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RESEARCH ARTICLE

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More crops whilst saving drops using an optimization model—A case from Bangladesh*

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Abstract

This study aims to determine the optimal use of irrigation water and irrigable area in the Karnafuli Irrigation Project (KIP) of Bangladesh by developing an optimization model using linear programming. The project consists of two units, namely, Halda and Ichamati, and the units are fed with Karnafuli river water. Required data were collected from several government offices and from the CMIP5 model. Considering existing cropping practice, irrigation supply, and future climate, the optimization model was run for four different scenarios. Climate change-induced effects appeared as non-significant in the optimization. In the Halda Unit, the existing cropping intensity is 136%, whereas optimal cropping intensity can be increased up to 200%. In the Ichamati Unit, optimal cropping intensity for all scenarios is in between 175% and 200%, where the existing intensity is 150%. An increase in cropping intensity in both the units in optimal scenarios results in higher benefits. At the same time, the implementation of the optimal situation in the KIP can save 20% of the diverted water, indicating the possibility of greater yields and subsequent greater benefits even if the existing water supply is saved. The outcomes of the research have been communicated to the regional extension office for implementation.

KEYWORDS

Bangladesh, Karnafuli Irrigation Project (KIP), linear programming, optimization, water productivity

Résumé

Cette étude vise à déterminer l'utilisation optimale de l'eau d'irrigation et de la zone irrigable dans le projet d'irrigation de Karnafuli (KIP) au Bangladesh en développant un modèle d'optimisation utilisant la programmation linéaire. Le projet se compose de deux unités, à savoir les unités Halda et Ichamati, et les unités sont alimentées en eau de la rivière Karnafuli. Les données requises ont été collectées auprès de plusieurs bureaux gouvernementaux et du modèle CMIP5. Compte tenu des pratiques culturales existantes, de

* Plus de récoltes tout en économisant des gouttes grâce à un modèle d'optimisation – Un cas du Bangladesh

l'approvisionnement en irrigation et du climat futur, le modèle d'optimisation est exécuté pour quatre scénarios différents. Les effets induits par le changement climatique apparaissent comme non significatifs dans l'optimisation. Dans l'unité Halda, l'intensité de culture existante est de 136% alors que; l'intensité de culture optimale peut être augmentée jusqu'à 200%. Dans l'unité d'Ichamati, l'intensité de culture optimale pour tous les scénarios est comprise entre 175 et 200%, là où l'intensité existante est de 150%. Une augmentation de l'intensité de la culture dans les deux unités dans les scénarios optimaux entraîne des bénéfices plus élevés. Dans le même temps, l'eau détournée peut être économisée de 20% dans le KIP en mettant en œuvre la situation optimale indiquant la possibilité de plus de cultures et de plus d'avantages ultérieurs, même en économisant l'approvisionnement en eau existant. Les résultats de la recherche ont été communiqués au bureau régional de vulgarisation pour la mise en œuvre.

MOTS CLÉS

productivité de l'eau, Karnafuli Irrigation Project, Bangladesh, optimization, programmation linéaire

1 | INTRODUCTION

Food security is one of the most challenging problems around the world. With the declining rate of cultivated land and a rapidly growing population, the global food demand is predicted to increase by 70% by the year 2050 (Memmah et al., 2015). On the other hand, food production decreases as time progresses due to several reasons such as reduction of arable land, lack of irrigation water availability, and the low efficiency of irrigation systems. Global croplands are being lost by around 10 million ha per year due to erosion, soil degradation, non-conservation, non-farm uses worldwide (Pimentel & Burgess, 2013). About 70% of global water withdrawal is used in the agriculture sector, which is about 6,800 km^3 annually (Food and Agriculture Organization of the United Nations (FAO), 2016). However, the supply is at risk due to poor irrigation efficiency. In many regions of the earth, besides the food security problems, water scarcity is also visible because of increased population, rapid industrialization, and poor water resource management. Water shortage creates a barrier for reliable food production and economic growth in many regions (Distefano & Kelly, 2017). Therefore, the availability of water plays a crucial role in food and nutrition security (Pereira, 2017) and ensures land productivity (Postel, 1998). Along this line, increased crop production with available water drops will ensure both food and water security.

Ensuring food and water is critically important in a densely populated developing country like Bangladesh, where the economy largely depends on agriculture. The contribution of agriculture to the gross domestic product (GDP) is 14.8% in Bangladesh (Bangladesh Bureau of Statistics (BBS), 2017). Food demand in Bangladesh is increasing with 1.1% population growth per annum, whereas food production is declining with time with a decreasing rate of contribution of agriculture to the national GDP. Tackling this situation, irrigation water management becomes more challenging. Such a problem exists in the south-eastern region of Bangladesh, where only one major irrigation project exists named the Karnafuli Irrigation Project (KIP). Established with the objective of an increase in crop production by about 35,000 t (World Bank, 1975), the KIP is losing its performance due to low irrigation efficiency (Miah & Mohit, 1996). The agricultural output of the south-eastern region of Bangladesh is dependent on the KIP to a large extent (Rahman et al., 2019). Local agricultural offices reported that edible seeds, fertilizer, pesticides, and insecticides are available, but sufficient irrigation is not. A vast area of cultivable land remains fallow due to low water supply and inefficient cropping patterns during both the *robi* (November–April) and *kharif* seasons (May–October). According to the local Department of Agriculture Extension (DAE), the fallow land is about 50% and 80% in robi and kharif (kharif I and kharif II), respectively, which results in a decrease in food production in this region. Such a situation raises the central research question: Is it possible to use the available water resources more efficiently and increase cropping intensity so that net profit and food safety can be elevated?

Optimization is one of the most efficient and practiced techniques to develop an effective irrigation management system (Park & Allaby, 2013) and has been used in several places (Singh et al., 2001). Linear programming is a widely used mathematical technique that leads to solving the optimization problem of a linear objective function subjected to a well-defined set of linear equations or inequalities considered as constraints. In order to analyse the inter-seasonal water allocation and agricultural impact (Salman et al., 2001), we developed a linear programming optimization model with the objective function of maximizing net agricultural revenue considering water and land as a constraint. France (1981) proposed a non-linear optimization model, dynamic programming, and linear programming optimization system for the agricultural and water resource system. Jacovkis et al. (1989) developed a linear programming optimization model for a multi-objective water resource system considering continuity, reservoir, irrigation, hydroelectric, artificial effluent, and navigation conditions as constraint functions. Singh (2012) briefly reviewed the application of different optimization techniques, especially for irrigation management and achieving an optimal cropping pattern and ultimately making a robust decision under uncertainty. Zhang & Guo (2018) proposed a mixed integer linear programming approach for agricultural water management under uncertain conditions. In this study, considering the local condition, we developed a linear programming optimization model with the objective function of maximizing net profit of crop production considering irrigation, land, and crop area as the constraints.

Additionally, the Food and Agriculture Organization (FAO) and International Water Management Institute (IWMI) declared the theme of "more crops per drops" to ensure both food and water security with an ultimate goal to feed 2 billion people by the year 2030. This theme will create a new paradigm in the sustainable agricultural system by increasing water and food productivity. Action concerning the theme is very much essential for developing countries like Bangladesh as the food and water crisis is evident with the increasing population. Along with the agricultural sector, crops and water productivity increase the economic, social, and ecological service to the society. Considering the problem and solution techniques used in different places, this study aims to develop an optimization model using linear programming for optimal allocation of the irrigable area and irrigation water to a specific crop, hereby increasing the cropped area and the net profit from KIP. This research will also ensure better water resource management in the KIP based on optimal water allocation and crop areas. The purpose of this study will be accomplished by contributing to the FAO and IWMI "more crops per drops" theme. Our work is a pioneering research in Bangladesh using an optimization model to increase crop production whilst efficiently using every drop. Since climate change affects reference crop evapotranspiration (ET_0), crop water requirements, and water availability to some extent, this study will also investigate the climate change impacts on optimization results.

2 | MATERIALS AND METHODS

2.1 | Study area—Karnafuli Irrigation Project

The KIP is an irrigation-cum-flood control scheme. The project consists of two components—one is the Halda Unit and the other the Ichamati Unit (an extension of Halda is also available called Halda Extension Unit) (Figure 1). It is situated in the tributaries of the Karnafuli River in the south-east part of Bangladesh. About 1,093,000 people live in the area, of which 212,000 belong to farm households (BBS, 2013). Mainly three seasons are dominant in the KIP, namely, pre-monsoon, monsoon, and dry season. Monsoon starts from June and ends in October; the dry season lasts from November till February, whereas the pre-monsoon season covers the remaining time of March to May. About 80% of the total annual rainfall occurs in the monsoon. The dry season has very little rain with the lowest temperature and humidity, and the pre-monsoon season sees high temperature and evaporation and sometimes heavy rainfall. The project is not usually affected by cyclones for its unique geographical location. The mean annual temperature is about 25°C, with extremes as low as 4°C and as high as 43°C. Humidity ranges between 60% in the dry season and 98% during the monsoon. Since the annual rainfall in the project area is 2,500–3,000 mm (above 750 mm), the project area lies in the humid regions (Raghunath, 2006; Bokhtiar et al., 2015). Three cropping seasons are practiced in the KIP (Alamgir et al., 2015), namely, robi (from October 16 to March 15), kharif I (from March 16 to June 30), and kharif II (from July 1 to October 15).

