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IRRIGATION REQUIREMENTS ASSESSMENT IN A SELECTED IRRIGATION UNIT

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Abstract

Better understanding on water management in any irrigation project plays vital role in incremental crop yield. The Karnafuli Irrigation Project (KIP) in the south-eastern region of Bangladesh is a flood control, drainage and irrigation project. The project is well known for its success in achieving irrigation, except few crop damages due to flooding and water logging. Among two units of this project, CROPWAT 8.0 has applied on the Halda unit by using 15 years (1993 to 2007) climate data, considering two scenarios, i.e., rainfed and irrigation. The aim of this study is to estimate total irrigation water requirements (IWR) using CROPWAT. For total IWR estimation, CROPWAT could reasonably represent the soil moist deficit under rainfed and irrigation scenarios. A water balance calculation was carried out to estimate the surplus water, and hence CROPWAT is found to be a useful tool in estimating irrigation requirement against flooding condition. This study is being expected to contribute to the decision process on optimal irrigation supply.

Keywords: *Irrigation Water Requirements (IWR), CROPWAT, Halda, Evapotranspiration (ETo), Karnafuli Irrigation Project (KIP).*

Introduction

The Food and Agriculture Organization (FAO) introduced CROPWAT as a numerical model to calculate the crop water requirements and irrigation water requirements (IWR) from climate, crop and soil data. This model also allows for developing irrigation schedules for different management conditions and the calculations of water supply scheme for varying crop patterns. The CROPWAT model comprises of (i) Penman-Montieth method for calculating evapotranspiration (ETo) (Smith, 1992), and (ii) the calculation of crop water requirements and IWR requirements are mainly based on FAO irrigation and drainage papers, are (a) Guidelines for computing crop water requirements and (b) Yield response to water (Doorenbos and Kassam, 1979.).

CROPWAT have been using by researchers for estimating the evapotranspiration ETo (Shakoor et al., 2006; Najafi, 2007), crop water requirements (Döll and Siebert, 2002; Shakoor et al., 2006; Cazanescu et al., 2009), water deficit (Severini and Cortignani, 2008) and soil moisture deficit (Roy et al., 2009). CROPWAT seemed promising in predicting the crop water requirements under water stress (Cavero et al., 2000; Marica et al., 2001;Hassanli et al., 2008; Nazeer, 2009) and climate change (Moussa and Amadou, 2006; Nazeer, 2009; Roy et al., 2009). Roy et al. (2009) estimated the soil moisture deficit using CROPWAT in selected parts of Bangladesh over the projected climate scenarios for the years 2030 and 2075 along with the crop water requirement assessment and yield variations. So, there is a knowledge gap on applicability of this model to estimate the excess water causing water logging or flood in irrigated area.

Study site

The project area under Halda unit of KIP is 15386 ha and the irrigable area is 12550 ha, located in 22°25'-22°35' latitude and 91°45'-91°60' longitude (Figure 1). Miah (1986) observed this area comprises of three main seasons, namely, monsoon (June-October), dry season (November-February) and pre-monsoon (March-May). About 80% of the total annual rainfall recorded during monsoon, dry season comprises of lower rain whereas the pre-monsoon comes with occasional heavy rain storms (Miah, 1986). Top soil textures of this area range from loam to clay, with silty clay loam and silty clay are the most common (JCHW, 1968).

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The KIP is supervised by three agencies, the Bangladesh Water development Board (BWDB), Department of Agricultural Extension (DAE) and Bangladesh Rural Development Board (BRDB). The BWDB is responsible for the hydraulic and river training structure operation and maintenance, DAE works for people motivation and participation for High Yield Variety (HYV) crop cultivation and BRDB works for capacity build up through formation of farmers' cooperatives (KSS) and micro credit.

