT under stressed condition (Table 9). CT at 60 days after sowing (DAS) was in non-stressed condition. Therefore, yield and yield components were positively correlated with CT_{60} except number of spikelet per panicle. Under stressed condition, canopy temperature (CT) correlated negatively with grain yield (r=-0.937**). Result revealed that CT correlated positively with grain yield under non-stressed condition (CT_{35} and CT_{60}). Spikelet fertility% (SF%) correlated negatively with CT_{35} and CT_{46}. Rest of the CT was correlated positively with yield and yield components.

CONCLUSIONS

Correlation of water stress was examined with CT. Three levels of water stress (-10, -20 and -40 kPa) were imposed at three crop growth stages. CT was recorded during vegetative and flowering stages. This study shows that water stress had influence on canopy temperature and grain yield. Grain yield was not significantly different with water stress but decreasing trend was observed with higher water stress during panicle initiation to flowering. Grain yield was negatively correlated (r=-0.937**) with CT.

Table 8. Correlation between CT (different days after sowing) and LAI and BM under different water stressed conditions.

	LAI at PI	LAI at FL	LAI at PM	BM at PI	BM at FL	BM at PM
CT_{35}	-0.362	-0.432	-0.76	-0.537	0.098	-0.763
CT_{46}	-0.017	-0.385	-0.602	-0.526	-0.365	-0.964**
CT_{50}	-0.499	-0.151	0.078	0.508	0.459	-0.049
CT_{60}	-0.238	0.149	-0.022	-0.205	0.745	0.378
CT_{67}	-0.870*	-0.656	0.130	-0.011	0.593	-0.061
CT_{71}	-0.710	-0.468	0.202	0.052	0.643	-0.122
CT_{73}	-0.335	0.010	0.269	-0.012	0.810*	0.046

LAI: Leaf area index, BM: Biomass, CT: Canopy temperature
*p<0.05, **p<0.01, ns= not significant

Table 9. Correlation between canopy temperature (CT) (different days after sowing) and yield and yield components under different water stressed conditions.

	Panm^{-2}	Spikeletpan^{-1}	SF%	1000 GW	SW	HI	GY
CT_{35}	-0.099	-0.576	-0.0016	0.199	-0.278	-0.467	0.593
CT_{46}	-0.206	-0.392	-0.195	-0.311	-0.545	-0.691	-0.937**
CT_{50}	-0.846*	0.149	0.597	0.368	0.391	-0.390	-0.245
CT_{60}	0.393	-0.297	0.140	0.499	0.420	0.316	0.563
CT_{67}	-0.531	-0.719	0.779	0.724	0.668	-0.578	-0.186
CT_{71}	-0.663	-0.525	0.743	0.515	0.633	-0.695	-0.321
CT_{73}	-0.369	-0.260	0.487	0.267	0.575	-0.455	-0.0999

Panm^{-2}: panicle per m^2 area, Spikelet pan^{-1}: Spikelet per panicle, SF%: Spikelet fertility%, 1000 GW: 1000 grain weight (g), SW: Straw weight (t/ha), HI: Harvest index, GY: Grain weight (t/ha), *p<0.05, **p<0.01, ns= not significant

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Design and Development of Check Valve for Irrigation Pump

M Maniruzzaman[1*], A K M S Islam[2] and M M Alam[3]

ABSTRACT

Shallow tube wells (STW) are widely operated in Bangladesh to draw groundwater for irrigating the crop field. About 65% of irrigated area is covered by more than 1.3 million STW. However, farmers are facing difficulties in starting STW due to priming problem. Therefore, this study was undertaken to design and develop a *check valve* (CqV)/non-return valve to overcome the priming problem as well as reduce the drudgery of farmers while starting STW. The *check valve* was designed based on the working principles of hand tubewell operating system. Considering the tubewell size of 100 mm, check valve having three diameters of 125 mm, 150 mm, and 175 mm for two-valve fitting lengths of 150 mm and 225 mm based on the flange or thread joint were fabricated using locally available material at Bangladesh Rice Research Institute (BRRI) research workshop. *Check valves* were tested at the field level in different locations of Bangladesh. The results revealed that the field performance of *check valve* overcame the priming problem, made easy starting and reduced the drudgery of farmers. The best performance was found when the diameter of the *cheque valve* was at least 50 mm over the size of tube well and the minimum length was 150 mm. The installation of *check valve* could not create any adverse effects on tube well discharge and engine revolution per minute (RPM). It could successfully reduce the starting time and facilitate the easy use of plastic pipe/ polythene pipe, which reduces the water conveyance loss and pumping hours.

Key words: Priming, groundwater, irrigation, shallow tubewell, priming, drudgery, discharge, impeller revolution

INTRODUCTION

Bangladesh agriculture and its national economy are depending upon groundwater irrigation. The net cultivated area was 8.25 million hectares (ha) in 1971, of which only 3% area was irrigated by groundwater (BBS, 2000). In 2018-19, about 5.59 million ha of land is irrigated, of which about 73 percent are served by groundwater (BADC, 2020). At present, Bangladesh has about 8.55 million ha of net cultivable land of which about 65% is irrigated by 13,57,532 shallow tube wells (STWs), 37,634 deep tube wells (DTWs), 1,87,188 low lift pumps (LLPs) and other traditional methods (BADC, 2020). Within the total irrigated area, surface water covers only about 26.9%, though it is a riverine country and groundwater covers about 73.1% (BADC, 2020) and thus groundwater irrigation plays a crucial role in Bangladesh and the national economy. In groundwater irrigation, STW contributes about 73.3%. In the farmers field, STW is more popular than DTW, because of its low installation and maintenance costs as well as ease of operation. Both, DTWs and STWs, generally pump from the same aquifer, but because of larger investment cost and complex operation and management, the number of active DTWs has steadily declined after privatisation (Mondal and Saleh, 2003). Besides, farmers are facing difficulties in STW operation due to its *priming* problem. Priming is an activity by which STW's suction pipe and pump filled with water. It is a challenging task for the farmers. At each starting time of STW, minimum two-person are needed. One person removes the air by pumping hand tubewell attached to the delivery pipe of the pump and another person closes the outlet pipe with a piece of wood and mud. In the peak irrigation period, it needs to be started STW 2-3 times a

[1]Principal Scientific Officer, Irrigation and Water Management Division; [2]Principal Scientific Officer, Farm Machinery and Post Harvest Technology Division; [3]Senior Scientific Officer, Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701, Bangladesh
*Corresponding author's Email: mzamaniwm@yahoo.com (M Maniruzzaman)

day. This may be frequent in electrically operated pumps for uncertain power dropping.

