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Optimal Crop Planning Using Deficit Irrigation

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ABSTRACT: In situations where increasing irrigation demand for growing high yielding varieties of crops is to be met, deficit irrigation might be a better option to cover more areas and thus extend benefits to more farmers with increase of overall yield and return at some sacrifice of unit yield. Optimal area under two major crops using deficit irrigation is determined in a groundwater based tubewell irrigation system in the High Barind Tract, a drought prone area in the northwestern Bangladesh. Study area comprises four thanas having an irrigable area of 90,660 ha and 1463 deep tubewells, each of capacity 56.6 l/s. Yield and the yield response factors for deficit irrigation determined from experimental plots at the farm of Bangladesh Agricultural Research Institute, Shyampur, Rajshahi for Boro rice and wheat repeating the experiment in two cropping seasons of the year 2001–2002 and 2002–2003 (Islam, 2004). Using the experimentally determined yields and yield response factors, yield and net return for farmer's field condition under deficit irrigation were estimated. Then optimal areas under each crop determine by a liner optimization model which demonstrates that practicing deficit irrigation with limits on area under Boro rice and wheat to maintain the present area under respective crops as farmer's preference, the total coverage of irrigated area can only be increased if the pumps operate at full capacity, the amount of increase being 50, 60 and 80%, respectively in dry, average and wet years from present coverage of 39%. Growing wheat seems more profitable because Boro rice is consumes more water. At 80% pump capacity, only the minimum areas specified under crops could be irrigated, and operating pumps at 60% capacity no irrigation could be provided satisfying the minimum area limits. Eighty percent dependable rainfall is generally used for irrigation design and as such additional tubewells need to be installed to increase irrigated agriculture.

INTRODUCTION

Deficit irrigation can be useful in bringing more area under irrigation to increase crop production and maximize net return per unit of applied water in situations where water supply is limited or the irrigation costs are high. The concept of deficit irrigation is not new and has been around for some time. Israelsen and Hansen (1962) described the limited water supply and high water costs as the principal reasons for considering deficit irrigation. To improve crop quality, control disease and regulate maturity of crops, deficit irrigation may be quite helpful and they suggested not imposing this water deficit at the critical growth stages of crops. Barret and Skogerboe (1980) made similar observation that a larger irrigated area and increased net return can be obtained by deficit irrigation, but care should be taken so that the deficit occurs at the least damaging stage of crop growth. English (1990) also stated that deficit irrigation is profitable when irrigation costs are high and water supplies are limited. The water saved from one piece of land by deficit irrigation might be used to irrigate additional land, thus increasing the farm income. Hall and Butcher (1968) emphasized the uniformity of water application along with the deficit irrigation to increase the net returns.

Deficit irrigation takes into account the function that links the phenomenon of water exchange in the plant-soil-atmosphere system which is influenced by crop-soil-unit, cultivars, weather etc. that produce variations in production (Jensen, 1968; Sudan *et al.*, 1981). Marginal capital costs and opportunity costs tend to be reduced making the irrigation system more efficient with deficit irrigation (English and Nuss, 1982). As the amount of applied water approaches full irrigation, deep percolation increases (Peri *et al.*,1979, Norum *et al.*,1979, Shearer, 1978) leading to a less efficient irrigation system. This decline in efficiency is largely associated with variability in applied water, crop characteristics and soil characteristics (English *et al.*, 1986; Peri *et al.*, 1979; Stewart and Hagan, 1969). This

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was further revealed when Onta *et al.* (1995) found that deficit irrigation in early paddy appeared attractive under favourable hydrologic conditions. Khepar and Chaturvedi (1982) also obtained higher returns from crops for deficit irrigation over full irrigation considering the alternative levels of irrigation as 25, 50, 75 and 100 percent of water required for maximum production.