2.1.1 | Halda Unit

The Halda Unit of the KIP is located in Hathazari and Raozan Upazila in the district of Chattogram. The area

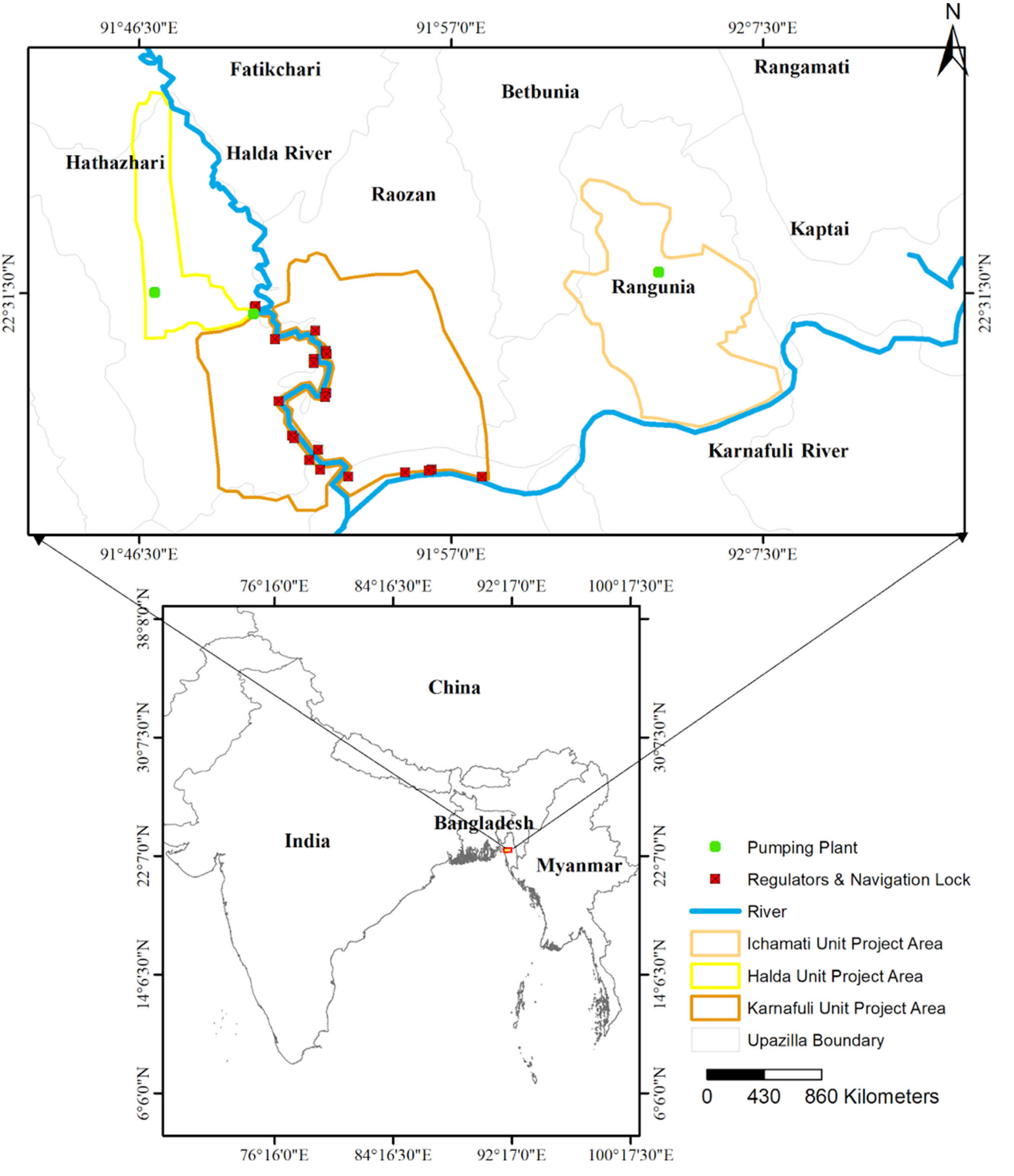


FIGURE 1 Location of study area [Colour figure can be viewed at wileyonlinelibrary.com]

covered by the Halda Unit is about 15,386 ha, and the irrigable area is 12,550 ha. According to the local office of the DAE, there are about 1,144 irrigation pumps to abstract water from the canal at the farmer's level. The overall irrigation efficiency of the Halda Unit is about 51% (Rai et al., 2017).

2.1.2 | Halda Extension Irrigation Project

The Halda Extension Irrigation Project is situated at both sides of the Chattogram-Khagrachari Highway, some 25 km away from Chattogram City. The gross area of the project is about 5,000 ha, whereas the irrigable area is

1,390 ha. Providing irrigation in the dry season and protecting the areas from floods in the wet season were the prime objectives of the project. The overall irrigation efficiency of the Halda Extension Unit is about 51% (Rai et al., 2017).

2.1.3 | Ichamati Unit

The Ichamati Unit is located on the east side of the valley of the Ichamati River and spreads over Rangunia Upazila of Chattogram District. The Ichamati Unit area is 3,238 ha, out of which about 2,280 ha are irrigable. Water for irrigation in this unit is not pumped from Ichamati River, a tributary of the Karnafuli River, but through a pumping plant located 283 m away from Karnafuli River's mouth, where flood or excess rainwater are drained out to the Karnafuli by Mahfez Khal. The Ichamati Unit takes its name from its location in the valley of Ichamati. The overall irrigation efficiency of Ichamati Unit is about 48% (Rai et al., 2017).

2.2 | Methods

2.2.1 | Linear programming optimization model

A linear programming model was set up consisting of three components: (i) the linear objective function to maximize the net return, (ii) a set of linear constraints, and (iii) a set of non-negative linear constraints. It was subjected to water availability in the canal and land area limitation with different specific crops and seasons. The model is described in Figure 2.

Objective function

The objective function of the research is to maximize the net profit from food production, which generally depends