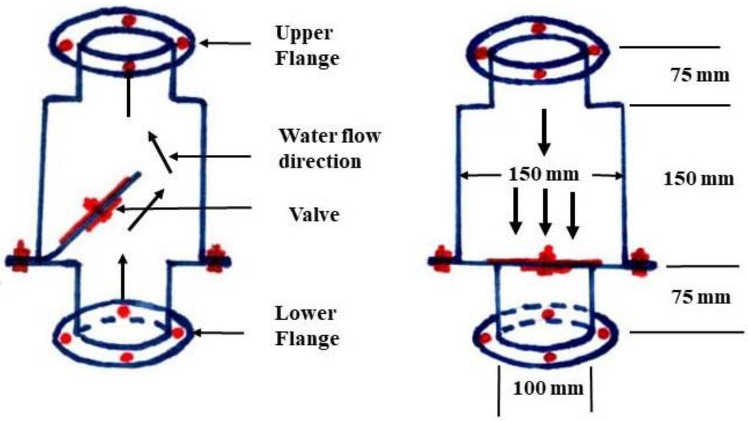
Earthen open channels are common in minor irrigation distribution systems. These channel distribution systems suffer from low conveyance and, application efficiencies, less area coverage and high maintenance cost. The open channel distribution system occupies 2 to 4% of the cultivable land (Michael, 1987) and confronts some physical obstructions such as natural drainage channels or *khals*, embankment or road, high land, irregular or fragmented topography and, permeable soils. These obstructions cause high seepage and percolation losses, leakage, and evaporation losses and right of way problem to the canals. High water loss depends upon the soil texture is a common phenomenon in the earthen channel irrigation schemes of Bangladesh. To improve scheme efficiency, this loss must be minimized. So, the farmers are thinking how to minimize the loss of costly but limited irrigation water and trying to increase the duty of water.

The performance of the existing irrigation systems was extremely poor and most of the planners, administrators and donor agencies trying to improve the performance of those systems from which the farmers achieve the benefits of costly irrigation water use. Construction of improved (compacted) earthen channels, lined channel and, buried pipe system may be the solution to improve the tubewell performance. But all are highly expensive. Buried pipe distribution systems are installed in DTW by institutions like Barind Multipurpose Development Authority (BMDA) and Bangladesh Agricultural Development Corporation (BADC). Now-a-days plastic/polythene pipe water distribution systems become popularized in STW. But farmers facing difficulties in fitting of plastic/polythene pipe on the outlets of STW due to the priming problem. Therefore, this study was undertaken for designing, development and performance testing of a *check valve* (CqV) i) to overcome the priming problem in STW; ii) to reduce the manpower in STW starting; iii) to reduce the drudgery of STW starting and iv) to ease the plastic/polythene pipe fittings on the outlet of STWs.

METHODOLOGY

Principles and Design of a *Check Valve*

Check valve/non-return valve was designed based on the working principles of the hand tubewell operating system. In hand tubewell, when pressing the handle downward then its bucket (piston) moves upward and creates upward pressure on the valve and it opens the suction pipe passage and the water flows into the tubewell chamber from the suction pipe and consequently, some water flows out through the outlet. Again, when pulling the handle upward then the bucket (piston) moves downward and creates downward pressure on the valve and it closes the opening of the suction pipe and the water could not back into the suction pipe from the tubewell chamber. Similarly, when starting the STW pump, it creates a suction pressure on the valve then the valve opens and the water flows into the pump and, it delivers water through outlet of STW. Again, when the pump stops then the weight of the water column in the suction and delivery pipe closes the valve by placing it on the suction pipe (Fig. 1). For these reasons, *check valve* was placed in the joint of tubewell and pump. By this process, the *Check Valve* retains water in whole suction pipe up to the delivery outlet of STW, by which it overcome the STW priming problem. When we start the STW again, no need to go for the priming activities. *Check* valve does not have spring, it relies on gravity to close. For the construction of a *check valve*, a rubber valve was set on a galvanized iron (GI) pipe of the same diameter as the suction pipe of STW (Fig. 1).



a) When the pump is in operation b) When the pump is stopped

Fig. 1. Working principles of *check valve* with different parts and dimensions.

Manufacturing method of *check valve*

The size of the *check valve* depends on the size of the tubewell and the jointing method in the tubewell. In field level, most of the STW size varied from 100 mm (4 inches) to 125 mm (5 inches) and the jointing method of tubewell and pump set by flange joint or thread joint. Considering the STW size of 100 mm, three diameters of the *Check Valve* were designed: i) 125 (CqV diameter) x 100 mm (tubewell suction pipe diameter), ii) 150 x 100 mm, iii) 175 x 100 mm. Also, selected two lengths of valve portion: i) 150 mm (6 inches) and ii) 225 mm (9 inches). In both the sides, 75 mm (3 inches) length of same diameter pipe of the tubewell was welded with the same diameter of flange or thread of the tubewell for easy fitting with the tubewell (Fig. 2). At the bottom of the oversized pipe i.e., *check valve*, a rubber sheet of about 3 mm thick was placed and tightened with the flange and nut-bolt that no leakage was found there. After that, the rubber sheet was cut in such a way that it was about 10 mm oversized diameter of the tubewell suction pipe and about 30-40 mm hinge (i.e., uncut part) with the flange or rubber sheet for free movement of the valve. Then a thin steel sheet of the same size of cut rubber sheet was coupled by a nut-bolt to protect the deformation of the valve from the water pressure of the tubewell suction and delivery pipe (Fig. 1). Figure 2 shows a complete *check valve* with different parts.

Fig. 2. Different components of the *check valve* with threaded fittings

***Check valve* fitting procedure with STW**

Two types of *check valve* were designed based on the coupling system of tubewell and pump set. Normally, the northern part of Bangladesh use thread joint and, rest of the Bangladesh use flange joint system in STW. A suitable *check valve* was fitted in the joint of the tubewell, and pump set in such a way that no leakage was found (Fig. 3). For flange-type joint, a rubber gasket was placed and well tightened. For thread type joint, thread tape was used to protect leakage.

a) Check valve with flange joint. b) Check valve with thread joint.

Fig. 3. Check valve fitted with shallow tubewell.

Testing locations of *check valve* and data analysis

Different sizes of *check valve* were tested in different locations of Bangladesh with the different time span. Table 1 shows the details of locations with installation time of CqV with groundwater level. For testing the performance of the *check valve,* some necessary data like discharge, revolution of the pump impeller and time required to start the pump were recorded before and after the installation of the *check valve*. Also, the performance of plastic pipe fittings to the outlet of STW was tested and estimated the manufacturing cost. Farmers or users' opinion was collected to find out the suitability of the *check valve*. Data were analysed by using statistical tools.

