Heliyon 10 (2024) e28404

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.cell.com/heliyon

Research article

Optimizing crop planning in the winter fallow season using residual soil nutrients and irrigation water allocation in India

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ARTICLE INFO

Keywords:
Environmental flow release
Crop diversification
Irrigation water allocation
Residual fertilizer
Crop preference
Food security

ABSTRACT

Effective management of water resources is essential for crop diversification and food security. This study proposes an Irrigation-Food-Environment-Chance-constrained Programming (IFEC) model for simultaneously optimizing crop planting area, irrigation water, and residual fertilizer considering inflow uncertainty along with farmer preference crop. Eight irrigation water allocation optimal models were constructed, fixing the preference crop cultivation area, while deviations in downstream release, and vegetable crop area cultivation were executed for sensitivity analysis. Model is then applied in a command area fed by a sub-tributary of Brahmaputra, India. On averaging, plant available N and P for the area were 62.14 kg ha^{-1} and 1.13 kg ha^{-1} respectively. With variation in available water, changes would occur in vegetable and cereal crops having higher yield and relatively less crop water requirement as compared to maize. Results showed that complying with preference crop area up to 60% would decrease the profit by 49% as compared to 20% at even 10% risk probability for 70% release. At existing conditions, water would be insufficient at 60% preference crop. Further, R^2 value between benefit and water availability for vegetable cultivation varies from 0.99 to 0.78 for all scenarios. The tool featured that, setting specific preference crop areas provides equitable situation rather than monocropping. From the study findings, we suggest two salient recommendations: (1) promoting policies with appropriate financial subsidies for vegetable cultivation that focus on intensification with less water-requiring crops and (2) optimization results could be achieved by expanding the water utilization in the present condition while increasing efficiency.

1. Introduction

Agricultural irrigation shares a substantial part of freshwater withdrawal, for food production, which is around 85% of global freshwater. Further with the population growth, the irrigation area is predicted to nearly double by 2050 [1,2]. This continuously increases the water demand whereas the availability is constant. This leads to the scarcity of freshwater resources in different regions [3]. Along with this, food security is a fundamental challenge with limited available land and water resources. Inspite of the above fact, a considerable portion of agricultural land has been left uncultivated during the non-monsoon season in global rural locations due to mainly lack of adequate irrigation facilities. Globally, rice-fallow is a growing phenomenon and South Asia contributes approximately 79% of the total rice fallows [4]. These fallow lands possess varied climatic and soil conditions, which are fertile for growing multiple

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https://doi.org/10.1016/j.heliyon.2024.e28404
Received 10 March 2023; Received in revised form 18 March 2024; Accepted 18 March 2024
Available online 22 March 2024
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crops in a single field [5]. The fields remain fallow, in winter (rabi) and summer (zaid) seasons after the harvest of rice. Of the two seasons, the winter season has more potential area for cultivation as compared to the zaid season. The cultivation of oilseed, pulses and cereal crops, as a source of carbohydrates, protein and fats, provides fundamental nutritional needs. Apart from this, vegetable crops are also cultivated, which are a source of micronutrients and minerals. Therefore, the cultivation of all these crops in a single field helps in crop diversification and food security of a region.

On the other hand, the monocropping of cereal or any other crop is a growing phenomenon due to known yield, reduced investment, prior knowledge of the activity calendar, and lower market risk. This results in the adoption of one or two varieties by farmers for cultivation throughout the year depending on competition, yield stability, perceptions, preferences, and attitudes [6]. However, these lead to declining soil fertility. Also, crop production of subsequent cereal crops results in poor land productivity, biodiversity, food, and nutrition [7]. Legume-based rotation cultivation or intensive/multiple cropping is linked with higher food security and land quality management [8]. Apart from this, an increased cultivation of vegetable crops increases water availability in the face of water stress under climate change [9].

Crop production is primarily a function of soil and water, where the soil is the storehouse of nutrients required for crop growth by replenishment through fertilizers. The N and P nutrient accumulated in the soil, due to excess fertilization after crop harvest are prone to hydrologic loss, when the lands are kept fallow [10,11]. This leftover fertilizer can be used beneficially in subsequent crop cultivation, which also helps in reducing the cost of cultivation. Although crop yield depends on several other factors, with the application of the same amount of water and fertilizer, crop yield for a particular variety growing in similar climatic conditions remains almost static. Thus, with food security, and poverty elimination, ecology preservation, is one of the most prominent factors of the Sustainable Development Goal (SDG)s. Though studies reported crop diversification using Linear Programming (LP) and maximization of profit as an objective [12,13], there is only a few work that has taken into account residual nutrients in soil from the previous season cultivation.