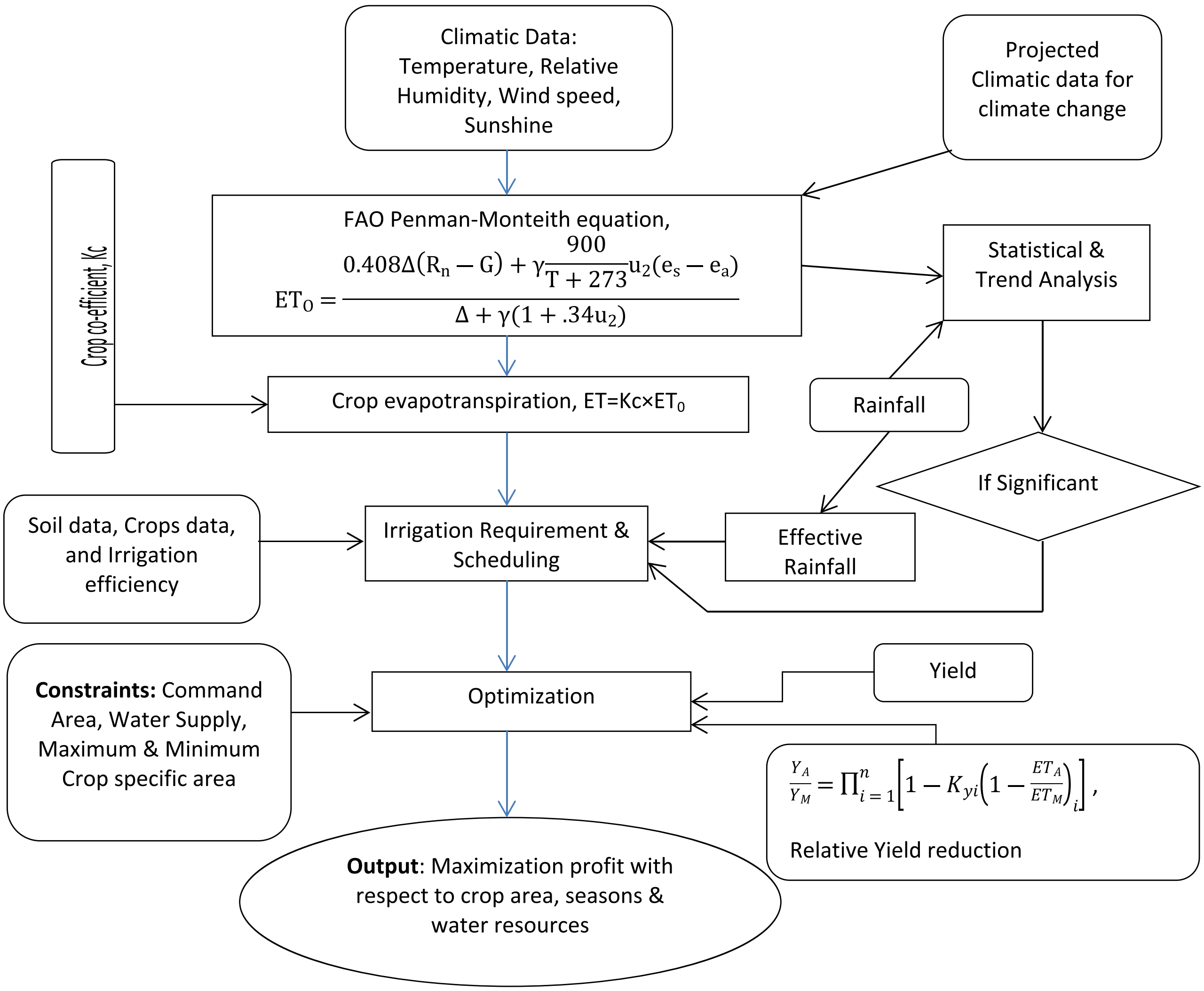


FIGURE 2 Methodological framework for the study [Colour figure can be viewed at wileyonlinelibrary.com]

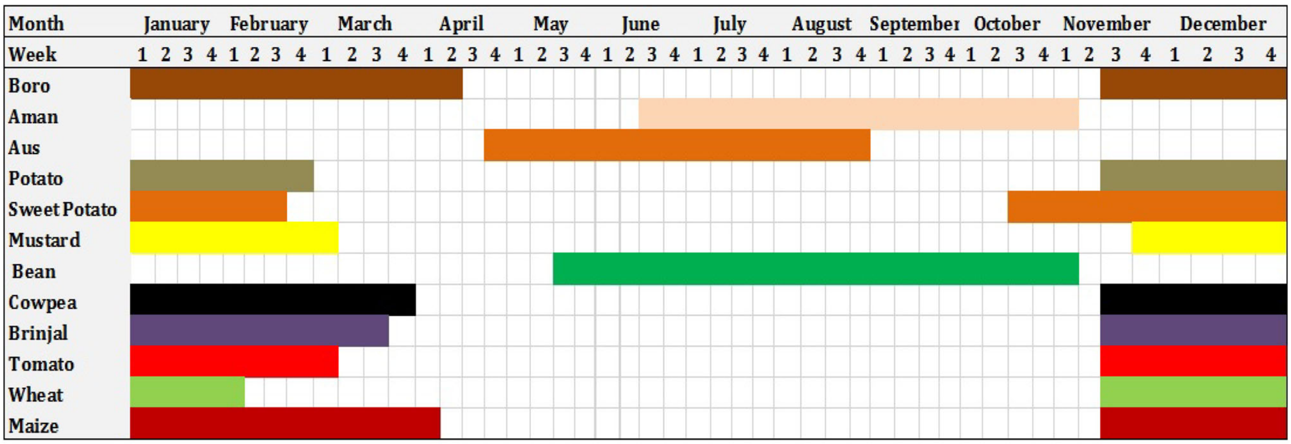
on the value of the product in the market, the cost of irrigation, and additional accessories, such as seeds, pesticides, fertilizers, and laborers' cost. Finally, the net profit is calculated by maximizing Equations 1 and 2 as specified below:

$$\text{Net profit}, Z = [\text{market value of product}] - [\text{cost of seeds, pesticides, fertilizers, and labour}] - [\text{cost of irrigation}] \tag{1}$$

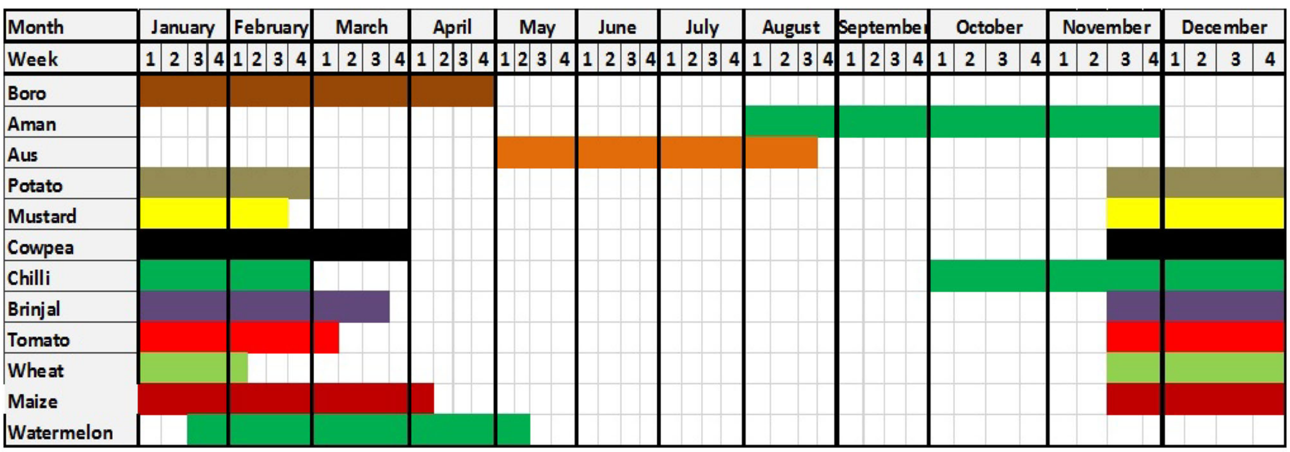
$$\text{Max}, Z = \left[\sum_{i=1}^{m}\sum_{t=1}^{12}(X_{it})(Y_{it})(\text{VC}_{it})\right] - \left[\sum_{i=1}^{m}\sum_{t=1}^{12}\{(S_{it})+(P_{it})+(F_{it})+(L_{it})\}*(\text{TCA}_{it})\right] - \left[\sum_{i=1}^{m}\sum_{t=1}^{12}(C_{it})(\text{IG}_{it})\right], \tag{2}$$

where i = index of crop types, t = index of month in crop seasons for crop production, X = irrigation area of crop production (ha), Y = yield per ha of i^{th} crop (kg/ha), VC = value of crop (Tk/kg)[1], S_{it} = cost of seeds (Tk/ha), P_{it} = cost of fertilizers (Tk/ha), L_{it} = cost of labour (Tk/ha), TCA = total or actual cultivated land area (ha), C = cost of water (Tk/mm-ha), and IG = amount of water used for irrigation or gross irrigation water (mm-ha). [1 mm-ha is equivalent to 10 m^3 of water].

The developed model is an optimization case, where a monthly time step has been considered. Considering all the factors and particularly the availability of water in different months within a cropping season and for a particular crop, the model optimized the cropping area for that particular crop. The crop calendar for the Halda and Ichamati Units is given in Figure 3a and b, respectively. Besides, in Equation 2, some material and labour that are used only in one or two months are considered for that particular month. For example, potato is sown in the



(a) Crop calendar in Halda unit



(b) Crop calendar in Ichamati unit

FIGURE 3 (a) Crop calendar in Halda Unit. (b) Crop calendar in Ichamati Unit [Colour figure can be viewed at wileyonlinelibrary.com] third week of November in the robi season. The cost of seed for potato is considered only for the month of November, and the cost of the seeds for potato in other months will be 0.

The model considers the following constraints:

- *Irrigation constraints*. In order to maximize the net profit, the applied irrigation water is required to be less than or equal to the available canal water, which is considered as one of the boundary conditions as specified in Equation 3.

$$\sum_{i=1}^{m}\sum_{t=1}^{12}\mathrm{IG}_{it} * X_{it} \leq \sum_{i=1}^{m}\sum_{t=1}^{12}\mathrm{AW}_{it}, \quad (3)$$

where AW = available water (mm-ha), IG = amount of water used for irrigation or gross irrigation water (mm-ha), and X = irrigation area of crop production (ha).

The amount of available water is estimated from the daily pumping logbook of the irrigation office. In discussions with the pump operators, it was found that the operators normally pump the water based on pump capacity, available pump head, and demand of farmers.