Not much research on deficit irrigation has been undertaken in Bangladesh. Bari (1985) applied a linear programming model to determine the cropping pattern and month-wise irrigation water allocation for crops grown. The effect of changing crop prices and irrigation water amounts on the optimal solution was also investigated. Uddin (1988) developed a linear optimization model to determine the optimum acreage of different crops for Manu River Project. He applied water based on crop sensitivity to water stress using the equation suggested by Karim *et al.* (1985) to estimate deficit yields. Among the tested options of his study, diversification of crops was the best option in respect of service area and net return. However, deficit irrigation was found to give higher acreage and net return than that of full irrigation of rice. From above discussions it is evident that deficit irrigation may even be profitable because this will help bring more area under irrigation and lead to overall increase in crop production although unit yield will be less.

With increase of high yielding variety of rice and wheat requiring more water, practice of deficit irrigation has become necessary in Bangladesh so that more farmers can get the benefits of irrigated agriculture. One such area is the high Barind tract, located in a drought prone area with limited surface water supply in the northwestern part of Bangladesh. The groundwater is not also sufficient to provide full irrigation to the entire area. The present study is intended to explore the possibility of practising deficit irrigation in the High Barind tract with available groundwater supply pumped by deep tubewells. The main study objective is to investigate the different regimes of deficit irrigation for maximizing net return through optimal allocation of available land and irrigation water.

STUDY AREA AND EXISTING CROPPING ACTIVITY

The study area comprises four thanas: Tanor in Rjashahi district, Nachole and Gomostapur in Chapai Nawabganj district, and Niamatpur in Naogaon district in the High Barind tract, located in the western part of the greater Barind area. Boro rice and wheat are the predominant crops and cultivated in about 0.59 and 0.10 million hectares producing 1.62 and 0.23 million metric tons of foodgrain, respectively (BBS, 2000). Surface water is scarce and groundwater is the main source of irrigation. Only around 33 percent of cultivable area has so far been brought under irrigated agriculture (Rahman, 2003). Barind Multipurpose Development Authority (BMDA) was established in 1985 to promote agricultural activities in 25 thanas utilizing groundwater for irrigation. The total area under BMDA project is 0.78 million hectares of which 0.58 million hectares are cultivable. BMDA has installed over six thousand Deep Tube Wells (DTWs) in the Barind area for irrigation but still there is ample scope for further improvement both in terms of coverage and performance of DTWs through appropriate water use planning and design, especially improving the on-farm water application and management to extend irrigation benefits to more farmers.

In the study area selected for the present study, about 90,660 ha is irrigable and the principal irrigated crops are high yielding varieties of Boro rice and wheat. Soil is predominantly clay loam to silty clay loam having grey to mixed grey and brown colour. The organic matter content is only about 0.5–0.8% and the natural fertility ranges from moderate to moderately low. It is a drought prone area and semi-arid in character (Hunt, 1984) and experiences both the highest and the lowest temperatures in the country. Temperature ranges from 10 to 40°C, mean annual rainfall 1100 to 160 mm, and potential evapotranspiration 74 to166 mm. More than 90% of rainfall occurs during June to September. Moisture depletion starts from late October and no available soil moisture exits by the end of December. Groundwater table fluctuation varies between 4–8 m. Potential and useable recharge in the area are in the range of 178–198 million cu.m and 53–107 million cu.m, respectively. Present abstract is in the range of 17–49 million cu.m. There are 1463 DTWs installed by BMDA and were in operation during the Rabi season of 2003–2004 when Boro rice and wheat was grown. Design discharge of each DTW is 56.6 l/s and the tubewells could easily be operated for 16 hours a day without any machine trouble.

METHODOLOGY

Given two crops: Boro rice and wheat, three levels of dependable rainfall corresponding to 20, 50 and 80 percent exceedence probabilities, and five levels of irrigation (full and 10, 20, 30 and 40% deficit irrigation), area under different crops was determined maximizing the net return.