RESULT AND DISCUSSION

Technical performance of *Check Valve*

Table 2 presents information about The technical performance of the different sizes of check valve with manufacturing cost. The results indicated that when the diameter of CqV portion was less than 150 mm (Treatments T1 and T4 in Table 2) for 100 mm diameter tubewell, it could not be able to hold water in the CqV due to very small part of the valve overlaped inside the diameter of valve portion. However, when the diameter of CqV increased then the manufacturing cost was also increased. Moreover, no advantage was found in case of increasing length, but it increased the cost only. Therefore, for 100 mm diameter tubewell, the size of 150 x 100 mm CqV with 150 mm valve length was found suitable in all respects. Only the differences were found in CqVs for jointing system of tubewell, i.e., flange joint or threaded joint.

Table 1. Study locations of CqV with installation year and groundwater level.

Location	CqV installation year	Groundwater level before irrigation start	Groundwater level at peak irrigation time
Vawal Mirzapur, Gazipur	2004	4.0	8.0
Kurigram Sadar, Kurigram	2004	2.0	7.0
Pirganj, Thakurgaon	2005	2.5	7.0
Ishurdi-1, Pabna	2012	2.0	8.0
Ishurdi-2, Pabna	2012	2.5	8.5
Ishurdi-3, Pabna	2015	2.4	8.3
Ishurdi-4, Pabna	2016	2.6	8.8
Mithapukur-1, Rangpur	2015	2.0	7.0
Mithapukur-2, Rangpur	2015	2.2	7.5
Mithapukur-3, Rangpur	2016	2.5	7.8

Table 2. The technical performance of different types of check valves.

Type of check valve (CqV diameter x tubewell diameter)	Length of check valve (mm)	Performance of check valve portion	Cost of check valve (Tk)
T1 = 125 x 100 mm	150	It could not be able to leak proof and hold the water above the valve.	2500-3000
T2 = 150 x 100 mm	150	Could be leak proof and hold the water above the valve.	3000-4000
T3 = 175 x 100 mm	150	Could be leak proof and hold the water above the valve.	4000-5000
T4 = 125 x 100 mm	225	It could not be able to leak proof and hold the water above the valve.	3500-4500
T5 = 150 x 100 mm	225	Could be leak proof and hold the water above the valve.	4500-5500
T6 = 175 x 100 mm	225	Could be leak proof and hold the water above the valve.	5500-6500

Note: CqV = Check valve

Different types and sizes of *check valves* were tested in different locations of Bangladesh depending upon the size of STW, coupling type of tubewell and pump set, starting from 2004 to 2020. Before installation of CqV, the discharge, rpm (revolution per minute) and fitting performance of plastic pipe use for water distribution of each STW were measured. The same data were measured after the CqV installation. There was no significant difference was found in discharge and rpm of the STW before and after installation of the CqV (Table 3). After CqV installation, use of plastic pipe becomes easier and able to reduce the conveyance loss. CqV can be able to control the water level up to the outlet of STW, which completely removed the priming problem of the STW. For that reason, one can start the STW easily. This became prominent when the electricity interruption was more in the peak irrigation season. On the other hand, farmers can easily use the plastic pipe water distribution system for easy conveyance and reduce the conveyance loss of the earthen canal.

Table 3. Effect of *check valve* on discharge, rpm and plastic pipe used.

Location	Size of check valve with joint type & power source	Discharge (l/s)		rpm		Plastic pipe use		Comment
		Before	After	Before	After	Before	After	
Vawal Mirzapur, Gazipur	150 x 100 mm, flange joint, diesel engine	6.80	6.78	2200	2200	Difficult	Easy	• No significant difference found in discharge and rpm. • After check valve installation, plastic pipe use become easier.
Kurigram Sadar, Kurigram	150 x 100mm, threaded joint, diesel engine	8.75	8.74	1500	1500	Difficult	Easy	
Pirganj, Thakurgaon	150 x 100mm, threaded joint, diesel engine	13.25	13.23	1500	1500	Difficult	Easy	
Ishwardi -1, Pabna	125 x 75mm, flange joint, diesel engine	6.75	6.74	1500	1500	Difficult	Easy	
Ishwardi -2, Pabna	150 x 100mm, flange joint, diesel engine	9.25	9.24	1500	1500	Difficult	Easy	
Ishwardi -3, Pabna	150 x 100 mm, flange joint, electric motor	14.80	14.78	2200	2200	Difficult	Easy	
Ishwardi-4, Pabna	150 x 100 mm, flange joint, diesel engine	12.65	12.65	1500	1500	Difficult	Easy	
Mithapukur-1, Rangpur	150 x 100 mm, threaded joint, electric motor	17.75	17.73	2200	2200	Difficult	Easy	
Mithapukur-2, Rangpur	125 x 75 mm, threaded joint, diesel engine	9.55	9.53	1500	1500	Difficult	Easy	
Mithapukur-3, Rangpur	150 x 100 mm, threaded joint, diesel engine	8.45	8.42	1500	1500	Difficult	Easy	

Operating time and cost savings by *check valve*

Table 4 shows a comparison between the difficulty level for starting pump before and after installation of the CqV. It shows that normally at least two persons were needed to start the STW in every starting without CqV. Time required to start the pump was 5-15 minutes. However, after installation of the CqV, it requires only one person to start the pump in each starting time. The time required to start the pump was 1-3 minutes or less than that. Therefore, it is clear that CqV has reduced human drudgery in operation of STWs. It became easier for electrically operated pump, i.e., the pump could be started by pushing the switch button only.

Table 4. Persons and time required to start the STW in every starting time.

Unit	Persons required to start pump		Time required to start the pump (min)	
	Before use of CqV	After use of CqV	Before use of CqV	After use of CqV
1	2	1	5 - 10	1
2	2	1	5 - 10	1-2
3	2	1	10 - 15	1-2
4	2	1	10 - 15	2
5	2	1	10 - 15	1
6	2	1	10 - 15	3

Note: CqV = Check valve, Unit 1= Ishurdi-1, Pabna, Unit 2 = Ishurdi-2, Pabna, Unit 3 = Ishurdi-3, Pabna, Unit 4 = Mithapukur-1, Rangpur, Unit 5 = Mithapukur-2, Rangpur, Unit 6 = Mithapukur-3, Rangpur

Table 5 shows a hypothetical analysis of labour requirement for starting STW without and with a CqV based on the labour and operating time requirement. If a pump operates for 100 days in an irrigation season and on average, it required to start the pump three times a day, then the total number of times it has to start is 300. If the mean starting time is 10 minutes, then it was taken 3,000 minutes i.e., 50 hours for two persons to start the pump in a season. But if CqV is installed in the system and the average starting time was 2 minutes then the total starting time become 10 hours only. It indicates that time requirement for pump start reduces by 90 percent, whereas labour requirement reduces by 50 percent.