- *Land area constraints*. To maximize the net profit, another constraint is considered as follows: The area to be irrigated for different crops will be less than or equal to the total cultivated area as specified in Equation 4.

$$\sum_{i=1}^{m}\sum_{t=1}^{12}X_{it} \leq \sum_{i=1}^{m}\sum_{t=1}^{12}\mathrm{TCA}_{it}, \quad (4)$$

where TCA = total or actual cultivated land area (ha) and X = irrigation area of crop production (ha).

- *Crop area constraints*. Crop area constraints are considered to meet the crop demand, social practices, and local food security and habits. The minimum crop production area will be less than or equal to the prevailing crop production area, which will also be less than or equal to the maximum crop production area as specified in Equation 5.

$$\sum_{i=1}^{m}\sum_{t=1}^{12}\delta\min * X_{it} \leq \sum_{i=1}^{m}\sum_{t=1}^{12}X_{it} \leq \sum_{i=1}^{m}\sum_{t=1}^{12}\delta\max * X_{it}, \quad (5)$$

where $\delta_{\min}$ = minimum percentage of specific crop area required in a season (ha), $\delta_{\max}$ = maximum percentage of specific crop area required in a season (ha), and X = irrigation area of crop production (ha).

- *Non-negativity constraints*. Irrigation of the crop production area, water used for irrigation, and the total cultivated area will be greater than or equal to zero to maximize the net profit, which is considered non-negativity constraint as specified in Equation 6.

$$X_{it} \geq 0; \mathrm{IG}_{it} \geq 0; \mathrm{TCA}_{it} \geq 0, \quad (6)$$

where i = index of crop types, t = index of monthly crop seasons for crop production, X = irrigation area of crop production (ha), IG = amount of water used for irrigation or gross irrigation water (mm-ha), and TCA = total or actual cultivated land area (ha).

2.2.2 | Optimization with different scenarios

The linear programming optimization model was studied with different scenarios (Table 1) to visualize the change of net benefit in different possible circumstances. The optimization with the first scenario was performed for existing water delivery considering crop production for food security and local habits to meet up local demand for food. The optimization with the second scenario was without considering food security and local habits. The optimization for the third scenario was not limited to

TABLE 1 Optimization scenario

Scenario		Brief description
S-1		Existing water supply, crop constraints for regional food security and local habits and crop areas (baseline optimization)
S-2		Without crop constraints for food security and local habits
S-3	S-3a	Without irrigation constraint and with regional food security and local habits
	S-3b	Without irrigation constraint and without regional food security (with land constraint)
S-4	S-4a	Increased water charge from 2.5 Tk[a] /mm-ha to 25 Tk/mm-ha and existing water supply
	S-4b	Increased water charge from 2.5 Tk/mm-ha to 25 Tk/mm-ha and without irrigation constraint

Abbreviation: Tk, Taka (Bangladeshi currency).
[a]1 billion Tk = $11,779,470 (price level of 2021).

water supply for irrigation with or without food security and local habits. The fourth optimization scenario was studied with or without irrigation constraints increasing irrigation charges 10 times. The aim of the four scenarios is to optimize the cropping patterns, irrigable crop area, and water use.

2.2.3 | Reference crop evapotranspiration

The ET_0 is determined using the FAO Penman–Monteith equation (Allen et al., 1998). It was assumed that the available canal water was the amount of water withdrawn from the rivers Karnafuli and Halda by pumps, and the volume of water (V) is calculated by Equation 7 (Michael et al., 2012).

$$V(\mathrm{m3}) = n * Q * T * \eta, \tag{7}$$

where Q = discharge capacity (m^3/hr) of pump, T = duration of pumping (hr/day), η = efficiency of pumps, and n = no. of pumps. The efficiency of the pumps in the KIP is 85% (World Bank, 1975).

2.2.4 | Net irrigation water requirement estimation

Since the rice cultivation in Bangladesh is fully based on a wetland system, a field water balance approach using a spreadsheet model has been used for the estimation of the irrigation water requirement of rice. The water balance equation is presented in Equation 8 following Mullick et al. (2011):

$$S_t = S_{t-1} + I_t - \mathrm{ET_c} + \mathrm{ER}_t - \mathrm{SP}_t, \tag{8}$$

where S_t = field storage at the end of time period t, S_{t-1} = field storage at the beginning of time period t (it refers to applied irrigation during the period t), $\mathrm{ET_c}$ = actual evapotranspiration by rice during period t, ER_t = effective rainfall during period t, and SP_t = seepage and percolation losses during time period t.

One day is taken as a time step in the field water balance calculations. All the components of field water balance are measured in mm. Water requirement for land preparation is taken as 180 mm and seepage and percolation loss as 4.6 mm/day as mentioned by the Bangladesh Water Development Board.

Ponding condition is explicitly incorporated in the water balance approach. Featuring the local condition, minimum 50 mm and maximum 100 mm water depth has been considered to be maintained during the first 105 days of rice plants. For the other crops, crop evapotranspiration ($\mathrm{ET_c}$) has been calculated as respective crop coefficient K_c (Supplementary Material Table S3) times $\mathrm{ET_0}$, and irrigation requirement is estimated by deducting effective rainfall from $\mathrm{ET_c}$.

Overall irrigation efficiency is considered as $\eta = \eta_c \times \eta_a$, where η_c = conveyance efficiency and η_a = application efficiency. The gross and net irrigation requirement is estimated using the relationship IG (mm) $= \frac{\mathrm{IR}}{\eta}$ (Singh, 2014). IR is estimated from the water balance equation for rice, using CROPWAT for non-rice crop. This is the actual irrigation requirement, and after applying efficiency on this amount, the gross irrigation requirement was obtained.

2.2.5 | Yield reductions from water stress

The crop yield depends on irrigation water and continues to decrease with water application. The actual yield considering the water requirement can be calculated by Equation 9 (Tran et al., 2011).

$$Y_\mathrm{A} = Y_\mathrm{M}\left[1 - \sum_{i=1}^{n} K_{Yi}\left(1 - \frac{\mathrm{AW_{applied}}}{\mathrm{AW_{Req}}}\right)\right], \tag{9}$$

where $\mathrm{AW_{applied}}$ = depth of applied water used in calculation of yield (mm), $\mathrm{AW_{Req}}$ = irrigation water required (mm), Y_A = actual yield (t/ha), Y_M = maximum yield (t/ha), and K_{Yi} = average yield response factor to water (dimensionless) for the overall growth period.

Since the actual water used in evapotranspiration was not readily available for the study, in Equation 9, the ratio of applied water to required water has been used to estimate the yield response to water stress, even though Doorenbos & Kassam (1979) suggested to use the ratio of actual to maximum evapotranspiration. Average yield response factors are used as given by Doorenbos & Kassam (1979). Earlier a similar approach was used by Mullick et al. (2011), Tran et al. (2011), and Waller & Yitayew (2015).

2.3 | Climate change scenarios

Two climate change scenarios were developed considering RCP 2.6 and RCP 4.5 projected climate data over the period 2020–2099 (Table 2) to optimize water resources and irrigable areas for maximization of benefit. In this study, total monthly rainfall, $\mathrm{ET_0}$, and net irrigation water requirement's trend were estimated by the nonparametric Mann–Kendall test for testing the presence of the monotonic increasing or decreasing trend. The nonparametric Sen method was used for estimating the slope of a linear trend.

2.4 | Data source

Data regarding the KIP were collected from the Bangladesh Water Development Board, Chattogram, and the Institute of Water Modelling, Dhaka. Information regarding crop data was collected from the Upazila Offices, Department of Agricultural Extension, Bangladesh Agricultural Research Council. Meteorological data were collected from the Bangladesh Meteorological Department, Agargaon, Dhaka. Soil and hydrogeological data were collected from the district office, Soil Resource Development Institute (SRDI), Chattogram, and Bangladesh Agricultural Research Council, Dhaka.

3 | RESULTS

3.1 | ET_0 and rainfall

The ET_0 using the FAO Penman–Monteith method was determined (Supplementary Material Table S1). The ET_0 values varied within the range of 2.6–5.1 mm/day over the years 1990–2015 in the KIP. The highest ET_0 (5.1 mm/day) and lowest ET_0 (2.6 mm/day) were in April and December, respectively. The maximum and minimum rainfall in the project area was in July and January, respectively.

3.2 | Net irrigation water requirement

Net irrigation water requirement was calculated classifying all the crops into two categories, namely, rice and non-rice crops (Supplementary Material Table S2). Net irrigation water requirement was the same for non-rice crops of all units because agricultural practices like plantation, intercultural operations, and harvesting time were similar. But it was different for rice crops. The maximum net irrigation water requirement in the Halda Unit, Halda Extension, and Ichamati Unit is calculated from 1990 to 2016.