Crop planning under deficit irrigation requires determination of crop production function, yield and the yield response factors which were determined from experimental plots at the farm of Bangladesh Agricultural Research Institute, Shyampur, Rajshahi for Boro rice and wheat repeating the experiment in two cropping seasons of the year 2001–2002 and 2002–2003 (Islam, 2004). Using the experimentally determined yields and yield response factors for the two crops, yield and net return for farmer's field situation were estimated.

Finally the area under the chosen crops were determined with options for full and various levels of deficit irrigation using linear programming given the amounts of irrigable land and water. Other inputs, such as seeds, fertilizer, labour, etc required for crop production were assumed to be available as needed. Crop yield and return per ha obtained from experimental plots as well as estimated for farmers' field condition were considered to solve the LP model to determine the area under crops to maximize net returns earned using full and deficit irrigation.

DETERMINATION OF CROP WATER AND IRRIGATION WATER REQUIREMENTS

First reference crop evapotraspiration, ET_0 was computed using CROPWAT (Smith, 1992) with climatic data of a nearby meteorological station at Rajshahi and crop evpotranspiration ET_0 was obtained for vegetative, flowering, yield formation and ripening stages multiplying ET_0 by crop coefficient, Kc as determined for the study area. The time required both for Boro rice from transplantation to maturity and for wheat from germination to maturity is 110 days. Farmers practice staggered sowing of wheat and transplantation of Boro during a period of time which spans about 20 days for wheat and 30 days for Boro rice. Generally 70% of the wheat area is sown during the first 10 days and remaining 30% in the next 10 days. For Boro rice the transplanted areas are 20, 50, 30% during the first, second and third decades, respectively. Consequently area under crops are different in each month during the cropping season. The month-wise proportion of cropped area was determined as follows.

Crop	*Proportion of Cropped Area in the Indicated Month*						
	Nov.	*Dec.*	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*
Boro rice	–	–	0.47	1.00	1.00	0.97	0.35
Wheat	0.35	0.95	1.00	1.00	0.60	–	–

Due to staggered plantation crops do not attain the same growth stage in the field. Thus it was required to compute composite crop coefficients, cKc for each crop to determine crop ET. Dependable rainfalls (R) for chosen probability of exceedences as 80, 50 and 20% were computed using 32 years of daily rainfall, and seepage and percolation (S&P) losses determined from field experimental plots and farmers Boro rice plot. Generally 80% dependable rainfall is used for calculating irrigation requirement. Other two dependable rainfalls were chosen to examine the effect of rainfall on the redistribution of cropped area between the two crops.

Net Irrigation Requirement (NIR) for each month of the growing season for the two crops were then calculated (NIR = Crop ET– R + S&P). Gross irrigation requirement was calculated using irrigation efficiency of 65% for Boro rice and 55% for wheat. Such efficiency values are reasonable for a tubewell irrigation project.

DETERMINATION OF YIELD RESPONSE FACTORS FROM EXPERIMENTAL PLOTS

When deficits are imposed diving the growing season into stages for any crop, the multiplicative crop production given by Eqn. 1 (Stewart *et al.*, 1977) is preferred as it considers, along with other yield reducing factors, the effect of growth stages on yields,

$$\frac{Ya_{i,k}}{Ym_{i,k}} = \prod_{k=1}^{n} \left[1 - Ky_{i,k} \left(1 - \frac{ETa_{i,k}}{ETm_{i,k}} \right)_n \right] \quad \ldots (1)$$

where $Ya_{i,k}$ = yield of crop i under deficit irrigation level k, $Ym_{i,k}$ = yield of crop i under full irrigation, ET_m = water requirement met for crop i by full irrigation, ET_a = water requirement met for crop i by deficit irrigation, $Ky_{i,k}$ = yield response factor for crop i under deficit irrigation level k.