Farmers/users' opinion about the use of CqV

The farmers were asked about the requirement of priming activity for pumping operation. Everyone said that it requires to prime the pump at each starting time before the use of CqV and only once in the season, i.e., at the beginning of the pumping after installation of CqV. After initial priming, water always remains above the pump as well as water remains in the pump suction pipe. Several studies (Dey *et al.*, 2017; Aziz *et al.*, 2015; Mustafa *et al.*, 2017; Pena-Arancibia *et al.*, 2020) show that groundwater levels are falling in many parts of the country especially in NW region. The groundwater levels at many areas in the region fall below the suction limit of STWs (8 m) during March to May in peak irrigation period. Therefore, in some cases STW operation became difficult in many areas. So, deep set STW with CqV may be the solution and ease of STW operation.

Other concerns for the farmers were the problems in using of low-cost polythene pipe for irrigation water distribution in a STW. Due to minimum loss in water distribution system, no requirement for canal construction and easier placement, now-a-days, the farmers

Table 5. Cost saved by installation of CqV in the STW.

Condition	Times of start daily	Person needed to start	Time taken to start (min)	Duration of operation (day)	Total time needed (min)	Total labour (man-hr)	Total wage (Tk)*	Savings (%)
Before installation of CqV	3	2	10	100	3000	100	4000	
After installation of CqV	3	1	2	100	600	10	400	90

* Contractual wage for irrigation season

preferred polythene pipe water distribution system. But due to interruption in pump operation and frequent starting farmers were reluctant to use this technology. All the farmers said that it was awfully hard to use polythene pipe for distribution as they have to start the pump many times and for leakage, damage and change in alignment of the pipe. It was very hard to start the pump before installation of the CqV as it requires at least two persons and 10-15 minutes of time. Installation of CqV in STW provides an opportunity for using polythene pipe in water distribution systems. All the pump owners informed that it becomes very convenient to use polythene pipe in distribution system as starting pump was easier after installation of CqV. By observing the field performance farmers are highly interested to installed CqV in their STWs.

Overall impact on introducing *check valve*

Pump owner's reaction

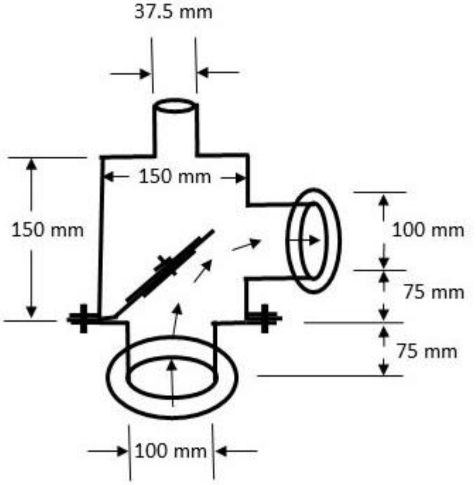
- The check valve reduced drudgery of the farmers.
- They were convinced that CqV did not reduce the discharge of the pump.
- It also provided the opportunity to use polythene pipe very easily that reduced irrigation water loss significantly; and
- Some other pump owners requested to install the CqV in their pumps.

Advantages

- Easy to install.
- Saves labour and reduced human drudgery.
- Offered uninterrupted operation while using plastic/polythene pipe for water distribution. and
- Wide-scale adoption of polythene pipe distribution system was possible by installing CqV.

Alternative design for reducing the cost of *check valve*

The cost of a CqV depends on the size and construction materials of the valve. For connecting of a pump and a tubewell, normally we use a 90º band of 0.60 m to1.0 m in length, that costs about BDT 800 to 1000 at present (Fig. 3). To reduce the cost of a pump by removing this band, an alternative design of a CqV was used (Fig. 4). The field performance of the newly designed was also tested. The performance was very good in all respect of solving priming problem and ease of operation. It also reduces cost of STW pump set by removing the band of the pipe.



a) Alternative design of a CqV

b) Field performance test of alternative CqV

Fig. 4. Alternative design of a check valve and its field performance test.

CONCLUSION

The field performance of CqV for overcoming the priming problem of STW for easy starting and reducing the drudgery of farmers for STW operation found successful. The most effective CqV diameter should be greater than 50 mm over the diameter of tubewell and the CqV length became 150 mm (i.e., 100 x 150 x 150 mm). The installation of a CqV have no adverse effects on tubewell discharge and impeller revolution. It could successfully reduce the starting time and reduce the labour wage to start the pump. It also facilitates the easy use of plastic pipe/ polythene pipe, which also reduced the water conveyance loss and pumping hours. It ultimately reduced the groundwater abstraction and irrigation cost for crop production.

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Behaviour of Groundwater Table with Rainfall in North-West Region of Bangladesh

M T Islam[1]*, M B Hossain[2], D Roy[2], M N H Mahmud[2], P L C Paul[2], M S Yesmin[2] and P K Kundu[3]

ABSTRACT

Groundwater is the major source of water to meet up the vast domestic and agricultural demand in Bangladesh. Additionally, reduction in reliable surface water resources resulting the increased reliance on groundwater day by day. Therefore, monitoring the groundwater fluctuation over time is crucial to ensure the sustainable use of groundwater resources in future. The present study analyzed historical groundwater data to know the behaviour of groundwater at four locations of two districts Pabna and Rangpur in the North-Eastern part of the country. Historical groundwater level data and monthly rainfall data from 1989 to 2017 were collected from Bangladesh Water Development Board and Bangladesh Meteorological Department, respectively. The annual maximum groundwater table depth (MaxGWT) and minimum groundwater table depth (MinGWT) and its trend was analyzed, and positive and negative recharge years were identified from these values. We found the maximum declining rate at 6.6 cm annually and the maximum 205 cm total depletion in the study area. The number of years of negative recharge is more than that of positive recharge for 32 years. As a result, a declining trend in groundwater table was found at three locations of the study area. The maximum groundwater table remains below suction limit at Ishwardi, causes no shallow tubewell (STW) works during that period. A declining trend in annual rainfall is observed in Pabna district. A linear relationship between rainfall and recharge was found at two locations of the study area.