TABLE 2 Baseline and climate change scenario periods

RCP 2.6	RCP 4.5	Baseline
2020–2039	2020–2039	1990–2015
2040–2059	2040–2059	
2060–2079	2060–2079	
2080–2099	2080–2099	

3.3 | Water demand and abstraction in KIP

3.3.1 | Halda Unit

According to Figure 4, peak water demand of and delivery to the Halda and Halda Extension Units were in January and February as robi crops were in development and mid-growth stages and there was less rainfall in this particular time. Irrigation water demand exceeded the abstraction of water in February, while during the other months water withdrawals were higher than the demand. No water was supplied to the kharif crops Aman, Aus, and bean during the mid-monsoon because the crop water requirements were met by rainfall.

3.3.2 | Halda Extension

Figure 4 depicts that water demand for irrigation was more than water abstraction in Halda Extension during February, March, and November. In the remaining months, water demand was less than water abstraction.

3.3.3 | Ichamati Unit

The peak water abstraction was in February and March in the Ichamati Unit (Figure 4). There was an excess of water abstraction over water demand throughout the year. In four months, that is, June, July, August, and September, there was zero water abstraction, and crop water requirement of kharif crops was met by rainfall in these months.

3.4 | Optimization of irrigation water and crop area

Halda, Halda Extension, and Ichamati Units. In case of optimization of irrigation water and crop area, four scenarios are considered, as mentioned in Table 1. Net benefit and optimal cropping intensity under existing and different scenarios are described in Tables 3 and 4, respectively. Considering all the scenarios, the net benefit in the Halda and Halda Extension Units followed the sequence of S-3b > S-2 > S-3a > S-1 > S-4b > S-4a, whereas the trend slightly changed for the Ichamati Unit (Table 4). Ichamati Unit followed the pattern of S-3b > S-2 > S-3a > S-4b > S-1 > S-4a. In the Halda Unit, optimization for the S-3b scenario provided the most effective result with 200% cropping intensity with the maximum net

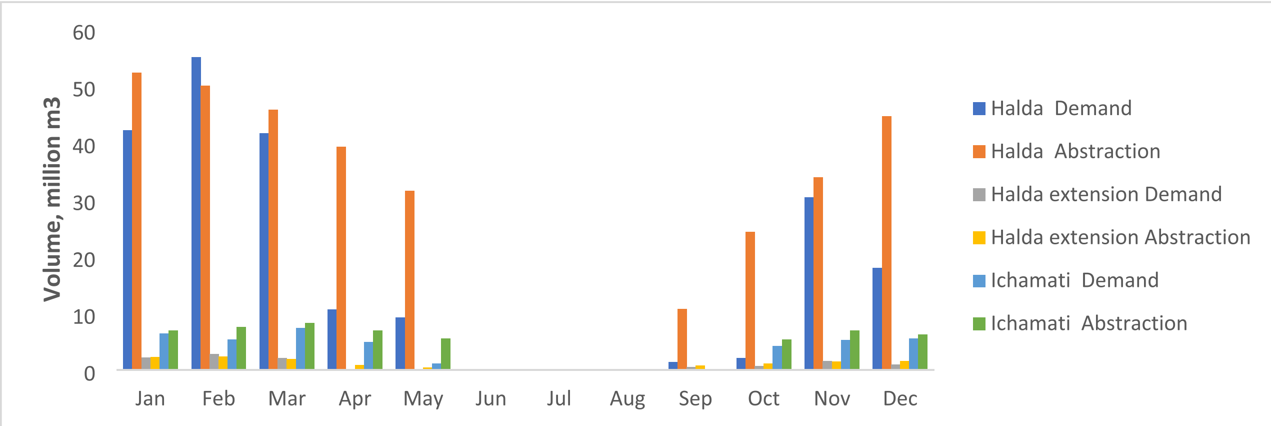


FIGURE 4 Water demand and abstraction in Halda, Halda Extension, and Ichamati Units [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 3 Net benefit: existing versus different scenarios

Net benefit (billion Tk[a])							
	S-1	**S-2**	**S-3a**	**S-3b**	**S-4a**	**S-4b**	**Existing**
Halda	4.2	23.4	4.3	23.5	3.8	3.9	3.2
Halda Extension	0.2	1.2	0.2	1.3	0.2	0.2	0.2
Ichamati	2.0	4.2	2.1	4.2	1.9	2.1	1.1

Abbreviation: Tk, Taka (Bangladeshi currency).
[a]1 billion Tk = $11,779,470 (price level of 2021).

benefit. The optimization was run for three seasons, namely, robi, kharif I, and kharif II, and crop area was separately estimated for both seasons (Table 4). Adding the areas from three seasons gives the overall cropping intensity. The net benefit was about 23.5 billion Tk from Halda Unit. Optimization for S-3b scenario was the most compelling case for Halda Extension, with 100% crop area in both the kharif and robi season securing 200% optimal cropping intensity and a net benefit of 1.3 billion Tk. The same scenario worked for the Ichamati Unit, with 200% cropping intensity with a net benefit of 4.22 billion Tk. The month with the highest water savings for the Halda and Halda Extension Units was April with about 85%. In the Ichamati Unit, May was the month with the highest water savings (nearly 55%). In the Halda, Halda Extension, and Ichamati Units, water savings throughout the year were nearly 30%, 20%, and 15%, respectively.

3.5 | Optimization under climate change scenarios

3.5.1 | Determination of trend of rainfall and ET_0

The trend analysis of historical rainfall (1961–2015) was studied with the Mann–Kendall test and Sen's slope method, and in Table 5, trend analysis results for the period 1961–2015 for total rainfall and ET_0 are presented. A non-significant trend for both rainfall and ET_0 was observed in all the months and on an annual basis, except for rainfall in May, which had an increasing trend of about 1.7 mm/year (Table 5). In the project area, this month (May) had a less critical period of crop irrigation water requirement. Thus, climate change had little effect on rainfall in the KIP. Rainfall and ET_0 for baseline (1990–2015) and projected climate change scenarios, that is, RCP-2.6 and RCP-4.5, are shown in Tables 6 and 7, respectively.

3.5.2 | Net irrigation water requirement under climate change scenarios

Halda and Halda Extension Units

Crops' irrigation water requirement, except for mustard, was slightly increased due to a decrease in rainfall and an increase of ET_0 for both the RCP-2.6 and RCP-4.5 scenarios in the robi season; mustard's irrigation requirement was reduced because of a change in rainfall pattern (Table 8). The irrigation water requirement of Aman rice decreased in both climate change scenarios because of increase in rainfall and decrease in ET_0 in its cultivation period of August and September. On the other hand, Aus

TABLE 4 Optimal cropping intensity: existing versus different scenarios

Cropping intensity (%)	S-1		S-2		S-3a		S-3b		S-4a		S-4b		Existing	
	Robi	Kharif	Robi	Kharif	Robi	Kharif	Robi	Kharif	Robi	Kharif	Robi	Kharif	Robi	Kharif
Halda	100	84	100	90	100	98	100	100	100	84	100	98	90	45
Halda Extension	100	84	93	88	100	98	100	100	100	84	100	98	85	53
Ichamati	100	74	100	49	100	83	100	100	100	58	100	67	84	65

rice irrigation requirement was raised by above 50% due to a decrease in rainfall in its production period (mid-April to August) and its water sensitive period (mid-April to July). According to the trend analysis of net irrigation water requirement based on data from 1990 to 2015 for the Halda Unit and Halda Extension Unit as shown in Table 9, only Boro has an increasing irrigation water demand at a 5% level of significance, and the net irrigation water requirement increased by 3.5 mm/year.

Ichamati Unit

Comparing Tables 8 and 10, it can be concluded that the irrigation water requirement in the Ichamati Unit was greater in comparison with the Halda Unit and Halda Extension Unit for the dominant cropping patterns Boro and Aman or Boro and Aus in climate change scenarios as the planting period of rice in the Ichamati Unit was little late. According to Upazila Agriculture Offices, DAE, the late plantation practice was due to traditional and social norms and customs. In the Ichamati Unit, there was non-significance in net irrigation water requirement (1990–2015) of all crops at 5% and 1% levels of significance. The net irrigation water requirement of Ichamati Unit crops was determined for the RCP-2.6 and RCP-4.5 climate change scenarios, and the baseline net irrigation water requirement was calculated averaging the net irrigation requirement over the period 1990–2015.