The KIP project implementation period was 1975-76 to 1982-83. Before starting the project a feasibility study was carried out in 1974 (IECO, 1974) and since 1982, Kaptai Operation and Maintenance Division, BWDB observing the achieved irrigated area over the target (Figure 2). Qasem (1984) reported during dry season around 800 low lift pumps were employed for High Yield Variety (HYV) rice cultivation using surface water. Miah (1986) described that per 0.05 cumec pump covers around 17 ha command area. Around 1214 ha of higher land was irrigated by ground water using shallow/ deep tubewells during dry season and about 10117 ha of low lying land near the Halda river tributaries used to irrigated by surface water (Miah, 1986).

Due to flood and water logging two major crops (i.e., Aman and Boro rice) under this project area often damaged (Miah and Mohit, 1996). So, proper management on the crop water requirements and irrigation supply need to be better understood. The study reported here addresses this through CROPWAT estimated surplus irrigation water. The available survey data in KIP shows in 1992 about 90% of the target irrigated area have achieved, so for calculation it is assumed that the 100% of target area (i.e. 12550 ha) had achieved in 1993 and onward.

Theory

Water balance studies play a vital role in IWR calculation as well as in the modern hydrology. The inflow to the field comprises of the total precipitation and irrigation, where water moves from the field through ETo, seepage, percolation and surface runoff. A generalized water balance equation for an agricultural field can be expressed as follows:

$$S(t+\Delta t) = S(t) + P(t, t+\Delta t) - ET_o(t, t+\Delta t) - R(t, t+\Delta t) - I(t, t+\Delta t) - S_1(t, t+\Delta t) + IR\ (t, t+\Delta t) \quad \ldots(1)$$

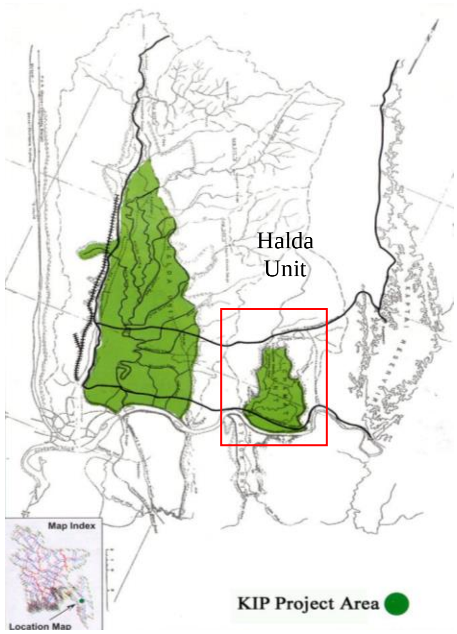

Figure 1. Halda unit in KIP project

Where,

$S(t+\Delta t)$	=	Soil moisture content at time $t+\Delta t$, mm
S(t)	=	Soil moisture content at time t, mm
$P(t+\Delta t)$	=	Precipitation of all forms between time t and $t+\Delta t$, mm
$ET_o(t+\Delta t)$	=	Reference evapotranspiration between time t and $t+\Delta t$, mm
$R(t+\Delta t)$	=	Runoff between time t and $t+\Delta t$, mm
$I(t+\Delta t)$	=	Percolation loss to groundwater between time t and $t+\Delta t$, mm

$S_1(t+\Delta t)$	=	Seepage loss between time t and $t+\Delta t$, mm
$IR(t+\Delta t)$	=	Irrigation supplied between time t and $t+\Delta t$, mm.

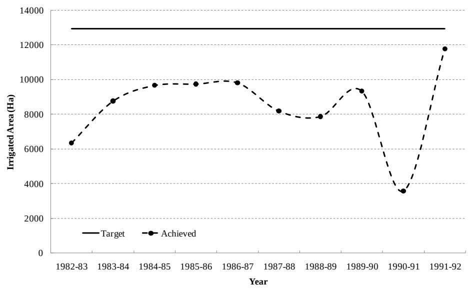

Figure 2. The target and achievement of irrigation area in Halda unit, KIP (Kaptai O &M Division, BWDB)