Key words: Groundwater recharge, deficit recharge, recharge depth, rainfall pattern

INTRODUCTION

Groundwater supplies eighty percent of agricultural water demand in Bangladesh, specially to cultivate the dry season crops (Boro rice and others). Surface water is very scarce during dry season in most of the agro-ecological zones, except in the Southern parts of the country. A huge withdrawal of groundwater during dry season causes decline of groundwater table. These decline of groundwater (strong declining trends, 0.5 – 1.0 m/year in the central part of the country; moderately declining trend, 0.1 – 0.5 m/year in Western, North-Western, and North-Eastern areas during dry season) is a threat to water resources if it is not replenished from annual seasonal rainfall. Groundwater depletion can be defined as long-term water level lowering caused by sustained groundwater withdrawing (USGS, 2003). Groundwater depletion can occur when groundwater withdraw exceeds groundwater recharge for a long time in aquifer (Gleeson *et al.*, 2010). According to the Bangladesh Water Development Board (BWDB), the groundwater existed beneath 2 to 14 meters of sediment during the pre-monsoon period. While in the dry season, it was found between 4 and 12 meters in the North-Eastern part of Bangladesh (Kutub, 2015). The larger values mostly represent the depletion in urban areas. In the South-Eastern part, groundwater level remained between 2 to 8 meters during the dry period, whereas this level was ranged in between 6 and 12 in urbanized areas. Previous study on groundwater resource using Visual MODFLOW modeling showed that groundwater recharge occurs due to percolation of rainfall and this recharge rate is lower in urban areas compared to village areas. Historical (1985–2016) trends of North-West hydrological region of Bangladesh revealed that the aquifers were not completely

[1]Chief Scientific Officer; [2]Senior Scientific Officer; [3]Scientific Officer; Irrigation and Water Management Division, Bangladesh Rice Research Institute, Gazipur 1701, Bangladesh
*Corresponding author's E-mail: islam.towfiq@yahoo.com (M T Islam)

replenished in the wet season and mining of groundwater tables were taking place (Mojid *et al.*, 2019). Water level fluctuates seasonally due to unequal recharge and discharge. In addition to rainfall, hydraulic connection between river and aquifer aids in groundwater recharge through influent flow. Nevertheless, groundwater shortage (1000 million liter/year) especially in the vicinity of the Padma River during dry season indicates the excessive use of groundwater. The total groundwater withdrawal in 2004 (15000 million liters) is less than the total input to aquifer, reveals a sufficient potentiality for groundwater declination with increasing demand (Haque *et al.*, 2012). However, no comprehensive studies so far have been conducted on the physical status of groundwater level fluctuation during wet and dry period over the NW region of Bangladesh. Therefore, the objectives of the present study were set to: (i) determine groundwater declination trend; (ii) investigate withdrawal and recharge pattern; and (iii) explore the relationship between rainfall and recharge.

METHODOLOGY

Study location

Four locations were selected to conduct this study in two districts (Figure 1): Ishwardi (24.13° N, 89.06° E) and Santhia (24.06° N, 89.55° E) upazila in Pabna district as well as Mithapukur (25.54° N, 89.27° E) and Pirganj upazila (25.50° N, 89.22° E) in Rangpur district. In Rangpur region, the mean annual temperature is 24.9 ºC. Rangpur region has the warmer period from April to May and colder period from December to January. Average annual rainfall of Rangpur is 2,200 mm and 80% of which occurs during the monsoon (June to October) period. In Pabna region, the average high and low temperatures are 31.2 °C and 20.8 °C, respectively, having average annual rainfall 1,603 mm (Hossain *et al.*, 2021b). The topography in both the locations is medium highland to highland. Soils of top layers is dominated by silt loam texture, the soils are moderately acidic (pH of 4.6–6.5), and organic carbon content is generally 0.94% (Hossain *et al.*, 2021a).

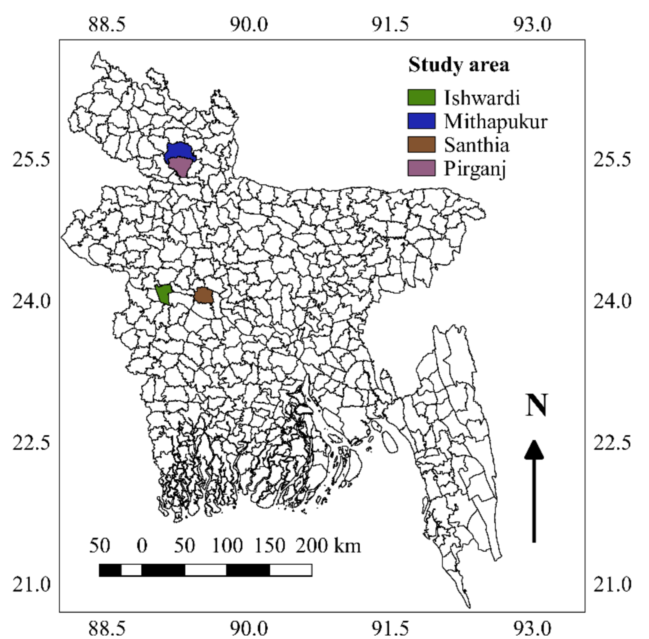


Fig. 1. Study locations.

The fertility of these regions soils ranges between low to medium and soils have good water holding capacity. Rice (Boro, T. Aman, and Aus) is the major crop in these regions. However, farmers also grow other crops like potato, wheat, vegetables etc. covering huge cultivable lands (Zaman *et al.,* 2017).

Data collection

Historical daily data of groundwater table (GWT) from 1987 to 2017 of four observation wells of four upazilas were collected from Bangladesh Water Development Board (BWDB). The observation wells are GT8576013 in Pirganj and GT8558008 for Mithapukur of Rangpur district, GT7639017 for Ishwardi and GT7672029 for Santhia of Pabna district. Besides, historical rainfall data of Ishwardi and Rangpur weather stations were collected from Bangladesh Meteorological Department (BMD).

Groundwater table analysis

The annual maximum (MaxGWT) and annual minimum (MinGWT) groundwater table of each year were determined from the daily data. The annual linear trend of MaxGWT and MinGWT were determined from the data. The groundwater table were compared to the reference value of shallow tubewell suction limit (8.0 m below ground surface). The average groundwater withdrawal and recharge was calculated from the maximum and minimum groundwater table data. Groundwater withdrawal is the difference between MinGWT of the (n-1) year and MaxGWT of the (n) year. Similarly, groundwater recharge was the difference of MaxGWT and MinGWT of the (n) year. A relationship exists between groundwater withdrawal and annual recharge with the annual rainfall. If the amount of withdrawal of groundwater is greater than the amount of recharge, deficit in groundwater storage (aquifer) occurs and it is called the year of negative recharge. As a result, both maximum ground water table (MXGWT) and minimum ground water table (MNGWT) go down from its previous position. If this scenario happens for more years through extended period, a declining trend both in MXGWT and MNGWT is shown after couple of years. Similarly, if the withdrawal amount is less than the recharge volume then the year is called positive recharge. It is mentionable that MXGWT and MNGWT occurs in April-May and September-October period, respectively, in Bangladesh. Groundwater depletion of the study locations were calculated from MinGWT of the base year 1989 to 2017. The difference between MinGWT for the "n" years is termed as groundwater depletion and the annual depletion rate was calculated from dividing the total depletion by "n."