Additionally, inspite of a huge irrigation potential in developing countries, most of its population and smallholder farmers depend on rainfall for their various agricultural activities. However, areas receiving comparatively less rainfall or erratic rainfall due to changing climate, negatively affect crop growth. Hence, the irrigation potential can be beneficially utilized by water management organizations, with the development of different irrigation schemes to increase and stabilize food production in the country. India, a developing country, has the potential to utilize surface water and groundwater at 690 km^3 yr^{-1} and 396 km^3 yr^{-1}, respectively. The state Assam, India is gifted with enormous water resources from the mighty Brahmaputra River and its tributaries, however, some of the regions within the state experience insufficient rain and fall under the category of rain-shadow area. Due to mountainous topography, many areas of Assam face relatively lesser rainfall on the leeward side of the mountains thus giving rise to arid situations. In order, to have multiple cropping in those areas, irrigation is essential. Further, optimal planning of crop area for irrigation after downstream environmental release is mandatory for the balanced use of surface water resources of rivers, for various water-demanding sectors in a drought-prone area all the year round [14].

More generally, the impact level of various water-demanding sectors, depends on the mechanism of water acquisition uncertainty, based on temporal and spatial targets [15]. Water resources are liable to variation, and uncertainties are inevitable in water resources management. However, chance-constrained programming (CCP) is a consistently robust and reliable approach to resolving uncertainty [16]. There is also substantial work considering chance-constrained scheduling and control policies to handle irrigation system operation uncertainties [17,18,19]. Environmental flow assessments, which define the amount of water needed in a given ecosystem, have become essential in surface water resources and reservoir management [20,21]. In Kim et al. [22], the reservoir operation module responds to irrigation water demand by controlling the environmental flow to keep the water level up. An agricultural water-environmental flow problem developed by Jägermeyr et al. [23], proposed managing irrigation systems to improve productivity in the face of freshwater crisis. Hence, CCP is applied in this study that considers river inflow uncertainty for irrigation planning and cropping area optimization. The objective of the optimization study carried out, is to find optimal cropping patterns that maximize profit. With the help of this research, irrigation managers can make robust decisions on the quantity of water that can be supplied for irrigating the crops. Apart from this, agricultural development of a region, includes reducing hunger and poverty in rural areas. Here, we assume that food is an economic good and therefore, food produced on the farm and consumed by small-holder farmer households' is in a true sense, an income. Thus, the proposed work emphasizes on regional food security and farmers' livelihood. To achieve this, we present a mathematical model, that optimizes cropping patterns, considering several aspects. Different water availability scenarios and the associated risk probabilities along with Environmental Flow Release (EFR) are formulated in this paper. The detailed analysis is done, using different water availability scenarios, to maximize benefit from the agricultural produce, which will allow us to understand the impact of river flow uncertainty on a benefit. In addition, land resources were considered in the form of quality and quantity. The methodology of the proposed work, utilizing residual nutrients from the previous season's cultivation to reduce cost; objective function and constraints that address crop diversification by automatically restricting farmers to go for monocropping with their preferred crop to honour farmers choice along with result analysis has been presented sectionwise in this study. In Section 2, the paper focuses on the model development process, along with the inputs used for the design of the model. Section 3 assesses the model performance through its application to a case study in the Jamuna River basin, a moisture-stressed area in Assam, in which satisfying crop water demand through irrigation is a serious concern. Results & discussion are detailed in Section 4. Section 5 brings out the conclusion of the study.

2. Model development

This study developed Irrigation-Food-Environment Chance-constrained (IFEC), a modeling-based pathway for the sustainable agricultural productivity of crops and its input-output balances to fulfil the operation of water diversion structure. First, a single objective linear programming model was developed to estimate trade-offs in input resources such as land and water resources. Secondly, stochastic nature of river water and instability in high and low flow levels in a river were quantified to understand the irrigation supply patterns for crop production. Further, food and cultivating preference of crops of the local people were considered. Third, residual soil nutrient from the previous cultivation was incorporated. Fourth, water, carbon, and material footprints were estimated to investigate the sustainability of the cropping pattern from the developed model. Fig. 1 depicts the technical pathway of this study. Fig. 2 illustrates the model structure.

2.1. Chance-constrained optimization model

In Chance-constrained Linear Programming (CCLP) optimization model, random uncertainty in river flow was solved to generate water availability options for allocating water resources in multiple crop planning. The linear optimization model developed in this paper is for administering land for fallow season crops. The model's objective is sustainable crop intensification in the rice-fallow