Effect of 10, 20, 30 and 40% deficit and full irrigation on yield was simulated in 3 m × 5 m experimental plots for two consecutive years. Deficit irrigation was imposed in either vegetative stage or grain formation stage or both because at these growth stages plants are less sensitive to water stress than the flowering or ripening stages (Stewart and Hagan, 1973 and Stewart *et al.*, 1976). A Randomized Complete Block (RCB) design technique was used in preparing the layout of experimental plots with 9 and 10 treatments, respectively for the first and second year as shown in Table 1. Note that in the second year, four additional treatments, T10 to T13 were included for examining the effect of imposing the same deficits both in vegetative and grain formation stages. Three replications were used for each treatment resulting in (9 × 3 =) 27 and (13 × 3 =) 39 plots, respectively in two years.

From experimental plots crop yield, *Ym* for full irrigation and the yield, *Ya* for deficit irrigation were determined. Substituting these values of *Ym, Ya, ETm* and *ETa* in Eqn. 1, two sets of yield response factors *Ky* were determined for two years. However, the values for the second year only are presented in Table 2 which seem to be better because in the first year experiment, entire amount of water deficit in a given stage was applied in the last irrigation of that stage whereas in the second year each stage deficit was applied in proportion of the irrigations applied in that stage. Thus it is expected that water stress was less due to gradual application of deficit water in any stage. As such the second-year *Ky* values were used in subsequent calculations.

ESTIMATION OF YIELDS AND NET RETURN FOR FARMER'S FIELD SITUATION

In the experimental plots, transplantation and sowing was done simultaneously on all plots on the same date. But as mentioned before, farmers practice staggered plantation. This required some adjustment in the yield and yield response factors *Ky* obtained from experimental plots to enable estimation of yields for deficit irrigation in farmers field. Based on prevailing yields on farmer's plots, 3.50 ton/ha for Boro rice and 3.0 ton/ha for wheat and experimentally determined *Ky* values and yields for deficit and full irrigation during second year experiment, yields for deficit irrigation in field situation were estimated.

Table 1: Treatments Showing Deficit Irrigation Application Scheme in Experimental Plots

Year	Full irrigation	Deficit Irrigation at Vegetative Stage				Deficit Irrigation at Yield Formation Stage				Deficit Irrigation at Both Stages			
		10%	20%	30%	40%	10%	20%	30%	40%	10%	20%	30%	40%
1	T1	T2	T3	T4	T5	T6	T7	T8	T9				
2	T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13

Table 2: Yield Response Factor (K_y) Determined Using Experimental Plot Yield Obtained in Second Year with Deficit Irrigation

Treatments (% deficit)	Stage at which Deficit was Imposed	Crop ET Met by Irrigation (mm)	Potential Crop ET (mm)	Yield with Deficit Irrig (ton /ha)	Yield Obtained from Full Irrigation (ton/ha)	Yield Response Factor (K_y)	Average K_y for the Stage
(a) Boro rice							
T2 (10%)	Vegetative stage	188	209	3.48	3.72	0.64	0.60
T3 (20%)		167	209	3.20		0.70	
T4 (30%)		146	209	3.05		0.60	
T5 (40%)		125	209	3.01		0.47	
T6 (10%)	Yield formation Stage	193	214	3.64		0.22	0.28
T7 (20%)		171	214	3.56		0.21	
T8 (30%)		150	214	3.40		0.29	
T9 (40%)		128	214	3.12		0.40	
(b) Wheat							
T2 (10%)	Vegetative stage	82	91	4.04	4.10	0.15	0.18
T3 (20%)		73	91	3.96		0.17	
T4 (30%)		64	91	3.85		0.20	
T5 (40%)		55	91	3.75		0.21	
T6 (10%)	Yield formation Stage	86	95	3.92		0.44	0.46
T7 (20%)		76	95	3.73		0.45	
T8 (30%)		67	95	3.54		0.46	
T9 (40%)		57	95	3.32		0.48	

Net return for estimated yields was calculated based on cost of crop production inputs and price of produced crops and byproducts. Among the inputs, land preparation, weeding, fertilizer, pest control, irrigation, harvesting, carrying, threshing and cleaning were considered for both Boro rice and wheat. Additionally, cost of seedbed preparation and transplanting was required for Boro rice. The labour requirement per hectare of land for transplanting, weeding, harvesting and carrying of Boro rice were obtained from BRRI Annual Report (1999) and those for wheat from BARI Annual Reports (2000 and 2001). The unit cost of water was obtained from BMDA sources as Tk.4000 per ha-m. Finally, the net returns per hectare were determined as the difference between the gross return from crops and the total cost of production. These net returns per hectare were the coefficients of the net benefit function maximized in the linear programming model formulated and solved next.