Groundwater recharge with rainfall

A relationship was derived from the annual rainfall to MinGWT and recharge depth. A linear trend line of recharge depth and rainfall was developed from the historical data of each station.

RESULTS AND DISCUSSION

Trend of ground water table

Figure 2 presents minimum and maximum groundwater table trend which was analyzed. The figure shows that minimum groundwater table had the declining trend in all the study locations. The maximum declining rate of MinGWT was found 0.073 m year^{-1} at Ishwardi, Pabna whereas, the lowest rate was found in Pirganj, Rangpur (0.0092 m year^{-1}). Rangpur showed the lowest declining rate than Pabna since comparatively higher recharge was occurred in Rangpur areas. The higher rainfall, higher surface water bodies, less crop diversification led to less water declination in Rangpur areas. The MaxGWT trend revealed that almost every location there was a declining trend in groundwater table except Santhia, Pabna. The maximum declination of MaxGWT was found in Ishwardi and the minimum rate was in Mithapukur, Rangpur. Santhia showed the positive trend of groundwater table declination.

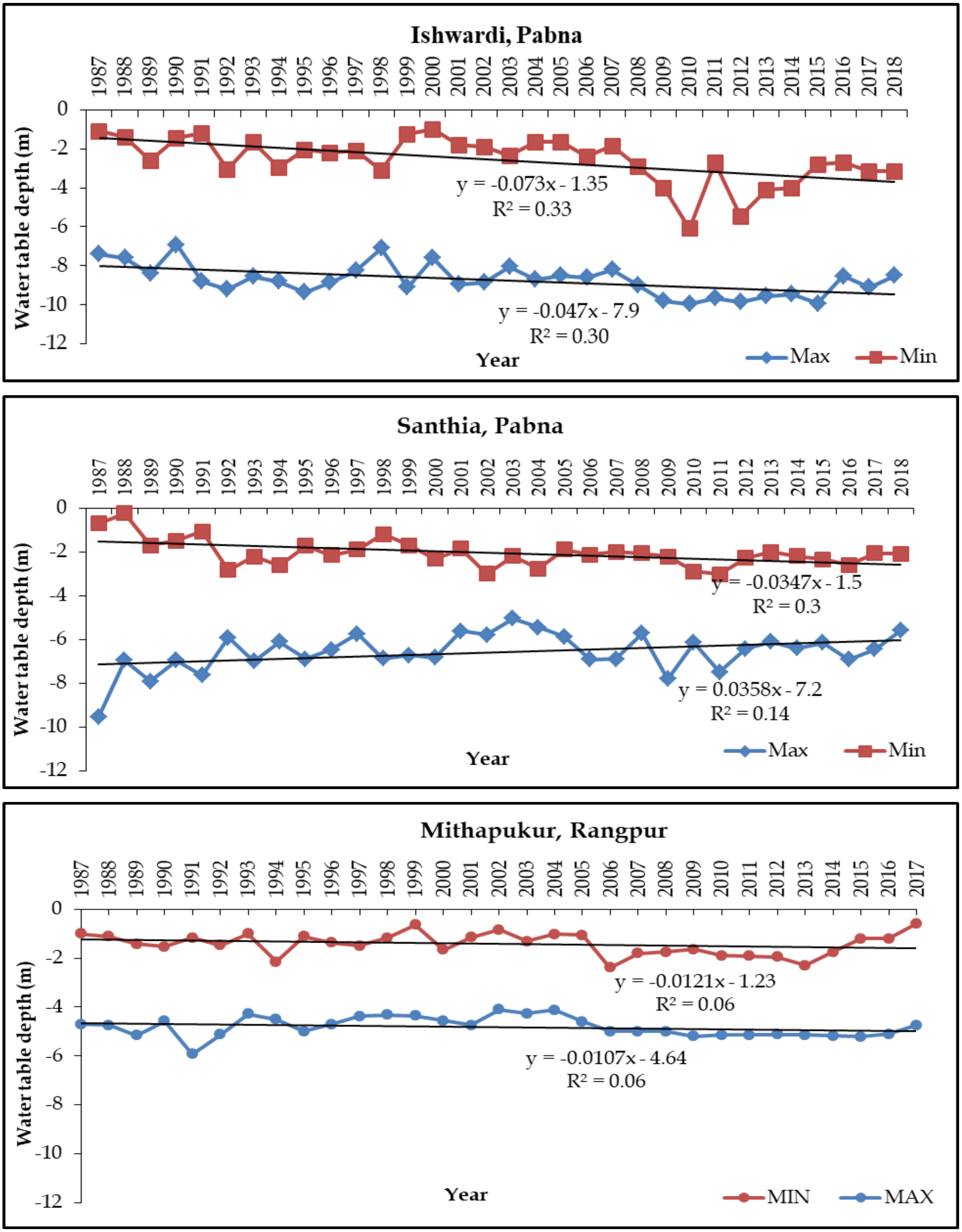


Fig. 2. Trend and fluctuation of groundwater table in various locations of the project area.

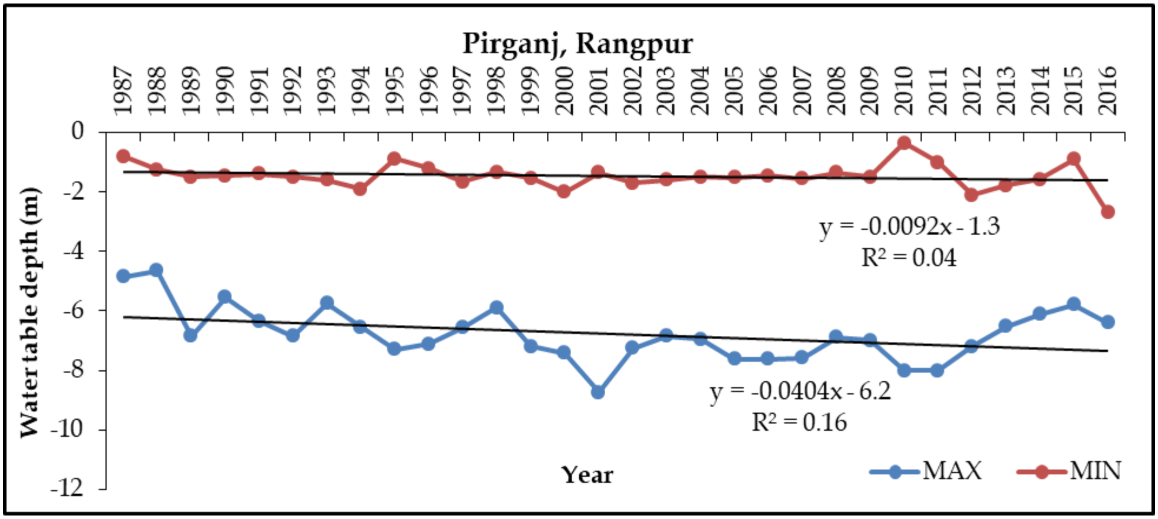


Fig. 2. Continued.