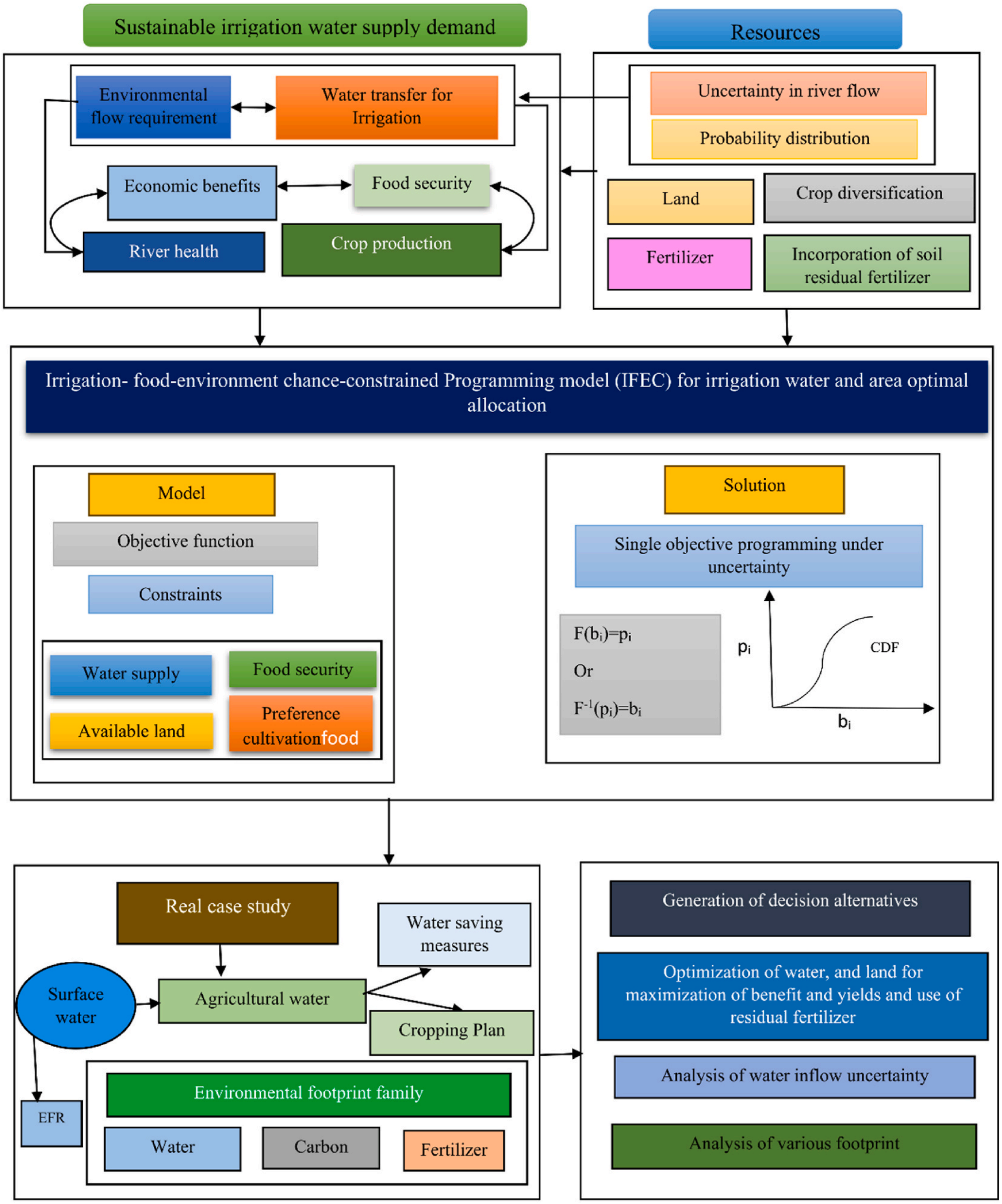


Fig. 1. The roadmap of the IFEC optimal model.