3.5.3 | Optimization of irrigation water and crop area with climate change scenarios

Halda Unit and Halda Extension

Optimization for two climate change scenarios, that is, RCP-2.6 and RCP-4.5, with existing water supply, crop constraints for regional food security and food habits, and crop areas, was studied in the KIP. Optimization considering climate change scenarios was compared with the existing optimal scenario (S-1). An optimal cropping pattern in the Halda Unit and Halda Extension due to climate change would not change the existing optimal cropping pattern. The optimal cropping pattern is Aus and Aman in the kharif season, and Boro, potato, mustard, cowpea, chilli, brinjal, tomato, and wheat in the robi season. Sweet potato, bean, and maize should be cultivated in zero areas. Optimal crop area allocation under two climate change scenarios up to 2099 are shown in Figures 5 and 6 for the Halda Unit and Figures 7 and 8 for Halda Extension. Climate change would have almost no impact on optimal crop area distribution in the robi season. In the kharif season, the cultivable area would increase, when

TABLE 5 Trend analysis of total rainfall and ET_0 in Karnafuli Irrigation Project over the period 1961–2015

Month	Total rainfall (mm) Mann–Kendall trend Z-value	Total rainfall (mm) Sen slope estimate Q	ET_0 (mm/day) Mann–Kendall trend Z-value	ET_0 (mm/day) Sen' slope estimate Q
JAN	−0.9	0	−0.5	0
FEB	0.6	0	0.9	0.003
MAR	−0.4	−0.1	0.01	0
APR	1.6	0.8	−1.7	−0.006
MAY	2.3*	1.7	−2.4	−0.008
JUN	0.3	0.6	0.01	0
JUL	0.1	0.2	−1.8	−0.005
AUG	−0.7	−0.9	−0.8	−0.003
SEP	0.8	0.8	−1.7	−0.004
OCT	−0.3	−0.3	−1.4	−0.004
NOV	0.2	0.01	0.4	0
DEC	0.1	0.01	0.07	0
ANNUAL	0.7	2.9	−0.3	0

Abbreviation: ET_0, reference crop evapotranspiration.
*If trend at $\alpha = .05$ level of significance.

TABLE 6 Rainfall for baseline (1990–2015) and selected climate change scenarios in Karnafuli Irrigation Project (monthly and annual)

	Baseline (1990–2015) mm	RCP-2.6 2020–2039 mm	RCP-2.6 2040–2059 mm	RCP-2.6 2060–2079 mm	RCP-2.6 2080–2099 mm	RCP-4.5 2020–2039 mm	RCP-4.5 2040–2059 mm	RCP-4.5 2060–2079 mm	RCP-4.5 2080–2099 mm
Jan	9	7	6	10	10	7	12	10	9
Feb	45	11	11	12	14	14	13	14	15
Mar	80	30	30	29	32	31	33	31	28
Apr	122	88	103	93	90	96	80	93	93
May	353	251	231	225	199	221	236	241	231
Jun	570	339	309	281	335	319	317	237	348
Jul	707	577	593	555	516	541	578	594	712
Aug	545	776	777	707	748	800	835	844	902
Sep	251	467	449	473	412	496	496	472	466
Oct	223	144	147	158	146	139	167	161	151
Nov	63	26	26	31	23	25	30	25	27
Dec	18	11	6	11	7	9	9	9	9
Annual	2,985	2,726	2,687	2,585	2,532	2,697	2,807	2,732	2,990

comparing the existing optimal crop area with the optimization considering the climate change effect, mainly due to increase in rainfall. Both Aman and Aus production areas would increase in Halda and Halda Extension. The optimal cropping intensity in Table 11 shows that from an existing condition, cropping intensity would increase by 184% up to 200% for the RCP-2.6 and RCP-4.5 climate change scenarios.

Ichamati Unit

Climate change would have a minor effect on the optimization of irrigation water and crop areas in the Ichamati

TABLE 7 ET_0 for baseline (1990–2015) and selected climate change scenarios in Karnafuli Irrigation Project (monthly and annual)

		RCP-2.6				RCP-4.5			
	Baseline (1990–2015) mm	2020–2039 mm	2040–2059 mm	2060–2079 mm	2080–2099 mm	2020–2039 mm	2040–2059 mm	2060–2079 mm	2080–2099 mm
Jan	80	92	92	91	91	91	90	91	91
Feb	97	111	111	111	111	111	109	110	110
Mar	136	157	155	157	154	155	154	154	155
Apr	147	177	173	176	175	172	174	174	173
May	144	184	185	184	188	184	184	184	184
Jun	121	174	175	179	176	174	178	182	178
Jul	115	163	164	167	169	166	163	164	162
Aug	118	133	133	135	137	133	130	131	131
Sep	112	112	113	113	115	111	110	111	111
Oct	108	106	106	106	108	106	102	104	106
Nov	87	88	88	88	89	88	87	87	87
Dec	76	81	82	81	82	81	81	81	81
Annual	1,341	1,578	1,576	1,588	1,593	1,571	1,562	1,575	1,568

Abbreviation: ET_0, reference crop evapotranspiration.

TABLE 8 Net irrigation requirement (mm) by crops for baseline (1990–2015) and selected climate change scenarios in Halda Unit and Halda Extension

		RCP-2.6				RCP-4.5			
	Baseline 1990–2015	2020–2039	2040–2059	2060–2079	2080–2099	2020–2039	2040–2059	2060–2079	2080–2099
Boro	927	992	991	989	990	990	983	989	989
Aman	269	154	152	143	176	158	133	139	148
Aus	196	309	339	377	356	343	348	403	318
Potato	196	200	205	195	204	201	193	199	198
Mustard	123	119	124	113	122	120	112	118	117
Cowpea	166	174	179	171	172	173	168	171	171
Chilli	244	258	263	252	259	257	249	254	253
Brinjal	261	277	282	271	278	276	267	274	272
Tomato	250	267	273	264	266	265	261	264	263
Wheat	166	173	178	170	171	172	167	170	169
Maize	322	357	362	355	353	355	347	352	353
Sweet Potato	290	305	311	299	307	304	295	302	300

Unit. The optimal cropping area for different crops under existing (S-1), RCP-2.6, and RCP-4.5 scenarios in the Ichamati Unit are shown in Figures 9 and 10. Optimal cropping patterns for both the RCP-2.6 and RCP-4.5 climate change scenarios would be similar to existing optimal patterns (S-1). According to Figures 9 and 10, the optimal cropping pattern would be Aman and Aus in the kharif season and Boro, chilli, tomato, and watermelon for the robi season. Potato, mustard, cowpea, brinjal, wheat, and maize should be cultivated in zero areas. In the robi season, optimal crop areas under climate change scenarios would be the same as the existing optimal

TABLE 9 Trend analysis of net irrigation water requirement (mm) in Karnafuli Irrigation Project over the period 1990–2015

Halda and Halda Extension Units			Ichamati Unit		
Crops	Mann–Kendall trend Z-value	Sen slope estimate Q	Crops	Mann–Kendall trend Z-value	Sen slope estimate Q
Boro	2.1*	3.5	Boro	1.7	4.8
Aman	−0.9	−3.3	Aman	−0.2	−0.3
Aus	0.7	2.4	Aus	0.7	2.4
Potato	1.4	1.0	Potato	1.5	1.0
Mustard	1.4	1.1	Mustard	1.4	1.1
Cowpea	1.5	1.4	Cowpea	1.5	1.4
Chilli	1.2	2.1	Chilli	1.2	2.2
Brinjal	1.3	2.4	Brinjal	1.3	2.4
Tomato	1	1.9	Tomato	1	1.9
Wheat	1.4	1.2	Wheat	1.4	1.2
Maize	1.6	3.7	Maize	1.6	3.7
Sweet Potato	1.3	1.9	Watermelon	1.8	3.7
Bean	0	0			

*If trend at $\alpha = .05$ level of significance (trend analysis of historical net irrigation water requirement (1990-2015) in Halda unit and Halda Extension was significantly found only Boro crop at 5% level of significance and net irrigation water requirement increased 3.5 mm/year wheras in Ichamati unit there was non-significance in net irrigation water requirement (1990-2015) for all crops).

TABLE 10 Net irrigation requirement (mm) by crops for baseline (1990–2015) and selected climate change scenarios in Ichamati Unit

		RCP-2.6				RCP-4.5			
	Baseline (1990–2015)	2020–2039	2040–2059	2060–2079	2080–2099	2020–2039	2040–2059	2060–2079	2080–2099
Boro	1,066	1,164	1,148	1,161	1,158	1,153	1,163	1,155	1,157
Aman	524	448	445	433	451	452	422	432	440
Aus	188	309	339	377	356	343	348	403	318
Potato	196	200	205	195	204	201	193	199	198
Mustard	122	119	124	113	122	120	112	118	117
Cowpea	164	174	179	171	172	173	168	171	171
Chilli	243	258	263	252	259	257	249	254	253
Brinjal	261	277	282	271	278	276	267	274	272
Tomato	248	267	273	264	266	265	261	264	263
Wheat	165	173	178	170	171	172	167	170	169
Maize	321	357	362	355	353	355	347	352	353
Watermelon	292	360	347	355	349	348	352	347	348

pattern (S-1), except for tomato, which would increase by 16 ha. In the kharif season, the Aman production area would be increased by 135 ha, and Aus production would decrease. Table 11 states that optimal cropping intensity in the Ichamati Unit for climate change effect would be slightly increased compared with the existing optimal cropping pattern.