Precipitation provides part of the required water for crops, need to satisfy their transpiration requirements. The soil acts as buffer to store parts of the precipitated water and supply to the crops under water stress. In humid condition, the whole mechanisms ensure satisfactory growth under rainfed agriculture. In dry condition irrigation needs to meet the deficiency due to evaporation and precipitation. The irrigation water requirements were calculated into the CROPWAT model by the difference between the crop evapotranspiration under standard conditions (ETc) and the effective rainfall contributions over the same time step, i.e.,

$$\text{IWR} = A\sum_{i=1}^{365}\left(ET_O \times K_c - P_{eff}\right) \qquad \ldots(2)$$

Where,

IWR	=	Irrigation water requirement (m^3/year)
ET_o	=	Reference evapotranspiration (mm/day)
K_c	=	Crop coefficient
P_{eff}	=	Effective precipitation (mm/day)
A	=	Irrigated area (percentage of total area)

Net irrigation requirements are therefore defined as the volume of water needed to compensate for the deficiency between the potential evapotranspiration and the effective precipitation over the crop growing period (Faurès et al, 2002). So, the IWR estimation was done using Equation 2 i.e. the standard CROPWAT calculation method. However, to evaluate the CROPWAT performance, the water balance has computed for irrigated lands in the study area using Equation 1.

Evapotranspiration (ETO) is defined as the consumptive use for a particular crop during transpiration and the evaporation either from the plant itself or from the adjacent soils (Gangopadhyaya et al., 1966, Garg, 1998). So, the precipitation, soil moisture condition, specific plan water requirement and the physical nature of the land cover or the studied watershed hydrology are the local factors, influence the evapotranspiration (Dunn and Makay, 1995). Generally, the irrigation requirements of the crops are calculated from the difference between the consumptive use and the effective precipitation (Garg, 1998). The well known methods for estimating ETo are the Penman (Penman, 1948), Penman-Monteith (Monteith, 1965 and 1981), FAO Penman–Monteith (FAO-PM) method, Pan Evaporation, Kimberly-Penman (Jensen et al., 1990), Priestley–Taylor (Priestley and Taylor, 1972), Hargreaves (Salazar et al., 1984), Hargreaves class A pan evaporation method (Garg, 1998), Samani-Hargreaves (Samani and Hargreaves, 1985) and Blaney–Criddle (Allen et al., 1998). Intensive studies carried out by different researchers for a suitable ETo estimating method in irrigation project context and the Penmen-Monteith model was reported to be the best suited model (Lee et al., 2004). ETo in CROPWAT is computed by FAO Penman-Monteith Model (Allen et al., 1998). The FAO Penman-Monteith method to estimate ETo is:

$$ET_o = \frac{0.408\,\Delta(R_n - G) + \gamma\dfrac{900}{T+273}\,u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \qquad (3)$$

Where,

R_n	=	Net radiation at the crop surface (MJ/m^2 day)
G	=	Soil heat flux density (MJ/m^2 day)
T	=	Air temperature at 2 m height (°C)
u_2	=	Wind speed at 2 m height (m/s^1)
e_s	=	Saturation vapour pressure (kPa)
e_a	=	Actual vapour pressure (kPa)
e_s - e_a	=	Saturation vapour pressure deficit (kPa)
γ	=	Psychometric constant (kPa/°C)
Δ	=	Slope vapour pressure temperature curve (kPa/°C) (ASCE, 2002)

$$= \frac{2504\, exp\, exp \left(\frac{17.27\, T}{T + 237.3}\right)}{(T + 237.3)^2}$$

Materials and Methods

Details on the collected climate data are given in Table 1. Generally, for a normal year the recorded precipitation in the studied station is 2900 mm and during 1993-2007 the driest most year was 1994 with 2258 mm precipitation. In CROPWAT, to account for the losses due to runoff or percolation, the effective precipitation (P_{eff}) can be estimated by four methods, namely Fixed percentage, Dependable rain, Empirical formula, and USDA Soil Conservation Service (FAO, 2010). The USDA Soil Conservation Service (SCS) described crops can use almost 60 to 80% of the total monthly precipitation (P_{month}) upto 250 mm and beyond this amount of precipitation the crop consumption eventually become less (USDA, 1993).Thus the effective rainfall (P_{eff}) is:

$$P_{eff} = \frac{P_{month} \times (125 - 0.2 \times P_{month})}{125} \quad (6)$$

for , $P_{month} <= 250\ mm$

$$P_{eff} = 0.1 \times P_{month} \quad (7)$$

for, $P_{month} > 250\ mm$

In last decade, during June to August the recorded amount of precipitation in the study area often become two to three times more than the USDA prescribed amount. So, to understand the general performance of the existing irrigation project both of the USDA and the fixed percentage (80% efficiency) rainfall/precipitation method were tested. As this study aimed to investigate optimal irrigation requirements against the water logging and flooding, so the fixed rainfall has chosen as higher possible value. One limitation in rainfall data entry in CROPWAT 8.0 is the present setup can only accept three digits plus a decimal for a given month. In July 1997, July 1998 and August 1998 the recorded rainfall data were 1033 mm, 1291 mm and 1194 mm respectively; the input were given as 999.9 mm in CROPWAT. So, the underestimation was 3% for 1997 and 22% for 1998.

The details on crop and cropping pattern input data tabulated in Table 2 and the percentage of cultivated area noted down in Table 3. Miah and Mohit (1996) observed that the available irrigation water had positive influence on the crop selection and cropping pattern in the KIP project area and the copping intensity in the whole project had increased from 181% (in 1981) to 200% (in 1990). The crop selection goes for transplanted Aman and Boro HYV instead of the local variety Aus, Aman and Boro (Miah and Mohit 1996). So, during calculation the available crop types in 1992 has considered throughout the study area reported in this paper. *Soil data* for the study area is tabulated in Table 4.

Irrigation water requirements (IWR)

United States Department of Agriculture (USDA) soil conservation method was used for estimating the actual irrigation requirements for different crops. Two scenarios were tested, i.e., (A) Rainfed and (B) Irrigation. The main differences in these two scenarios were in the growth stage of plant under same land preparing schedule. In scenario A there was no irrigation, where as the scenario B comprise of (i) For rice: irrigation timing at fixed water depth i.e. 5 mm and the refill application at fixed water depth would be 100 mm, and (ii) For Rabi crop: irrigation timing at 100% critical depletion and refill application at soil moisture content to 100% field capacity. The irrigation efficiency was considered as 70%.

Flow data

Fifteen years (1993-2007) monthly flow data were collected for the station Punchpukuria

(Longitude: 91° 46' E, Latitude: 22° 40' N) from BWDB.

Results and discussion

ETo Calculation

Except the minimum and maximum temperature there were discontinuous data series for other parameters in the meteorological station, so the relevant option in CROPWAT had used for estimating the missing parameters and then the ETo. Figure 3 represents the range of monthly ETo variation in last 15 years. The total ETo had calculated from the average monthly values (Table 5). Due to lack of details data on the Aus in literatures, the CROPWAT estimated value could not compare. However, Boro and Aman rice and the Rabi crops seemed well estimated using CROPWAT setup.

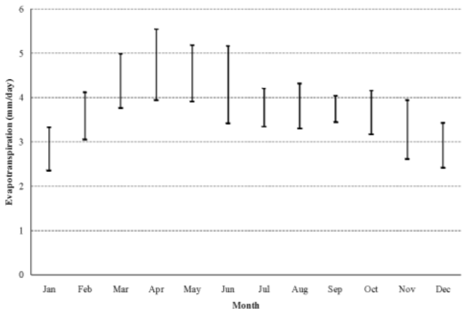

Figure 3. Average monthly CROPWAT estimated ETo in Chittagong station (1993-2007).

Irrigation requirements

The CROPWAT prediction for the *scenario A* showed cropwise yield reduction over last 15 years without irrigation Figure 4. Low rain year, like 2006, needed irrigation for all four category crops. But normally Boro and Rabi need irrigation for enhancing the growth. According to Mahmood (1997) Aman is rain-fed rice, supplement irrigation is required for Aus in initial stage and Boro needs irrigation. Similar conclusion can be made for the scenario A. 40 to 100 mm soil most deficits during harvest period observed under this scenario (Figure 5).