Character of groundwater table

Long term GWT data of various locations were analyzed to know why declination of groundwater occurred. Tables 1 and 2 present the outputs of withdrawal and recharge pattern of groundwater at different locations those were investigated. In Table 1, presents the ranges of maximum and minimum GWT depths from 9.95 m to 6.92 m and from 6.1 m to 1.0 m, respectively, at Ishwardi. These range values are comparatively higher than range values of other locations. It indicates that the groundwater level from the ground surface at Ishwardi always remained lower than those at Santhia, Mithapukur and Pirganj. Average withdrawal depth, i.e., difference between minimum and maximum GWT depth was also the highest (6.20 m) at Ishwardi among the locations. It means, per year withdrawal of ground water was more at Ishwardi than the other location. Mojid *et al.,* (2019) showed a significant falling trend of maximum groundwater table in about 65.71% observation wells in a study with 350 wells in North-West hydrological region of Bangladesh. They also noticed the over withdrawal of groundwater behind the GWT depletion. BRRI (2020) also found similar results of decreasing GWT in Pabna and Bogura. Number of years of negative recharge, when minimum GWT depth of any year is greater than last year means negative recharge, at every location except Mithapukur was higher than number of years of positive recharge (when minimum GWT depth of any year is smaller than last year means positive recharge). Beside that number of years of excess withdrawal (when maximum GWT depth of any year is greater than that of last year) at every location was higher than number of years of less withdrawal (reverse of excess withdrawal). Because of more negative recharge and more excess withdrawal, depletion in groundwater level is taking place. As for example, out of 30 years in Ishwardi, 14 years had positive recharge whereas 15 years had negative recharge and, in one year, there was no positive and negative recharge. Again, excess withdrawals were higher than less withdrawals at Ishwardi, so groundwater trend is declining.

Table 1. Water table, recharge, and withdrawal pattern of groundwater in Pabna and Rangpur.

Location	Period year	MaxGWT range (m)	MinGWT range (m)	Average withdrawal (m)	Positive recharge (yr)	Negative recharge (yr)	Less withdrawal (yr)	Excess withdrawal (yr)
Ishwardi	30	9.95-6.92	6.10-1.00	6.20	14	15	15	17
Santhia	32	9.56-5.05	3.02-0.25	4.40	14	17	17	14
Mithapukur	30	5.92-4.10	2.40-0.51	3.37	15	15	14	16
Pirganj	27	8.75-4.64	2.70-0.35	5.40	14	13	11	16

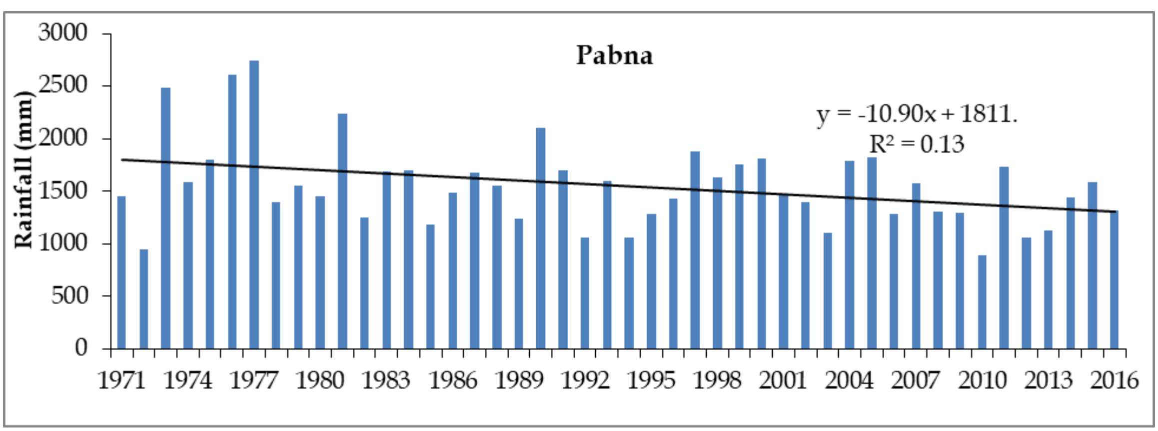
In Table 2, total depletion (difference between minimum GWT depths before 30 years and present year) has occurred in Ishwardi which was the highest (205 cm) among the locations and average per year depletion was 6.6 cm. Nevertheless, there was no depletion in groundwater in Mithapukur. In Ishwardi, maximum GWT remained beyond suction limit for 28 times out of 30 years (suction limit means a reference depth of eight meter below the ground surface). As a result, no shallow tubewell works during dry period in Ishwardi. But in Mithapukur, maximum GWT always remained above suction limit.

Annual rainfall and it's trend

Rainfall is one of the main sources for groundwater recharge. This study at first investigated the annual rainfall trend of the two districts form historical rainfall data. The amount of annual rainfall is not same in every year and variation was observed (Fig. 3). But deviation of the variation is more observed in Pabna district. As a result, there is a declining trend in annual rainfall occurred in Pabna district.

Table 2. Groundwater table depletion pattern in Panba and Rangpur district.