3.6 | More-crops-per-drop paradigm

The primary aim set for this study was to look into the possibility of growing more crops with the existing amount of water, and the proposed optimization model became successful by rejecting the null hypothesis. In this study, the considered four optimization scenarios

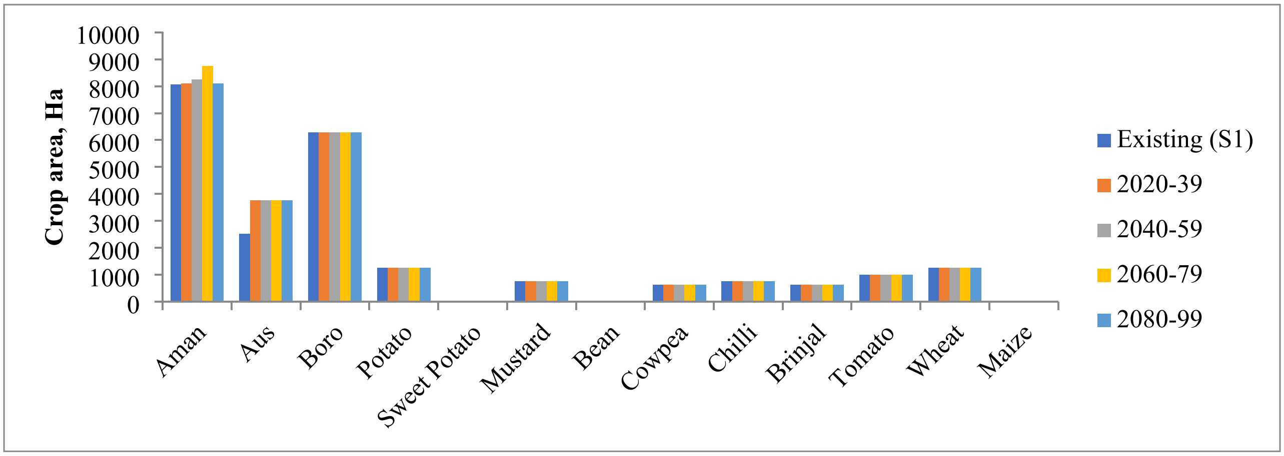


FIGURE 5 Optimal crop areas: existing (S-1) versus RCP-2.6 scenarios in Halda Unit [Colour figure can be viewed at wileyonlinelibrary.com]

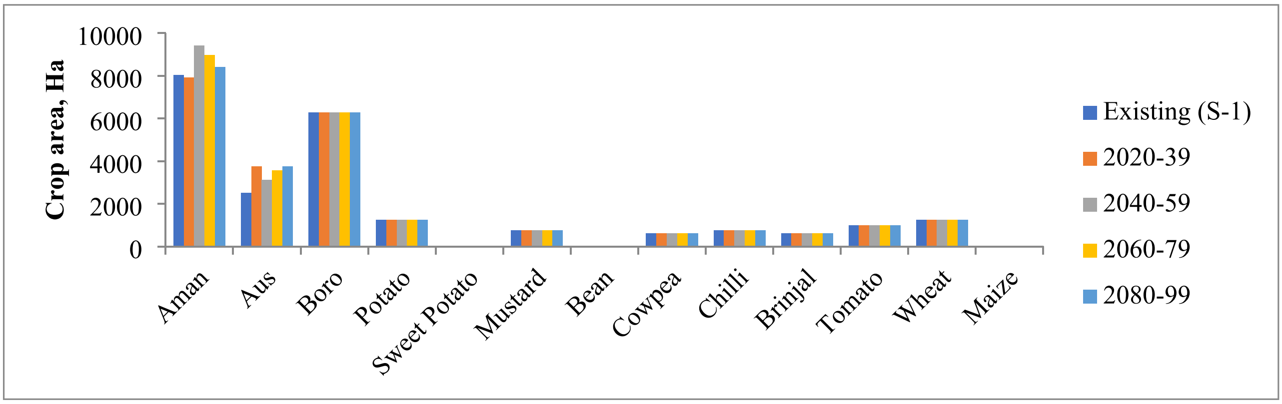


FIGURE 6 Optimal crop areas: existing (S-1) versus RCP-4.5 scenarios in Halda Unit [Colour figure can be viewed at wileyonlinelibrary.com]

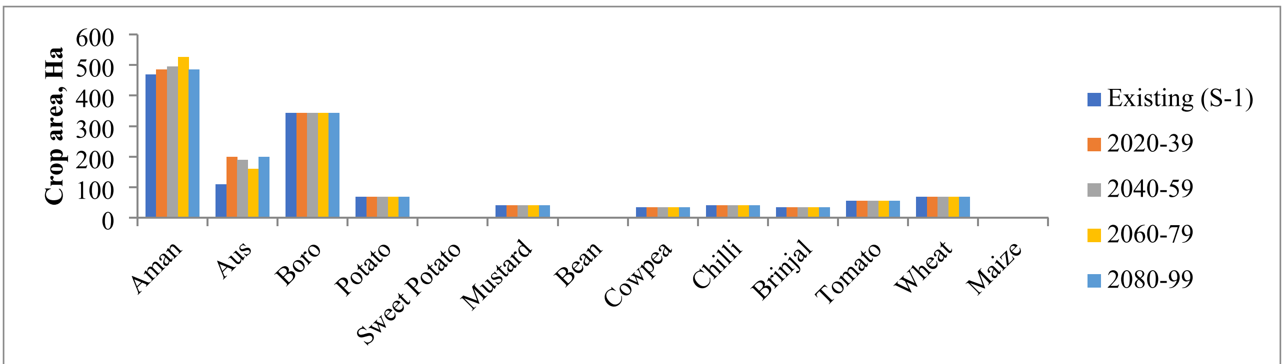


FIGURE 7 Optimal crop areas: existing (S-1) versus RCP-2.6 scenarios in Halda Extension Unit [Colour figure can be viewed at wileyonlinelibrary.com]

contribute to some extent to the "more crops per drops" paradigm. Among the four scenarios, the "without irrigation constraint and regional food security and with land constraint optimization" scenario (scenario S-3b) is the most justified in terms of economic benefit. One of the most effective ways to ensure the more-crop theme is to increase the cropping intensity within the existing setup. The scenario S-3b secures 100% crop area and 200%

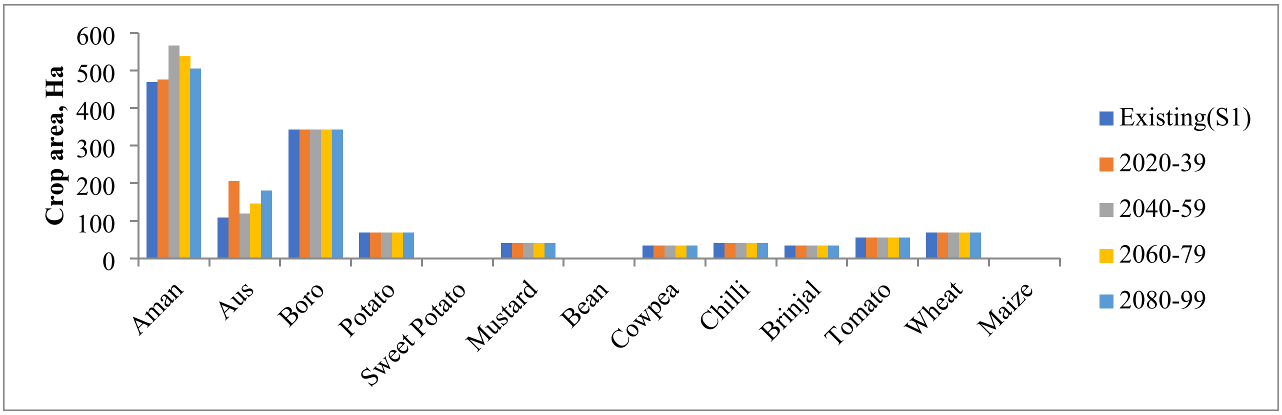


FIGURE 8 Optimal crop areas: existing (S-1) versus RCP-4.5 scenarios in Halda Extension Unit [Colour figure can be viewed at wileyonlinelibrary.com]

TABLE 11 Optimal cropping intensity: existing versus RCP-2.6 and RCP-4.5 scenarios in Halda, Halda Extension, and Ichamati Units

Optimum cropping intensity (%)										
	Existing (S1)		2020–2039		2040–2059		2060–2079		2080–2099	
	RCP-2.6	RCP-4.5	RCP-2.6	RCP-4.5	RCP-2.6	RCP-4.5	RCP-2.6	RCP-4.5	RCP-2.6	RCP-4.5
Halda	184	184	195	193	196	200	200	200	194	197
Halda Extension	184	184	200	199	200	200	200	200	200	200
Ichamati	174	174	173	169	172	173	171	170	172	174