In *scenario B*, Boro and Rabi need some additional irrigation, however with the provided amount of irrigation the CROPWAT prediction having soil moist deficit under 20 mm (Figure 5) and there was no yield reduction. The USDA soil conservation method showed the average effective rainfall for the studied period (1993-2007) for Aus, Aman, Boro and Rabi were 56%, 75%, 54% and 79% respectively. It is assumed that if a fixed rainfall of 80% is available then all of the four crops would be benefited. So, for water balance calculation this setup was continued for both of the USDA soil conservation services and fixed rainfall method.

The water balance had calculated using Equation 1 , in this calculation the total irrigated land had taken as 12950 ha (the target irrigated area) (Data Source: Kaptai O &M Division, BWDB). The CROPWAT estimated effective precipitation ‘Peff’ excludes the loss due to seepage and percolation from total precipitation, so the 2nd, 5rd and 6th term in Equation 1 represented by Peff. Then, CROPWAT estimated ETo had used. According to Alauddin and Quiggin, (2008) environmental changes might happen when freshwater diversion reaches 25 – 30% of historic seasonal low flows. Feld (1995) noted many of Bangladeshi rivers already exceed these levels and three highly affected rivers are Buriganga near Dhaka, Sitalakhya near Narayanganj and Karnafuli near Chittagong. So, for present study the irrigation supply (IR) was calculated by applying 12.5% as surface water efficiency of input of river flow (station Punchpukuria) in Halda unit. Garg (1998) demonstrated the runoff (R) can be calculated as (Runoff = Runoff coefficient × precipitation), where, the runoff coefficient for the clay and silty loam flat cultivated area is 0.30.

Two conditions, (i) 80% fixed rainfall and (ii) USDA soil conservation services, had evaluated under consideration of 70% irrigation efficiency, 100 mm fixed irrigation for rice, and irrigation for Rabi crop providing soil moisture content refill up to 100% field capacity.

So, from the comparison between the two methods it can be concluded that the selection of 12.5% extraction from river can be further reduce based on more details data from the irrigated land itself.

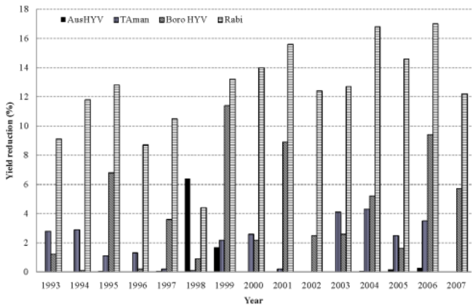

Figure 4. CROPWAT predicted crop yield reduction (Scenario A)

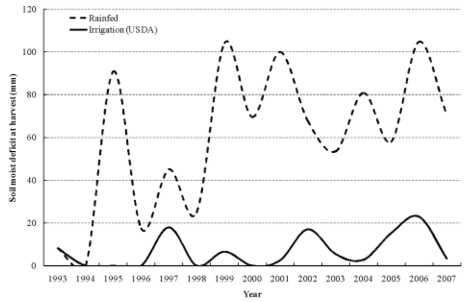

Figure 5. Comparative soil moist deficit under two scenarios

Table 1. Details on climate and precipitation data

Parameters	Duration	Details
Minimum temperature (°C)	1993-2007	Station: Chittagong Source: Bangladesh Meteorological Department Frequency: Monthly data
Maximum temperature (°C)		
Humidity (%)	1995-2001	
Wind (km/day)	1995-2001	
Sunshine (hour)	1997-2001	
Precipitation (mm)	1993-2007	