LINEAR PROGRAMMING MODEL FORMULATION

A linear programming model was formulated to determine the area under each of two crops: Boro rice and wheat to maximize net return from available land and irrigation water in Tanore, Nachole, Niamatpur and Gomostapur thanas in the High Barind tract. In formulating the model, the following assumptions were made.

1. Prices of crops and water were equal for both full and deficit irrigation;
2. Crop production would be optimum if water requirements, as obtained by the Penman-Monteith equation is fully met;
3. Groundwater was equally available to all tubewells;
4. All inputs except water were assumed to be available at optimum level; and
5. The information on yield response factors, crop ET and yields generated through field experiments at Shyampur, Rajshahi, were also applicable for the soils and climatic conditions in the study area.

The LP model was formulated as follows,

$$\text{Maximize } z = \sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} B_{ijk} A_{ijk}$$

where, z is the net return in Taka, A_{ijk} and B_{ijk} are the area under and net return per hectare, respectively for crop i, dependable rainfall j, with deficit irrigation level k. With two crops, three alternative dependable rainfall values corresponding to 20% 50%, and 80% representing wet, average, and dry years, and five levels of deficit irrigation, $l = 2$, $m = 3$, and $n = 5$.

Constraints

Month-wise irrigation water availability

Amount of water applied to crop field cannot exceed the water supplied from the tubewells in any period,

$$\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} W_{ijk}^{t} A_{ijk} \le P^{t} \quad \forall t$$

where, W^{t}_{ijk} is the water requirement per ha for crop i, dependable rainfall j and irrigation level k, and P^{t} is the available water in month, t.

Available land area in different months

$$\sum_{i=1}^{l}\sum_{k=1}^{n} \beta_{ijk}^{t} A_{ijk} \le A^{t} \quad \forall j,t$$

where, β^{t}_{ijk} is the fraction of land under crop, i with corresponding dependable rainfall, j and irrigation level, k.

Maximum and minimum area under crops

It is required to specify the area on which farmers grow Boro rice and wheat area as the minimum area under the crops and to provide upper limit under each crop to safeguard crop diversification,

$$\sum_{j=1}^{m}\sum_{k=1}^{n} A_{ijk} \le A_{i\max} \quad \forall i$$

$$\sum_{j=1}^{m}\sum_{k=1}^{n} A_{ijk} \ge A_{i\min} \quad \forall i$$

where, $A_{i\max}$ and $A_{i\max}$ are the maximum and minimum area under crop i,

Total available land for irrigation

$$\sum_{i=1}^{l}\sum_{j=1}^{m}\sum_{k=1}^{n} A_{ijk} \le A$$

where, A is the total area available for irrigation and A_{ijk} as defined above.

Non-negativity Requirements

$$A_{ijk} \ge 0$$

MODEL SOLUTION

Solution of the LP model required values of a number of parameters. Among these yield and net return per hectare as well as irrigation requirements of the selected crops have been determined earlier. Given

90,660 ha of irrigable land, the maximum and minimum areas under Boro rice were specified as 50,000 and 31,500 ha and that under wheat as 60,000 and 3610, respectively. Water was available from 1463 DTWs, each of capacity 56.6 l/s and operated 16 hours a day. The LP model was solved employing crop yield and net return obtained both with farmers' field conditions and at experimental plots to investigate the effect of difference in yield in two situations and the results obtained are shown in Tables 3 and 4, respectively. LINDO (Linear, interactive and discrete optimizer), version, 6.01 (Schearge, 1997) was used to obtain solution.