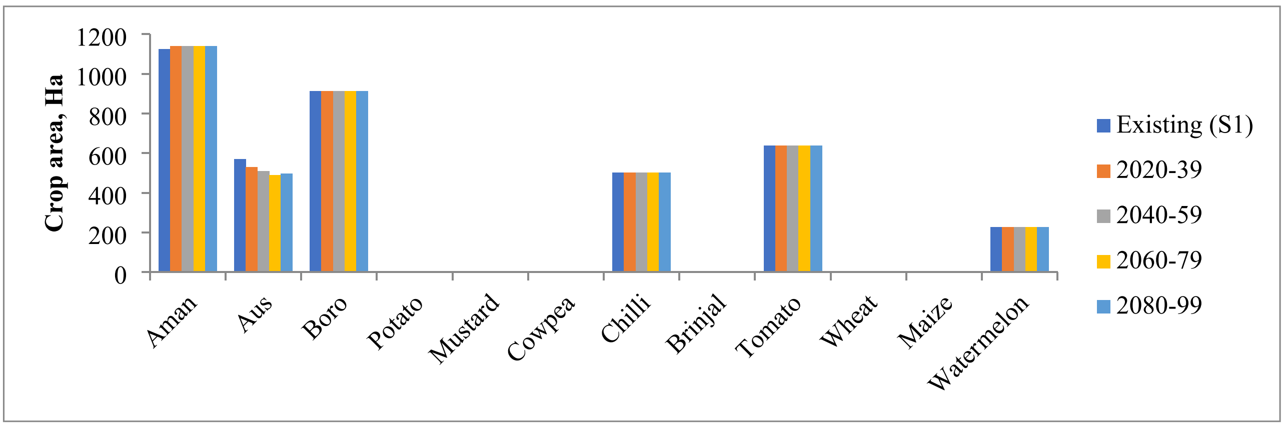


FIGURE 9 Optimal crop areas: existing (S-1) versus RCP-2.6 scenarios in Ichamati Unit [Colour figure can be viewed at wileyonlinelibrary.com]

cropping intensity for the Halda, Halda Extension, and Ichamati Units in both the kharif and robi seasons. Even with the existing water supply and maintaining local practice on cultivation, scenario S-1 generates more benefit and results in higher cropping intensity than the existing situation.

Additionally, this optimization scenario ensures the water-saving concept too. For the Halda and Halda Extension Units, the optimization scenario S-3b saves maximum water in April with about 85%. In contrast, for the Ichamati Unit, the top water-saving month is May and the saving is about 55%. The "more crops per drops" theme is fully justified for the KIP with this optimization model applied. To achieve the actual benefits from this study, implementation of either scenario S-1 or S-3b is required in the fields of the KIP.

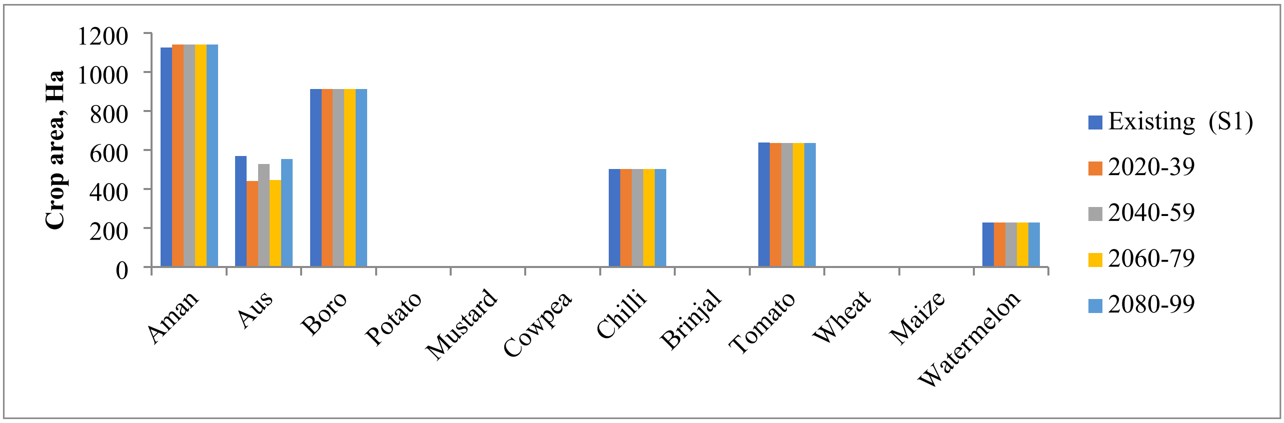


FIGURE 10 Optimal crop areas: existing (S-1) versus RCP-4.5 scenarios in Ichamati Unit [Colour figure can be viewed at wileyonlinelibrary.com]

4 | DISCUSSION

Maximizing the net benefit and crop production with existing resources is a challenging task, although it is critically important to feed the vast population of Bangladesh. This research addresses the challenge by developing a linear programming optimization model in one of the most important irrigation projects of Bangladesh. The work is a pioneering approach to use the existing water more effectively and to increase crop productivity for any irrigation project in Bangladesh. Analyses showed that the Halda and Halda Extension Units have the capacity to raise the cropping intensity and net benefit by about 5% and five times (scenario S-2), respectively, in comparison to S-1. For S-3a and S-4, the optimal cropping pattern and crop areas do not change significantly, but scenario S-3b results in a significant change over the existing situation. Climate change does not have any significant role over the crop production in the KIP. Only an increasing rainfall trend was observed in May (1.7 mm/month), and the net irrigation requirement for Boro is slightly increasing (3.5 mm/year). In Ichamati Unit for the S-3b scenario, the optimal cropping pattern is Aus in kharif and tomato in the robi season. The optimal cropping pattern for S-2 is chilli, watermelon, tomato in the robi season and only Aus in the kharif season. For the S-3a scenario, the optimal cropping pattern is Aman and Aus in the kharif season and Boro, tomato, and watermelon in the robi season. The cropping intensity and net benefit in S-3a is 10% and 110% more than in S-1, respectively. For the S-4 scenario, the optimal cropping pattern remains the same. Trend analysis of net irrigation water requirement (1990–2015) in the Ichamati Unit is again non-significant at 5% and 1% level of significance. The cropping pattern and intensity for optimization with climate change scenarios are similar to the existing optimal cropping pattern and intensity.

Overall, the S-3b scenario suits best with maximum profit and cropping intensity among the four optimization scenarios analysed; however, in this scenario local practices for cultivation have not been considered. Local practices of cultivation are important for regional food security, and that will help in market food price stability. From this point of view, adopting scenario S-1 would be reasonable, and scenario S-1 can still generate 1.0 billion Tk in additional revenue, as it increases the cropping intensity by 49% compared with the existing practice. The research outcome is in harmony with the FAO-IWMI global theme of more crop per drop. The research results have already been communicated to the regional agricultural extension office for field implementation with the suggestive scenario of S-1.

5 | CONCLUSIONS

In this study, a linear programming optimization model is set up to achieve optimization on use of existing water resources and crop land. Four scenarios (Table 1) have been analysed to have a clear idea on choice of constraints in optimization. The analyses showed that there is considerable scope for increasing the net benefits of the KIP through more effective use of the existing water resources. The optimization is carried out keeping the cost of agricultural inputs unchanged; however, analysis with changing prices for the agricultural inputs with their sensitivity demands further research. The price of agricultural input, irrigation efficiency, yield, and yield response to water application are considered constant over the analysis period for the optimization model. However, all these factors may face changes due to market behaviour, climatic condition, and management practices. Inclusion of all such issues will affect the overall optimization results. The research can be extended with inclusion of these factors, and that will make the model more robust. Additionally, due to the unavailability of a weather station at the study site, the meteorological data of Chattogram station and common soil data of the project areas were used. Furthermore, crop water requirements of different varieties of the same crop may be different, which needs to be explored. Future studies are suggested in this regard.

The applicability of the model is considered wide; not only in the KIP, but the model can also be applied to any irrigation project in Bangladesh or abroad to optimize the cropped area and existing water resources. The authors wish to carry out similar studies for other irrigation projects in Bangladesh to provide the country with a clear picture of possibilities to increase the efficiency of irrigation water use. It is proposed to the DAE to use this model for the KIP and other project areas and explore the possibilities of increasing their revenues as well as crop production. Increasing crop production will help achieve food security and expand the food safety net in the region. This research will contribute to attaining sustainable development goals and is in harmony with the FAO motto of "more crop per drop."

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from the corresponding author.

ENDNOTE

[1] Tk = Taka (Bangladeshi currency); 1 Tk = \$0.012 (price level of 2021).

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