Table 2. Details on crop input data for CROPWAT

Crop[c]		Growth Stage					Data Source
		Land preparation	Initial	Development	Mid	Late	
Length (Days)	Boro	30	15	65	45	25	Mahmood, 1997 Mondal et al., 2010
	Aman	30	20	50	30	15	Bangladesh Aman rice v.1, www.irri.org/irrc/ssnm
	Aus	30	30	30	60	30	Allen et al. (1998) for rice
	Rabi crop	30	35	50	25	30	Allen et al. (1998) for potato.
Kc wet	Boro	-	1.10	1.20	0.9	0.60	Based on wind speed and relative humidity, the initial, development and late stage value was taken from Allen et al (1998) for rice. Mid stage calculated from the average of the development and late stage.
	Aman	-	1.15	1.20	1.05	0.90	
	Aus	-	1.10	1.20	0.97	0.75	
	Rabi crop	-	-	1.15	0.95	0.75	
Rooting depth (m)	Rice	-	0.15	-		0.5	Yoshida (1981) for rice
	Rabi crop	-	0.4	-		0.75	Battilani et al. (2008)

Puddling depth (m)	0.12	-		-		Saunders and Hettel (1993)
Critical deple-tion	Boro	0.27		0.18	0.28	Based on average evapo-transpiration for relevant months and the crop coefficient, crop evapotranspitarion (ETc) was calculated. Then the critical depletion factor with respect to the ETc had taken from Allen et al (1998).
	Aman	0.2		0.21	0.29	
	T. Aman	0.23		0.21	0.29	
	Aus	0.17		0.16	0.28	
	Rabi crop	0.35		0.27	0.32	
Yield response factor	Boro	1.1	1.75	2.4	0.29	Mondal et al. (2010)
	Aman	1.1	1.1	2.4	0.33	Prasad et al. (2006)
	Aus	1.4	1.4	3.0	0.4	Doorenbos and Kassam (1979)
	Rabi crop	0.45	0.8	0.7	0.2	Allen et al. (1998)
Crop height (m)	Boro			1.1		Pathak et al., 1999
	Aman			1.5		Zubaer et al., 2007
	Aus			1		www.knowledgebank.irri.org/uplandRice/farmersGuideUplandRice.pdf
	Rabi crop			0.6		Allen et al., 1998

[c]CROPWAT model input planting date collected from cropping calendar of Halda unit adjacent upazila (smallest administrative unit of Bangladesh) (BBS, 1985): Aus (Local) - 15April, Aus (HYV) -15 May, Aman (Local) – 15 July, Transplanted Aman (HYV) – 15 August, Boro (Local) -15 January, Boro (HYV) – 15 February, Rabi crop – 15 November.

Table 3. Crop wise cultivated area, Halda unit (Without project, 1974 and with project 1986, Evaluation Studies of KIP by SARM, 1986 and For 1992, Household Survey by DPE, 1992)

Crops		Without Project (1974)		With Project (1986)		With Project (1992)	
		Area (Ha)[d]	Yield (Ton/Ha)	Area (Ha)[d]	Yield (Ton/Ha)	Area (Ha)[d]	Yield (Ton/Ha)
Rice	Aus (Local)	4452 (14%)	1.29	-	-	-	-
	Aus (HYV)	2832 (9%)	2.58	8175 (28%)	2.60	4655 (15%)	2.76
	Aman (Local)	8094 (26%)	1.94	-	-	-	-
	T.Aman (HYV)	6070 (19%)	2.95	10842 (38%)	3.07	13825 (44%)	3.08
	Boro (Local)	809 (3%)	2.30	-	-	-	-
	Boro (HYV)	7285 (23%)	4.24	8652 (30%)	3.57	11780 (38%)	4.15
Rabi	Pulses/ Oilseeds	1376 (4%)	0.74	382 (1%)	1.04	480 (2%)	1.22
	Vegetables	405 (2%)	6.99	672 (3%)	6.94	670 (1%)	7.02