Location	Period (yr)	GWT beyond suction limit (yr)	Total depletion (yr)	Average per year depletion (cm)
Ishwardi	30	28	205	6.6
Santhia	32	1	140	4.38
Mithapukur	30	0	0	0
Pirganj	27	3	155	5.7



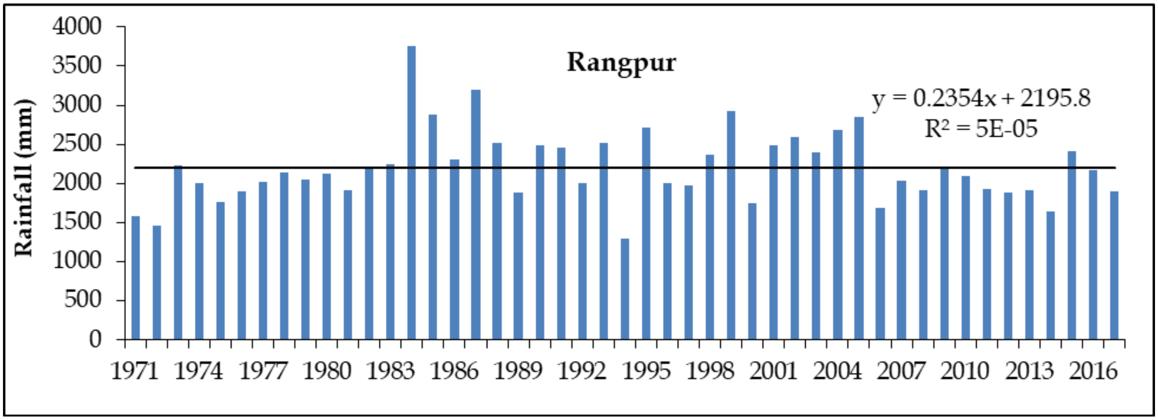


Fig. 3. Trend analysis of historical rainfall at Pabna and Rangpur district

Annual rainfall and minimum groundwater table relationship

Annual rainfall is one of the main sources for recharge and minimum GWT (MinGWT) is directly related to recharge. Figure 4 shows linear relationship observed between annual rainfall and MinGWT. It shows, MinGWT raised at a rate of 0.0025 m and 0.0008 m per each meter increasing rainfall at Ishwardi, Pabna and Mithapukur, Rangpur, respectively. It indicates the positive relation of groundwater recharge with annual rainfall. Shahid and Hazarika, (2010) found the same relationship between rainfall and groundwater recharge in North-West region of Bangladesh.

Recharge period rainfall and recharge depth relationship

Another attempt was taken to explore the relation between recharge period rainfalls (RPRF) and recharge period depth. Recharge period means the required time to reach groundwater table from its maximum depth position to minimum depth position in the same year (generally, May to October). Again, the depth between maximum groundwater table and minimum groundwater table in the same year is recognized as recharge depth (RD). However, Figure 5 shows that RD increased with the increasing of RPRF. Greater RD indicates minimum groundwater table was closer to ground surface.

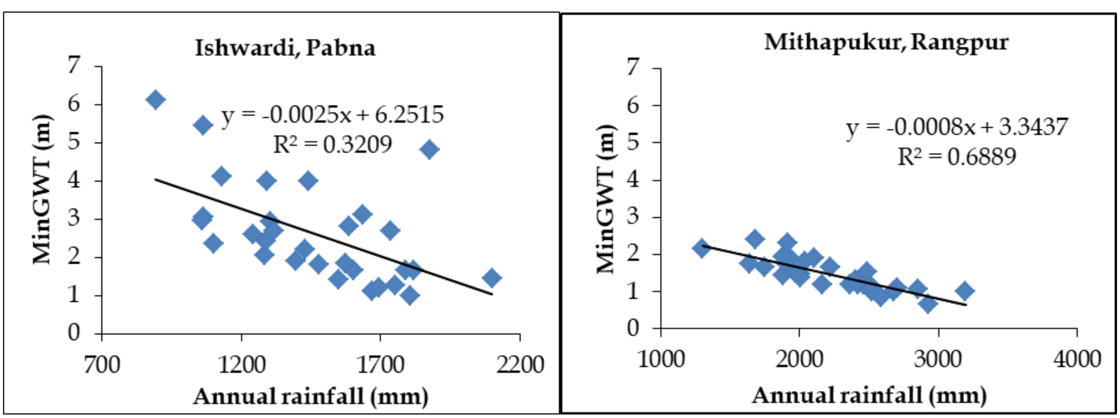
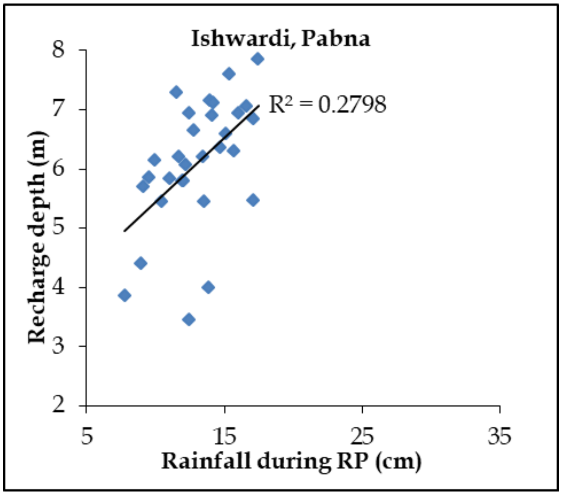


Fig. 4. Relationship between annual rainfall and minimum groundwater table at Ishwardi, Pabna and Mithapukur, Rangpur.



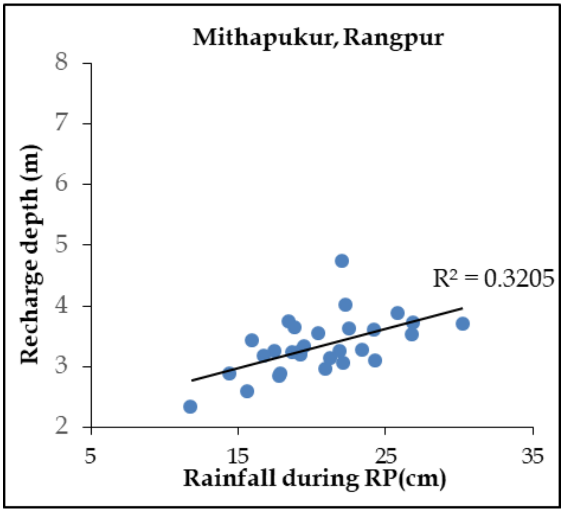


Fig. 5. Relationship between recharge depth and rainfall during recharge period at Ishwardi and Mithapukur.

CONCLUSION

A declining trend of groundwater table persists in the study area except at Pirganj, Rangpur. The maximum total depletion is 205 cm with the maximum 6.6 cm per year depletion and number of years of negative recharge is more than that of positive recharge for 32 years. The maximum groundwater table remains below suction limit at Ishwardi, causes no shallow tubewell (STW) works during that period. A declining trend in annual rainfall is observed in Pabna district. A positive linear relationship between rainfall and recharge was found at two locations of the study area.

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