RESULTS

Farmers Field Condition

Case 1: With Minimum and Maximum Area Limits for Crops

In Table 3, Case 1 shows the areas under two crops with minimum required and maximum permissible areas under each crop and Case 2 with no such limits on areas for three alternatives of pump capacity (100, 80 and 60% of design discharge) and dependable rainfall (20,50, and 80% reliability). Note that 20, 50 and 80% dependable rainfalls are considered to represent a dry, average and wet year. Table 3 shows that with options for deficit irrigation at full pump capacity in a wet year, the combined area for two crops shows significant increase ranging from 45,625 (30% increase) in a dry year to 77,056 (145% increase) ha in a wet year exceeding the existing irrigation coverage of 35,110 ha.

Looking at Boro rice, at full pump capacity the minimum required area of 31,500 can be supplied with full irrigation in a wet and average year, but in a dry year only 40% area appears under full irrigation, remaining 21,952 ha being under 30% deficit irrigation. When the pump discharge reduces to 80%, minimum area under Boro can still be covered in wet and average years with deficit irrigation only, splitting the area almost equally under 10 and 30% deficit, and in a dry year about 30% area is appearing under full and 70% under 30% deficit. With further decrease of pump capacity to 60% even the minimum required areas for either of the two crops could not be achieved.

Turning to wheat it is seen that only full irrigation appears in solution with no area under deficit irrigation in any year for all pump capacities. *At full pump capacity* in a wet and average year, 22,420 ha fall under full irrigation showing about 500% increase over the minimum required area of 3,610 ha, but in a dry year

Table 3: Area under Crops and Net Return Based on Farmers' Field Yield and Return

Case 1: With Existing Area as Limits on Area under Crops

Water Availability from DTW	Dependable Rainfall Probability	Boro Rice Area				Area under Wheat			Total Area	Net Return (10^6 Taka)
		Full Irrigation	Deficit Irrigation 10%	Deficit Irrigation 30%	Total	Full Irrigation	Deficit Irrigation	Total		
Design Discharge	20%	31,500		–	31,500	22,420		22,420	77,056	393
	50%	31,500			31,500	22,420		22,420	53,869	393
	80%	9,548		21,952	31,500	3,610		3,610	45,625	384
80% of Design Discharge	20%		16,627	14,822	31,500	3,610		3,610	35,062	150
	50%		16,627	14,822	31,500	3,610		3,610	35,062	150
	80%	9,497		21952	31449	3,610		3,610	35,062	104
60% of Design Discharge	20%									
	50%									
	80%									

Case 2: With no Limits on Area under Crops

Water Availability from DTW	Dependable Rainfall Probability	Boro Rice Area			Area under Wheat			Total area	Net Return (10^6 Taka)
		Full Irrigation	Deficit Irrigation	Total	Full Irrigation	Deficit Irrigation	Total		
Design Discharge	20%	1,685		1,685	88,975		88,975	90,660	540
	50%	157		157	90,503		90,503	90,660	531
	80%				87,288		87,288	87,288	506
80% of Design Discharge	20%				74,194		74,194	74,194	439
	50%				72,680		72,680	72,680	426
	80%				69,830		69,830	69,830	413
60% of Design Discharge	20%				55,646		55,646	55,646	329
	50%				54,510		54,510	54,510	319
	80%				52,372		52,372	52,372	304

only the minimum area can be met at full irrigation. Thus the maximum area limit of 60,000 cannot be attained in any instance. *Again at 80% pump* capacity, only the minimum area could be covered with full irrigation. Similar to Boro rice, when pump capacity is reduced to 60%, even the minimum required areas for any of the two crops could not be satisfied.