[d] percentage of the total cultivated area had represented in the parenthesis

Table 4. Soil input data

Parameters	Value	Sources
Total Available soil moisture (mm/m)	140	Silty clay composition (sand 20%, silt 30%, clay 50%) was derived for lower Atrai Basin in Bangladesh (Alam et al, 2007). Using these values the water content at field capacity and wilting point had found as 0.43 m^3 m^{-3} and 0.29 m^3 m^{-3} respectively.
Maximum rain infiltration rate (mm/day)	115	For the silty loam texture, the basic infiltration rate of 4.8 mm/h (Ali et al., 2007)
Maximum rooting depth (m)	0.75	Battilani et al. (2008)
Initial Soil moisture deplete (% of TAM)	40	Chowdhury (2009) used 5% and 20% of the total available for drought risk assessment numerical model in major rivers in Bangladesh. Parker (1992) found the amount not more than 40% of the total available water.
Drainable porosity	10	Using hydraulic properties calculator for silty loam http://weather.nmsu.edu
Critical depletion for puddle cracking	0.6	Allen et al. (1998) suggested values are between 0.4 and 0.6, whereas the lower values are for sensitive crops with limited rooting systems under higher evaporation rates, and higher values for deep and densely rooting crops and low evaporation conditions.
Water availability at planting (mm)	31	Samson et al. (2004)
Maximum water depth (mm)	101	Samson et al. (2004)

Table 5. Comparison between two methods for evapotranspiration estimation

Crop		Crop growing duration[e]	CROPWAT Total ET_o (mm)	Total ET_o (mm) from previous studies
Rice	Aus HYV	Apr to Sep (15/04 to 11/09)	650.43	---
	T Aman	Aug to Dec (15/08 to 7/12)	415.7	476 (Bhuiyan and Islam, 1991)
	Boro HYV	Jan to Jun (15/02 to 13/07)	652.86	741 (BRRI, 1985) 760 (Bhuiyan and Islam, 1991) 710 (Mahmood, 1997)
Rabi crop		Nov to Apr (15/11 to 3/04)	472.66	432 (Khan et al. 1981)

[e] details on crop growth with data sources has tabulated in Table 3

Table 6. Actual irrigation (mm) requirement[f] for different crops under scenario **A** using CROPWAT

Year	Aus (HYV)	T Aman	Boro (HYV)	Rabi	Summary
1993	-781.6	-573.6	-438.5	**190.3**	
1994	-687.7	-293.8	-272.5	**247.1**	
1995	-580.4	-654.9	-91.6	**321**	
1996	-715.7	-757	-354	**158.1**	Irrigation is required only for Rabi crop for 1993 to 2007.
1997	-601.9	-703.2	-122.6	**236.4**	
1998	-604.3	-555	-180.9	**100.4**	
1999	-573.5	-672.6	**43.8**	**362**	
2000	-725.5	-708.4	-172.6	**346.6**	
2001	-478.6	-450.4	-74.1	**413.8**	Additional irrigation is needed for Boro rice for the year 1999 and 2005.
2002	-703.2	-574.7	-174.5	**365.2**	
2003	-515.2	-300.9	-171	**290.5**	
2004	-514.9	-449.2	-269.3	**378**	
2005	-464.7	-683.4	**23.4**	**327.2**	
2006	-374.6	-317.9	-77.3	**431.9**	
2007	-658.2	-959.6	-241.6	**319.1**	

[f]negative sign represents excess water

Conclusion

The Halda unit once suffered with severe flash flood and in dry season it failed to achieve crop production. The Karnafuli Irrigation Project (KIP) (implementation period 1975-76 to 1982-83) brought significance change in this area with dual purpose pumping facility, i.e. use for irrigation in dry season and usage for drainage when it requires. With 15 years climate data, this study aimed to assess the CROPWAT model's applicability in excess water estimation. Most of the previous study using CROPWAT focused on irrigation requirements in water scarcity situation. Although the flooding affinity in Halda unit had minimized by the existing project, as this area prone to flooding and water logging improved prediction of excess water would be strengthen the project management.

In this study, CROPWAT showed reasonable values in ET_o computation. To predict the irrigation requirement, rainfall plays crucial role, in this case, the two years 1997 and 1998 were having reasonable rainfall throughout the year, so the under estimation didn't make noticeable difference. However, for enhancing use of this model there is an urgent need to improve the monthly rainfall data entry facility in CROPWAT. With the limited soil property data, the prediction gives sensible values however for intensive study more details are needed. On the other hand DAE already had done progress with the crop selection sector. So, the enriched knowledge on soil fertility and crop management integration with this prediction process for irrigation requirement can offer the optimal decision**.**

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