Farmers Field Condition

Case 2: With No Area Limits for Crops

In the lower half of Table 3, it can be seen that with no limits on area, growing wheat with full irrigation only appears to be the best option, except some insignificant area being under Boro rice at full pump discharge and wet and average years. This is because wheat requires much less water, all of the project area with wheat could be irrigated although the yield and net return per ha for wheat was about 20 less than that of Boro. Further, more than 52,000 ha of wheat could be irrigated even if the pump capacity reduces to 60%, increasing the coverage to about 80% to 100% of the irrigable area at 80% and full pump discharge, respectively in all years.

Experimental Plot Condition

Case 1: With Minimum and Maximum Area Limits for Crops

For experimental plot conditions, Table 4 presents area under two crops with associated net return. It is observed that the total net return is more than double when compared to those for farmer's field situation when with no limit on area under crops, but allocation of area under crops flows the similar pattern as with the farmer's field condition. The reason for such high net return is that for wheat, experimental yield and return were higher than those for the farmer's field condition. As before reducing pump capacity to 60%, even the minimum area irrigation requirement of either of the two crops could not be satisfied. Although unrealistic to some extent, the results obtained with experimental plots with no restrictions on area under crops indicates that there is scope for increasing yield of wheat on farmer's field.

Table 4: Area under Crops and Net Return Based on Experimental Plot Yield and Return

Case 1: With Maximum and Minimum Limits on Area under Crops

Water Availability from DTW	*Dependable Rainfall Probability*	*Boro Rice Area*				*Area under Wheat*				*Total Area*	*Net Return (10^6 Taka)*
		Full Irrigation	*Deficit Irrigation*		*Total*	*Full Irrigation*	*Deficit Irrigation*		*Total*		
			20%	*30%*			*30%*	*40%*			
Design Discharge	20%	31,500		–	31,500			43,046	43,046	74,495	561
	50%	31,500						41,788	41,788	73,237	543
	80%	27,652		3,797	31,500	20,878			20,878	52,327	486
80% of Design Discharge	20%		13,763	17,686	31,500			24,676	24,676	56,125	256
	50%			31,500	31,500			27,076	27,076	58,525	237
	80%			31,500	31,500		16,148		16,148	47,597	170
60% of Design Discharge	20%										
	50%										
	80%										

Case 2: With no Limits on Area under Crops

Water Availability from DTW	*Dependable Rainfall Probability*	*Boro Rice Area*			*Area under Wheat*			*Total Boro and Wheat Area*	*Net Return (10^6 Taka)*
		Full Irrigation	*Deficit irrigation*	*Total*	*Full Irrigation*	*Deficit Irrigation (40%)*	*Total*		
Design discharge	20%				90,660		90,660	90,660	1295
	50%				90,660		90,660	90,660	1290
	80%				87,288		87,288	87,288	1239
80% of Design Discharge	20%				56,297	34,363	90,660	90,660	1073
	50%				53,951	36,709	90,660	90,660	1050
	80%				60,380		69,380	69,380	990
60% of design discharge	20%				17,587	73,073	90,660	90,660	822
	50%				16,854	73,806	90,660	90,660	812
	80%				52,372		52,372	52,372	743

CONCLUSIONS

The results presented herein demonstrates that practising deficit irrigation additional land could be irrigated benefiting more farmers. However, it is to be noted that with limits on area under Boro rice and wheat to maintain the present area for respective crops as farmer's preference, the total coverage of irrigated area can only be increased if the pumps operate at full capacity making the increase from present coverage of 39% to 50, 60 and 80%, respectively in dry, average and wet years. Moreover, growing wheat seems more profitable because area under Boro rice remains at the minimum allocating the incremental area to wheat.

At 80% pump capacity only the minimum irrigated areas could be achieved and this shows that more tubewells need to be installed to increase irrigated agriculture because the 80 percent dependable rainfall is generally used for irrigation design.

At 60% pump capacity no irrigation could be provided satisfying the minimum area limits indicating that at least 80% pump capacity must be maintained or else more tubewells would be required.

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