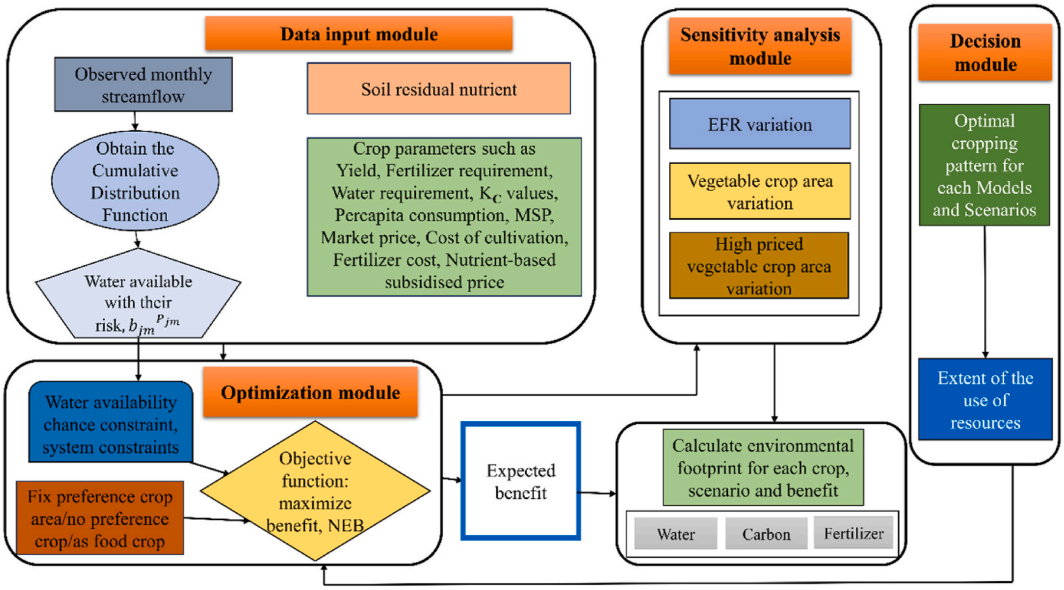


Fig. 2. Flowchart of the proposed IFEC model.

cropping system to manage available land and water for different crop production. For that purpose, high-profit, crop cultivating preference, and eco-friendly plans are proposed and considered in this study. Therefore, farmer benefit maximization criteria, considering sustainable use of land and water resources are confirmed for optimization. These objective functions were subject to constraints for natural resource availability (i.e., water and land), regional food demand, as well as crop diversification (such as perishable, nonperishable crops, and cultivating preference crops). The model decision variables are crop harvest areas for each crop. Specifically, crop yield per unit area and associated economic benefit depend collectively on various factors such as land, water, and soil nutrients. The IFEC model is now discussed in detail in what follows.

2.1.1. *Objective function*

Regional economic development and food security are reflected by net profit, which is always a major concern of decision-makers. The concept of food security is outlined, considering both real and economic access to food that combines people's nutritional requirements and food preferences [24]. There is a strong linkage between agricultural productivity, household income and regional food security, provided there is sufficient market access [25,26]. This objective function not only provides monetary value but also ensure food access in the form of economic benefit for the irrigated area from planting especially winter crops, by optimally allocating land and water while reducing N and P fertilizer use along with its corresponding cost. The difference between Revenues (R_s) and Cultivation Costs (CC_s) for seasons s, at time t can quantify the Net Economic Benefit (NEB):

$$NEB_t = R_s - CC_s \tag{1}$$

For an agricultural system, the revenues are from crop production. Hence, crop revenues can be described as a product price per kg. However, due to the perishability of many crops, there is fluctuation in product price. The revenues of the whole irrigated area are the summation of the revenues of various crops cultivated in the area. R_s is obtained from Eq (2).

$$R_s = \sum_{i=1}^{n} (Y_{is} \times P_{is}) \times A_{is} \tag{2}$$

where Y_i is a parameter that represents the yield of crop i in a particular agricultural region (kg ha^{-1}), P_{is} is a parameter that denotes the price received by the farmer in the market for crop i, A_{is} is the area allocated to each crop in season s.

The total costs for an agricultural production system primarily include fertilizers, pesticides, labour wages, seed cost and other costs such as various machinery, fuel, and irrigation used for food cultivation. However, as all such individual cost is generally not available or difficult to obtain, the average cost of cultivation as reported by Government of India for the similar area is considered in the proposed optimization model (Table S1).

Further, the cost of fertilizer can be minimized by using the residual plant-available-nutrients accumulated in the soil from the antecedent cultivation as in Eq. (3). This residual fertilizer is deducted from the amount of fertilizer required for growing various crops.

$$FC_i = \left(F_{total,i} - RF_{s-1}\right) \times P_{sub} \times A_{is} \quad \forall i, s > 1 \tag{3}$$

where FC_i is the fertilizer cost of crop i; $F_{total,i}$ is the fertilizer required for crop i; $RF_{s\text{-}1}$ is the residual fertilizer from previous season;

P_{sub} is the subsidized price of fertilizer and A_{is} is the area allocated to each crop in season s.

2.1.2. Constraints

The objective function mentioned above is subject to the following constraints. The maximization of the net economic benefit (Eq. (1)) in an agricultural region is subject to a set of criteria that vary as per the surface water availability and crop area allotted for each crop.

Constraint 1: *Water supply*. Surface water resources are used for various purposes for humankind's benefit such as drinking water, industrial use and agriculture. Agriculture has the lion's share. Thus, water demand depends on the population's size, level of economic development, and local climate conditions. Environmental Flow Release (EFR)s is essential for sustainable water resource management. Therefore, we considered uncertainty in water available as in Eqs. (4)–(8). Chance constrained Linear Programming (CCLP) models were developed by incorporating uncertainty of inflows at exceedance probabilities (ρ) of 90%, 80%, 50% and 10% or (100- ρ) risk probability of 10%, 20%, 50% and 90% [18]. It was assumed that the whole of the water required for crop growth in an agricultural area must be met from the reservoir release of surface water. Therefore, the water allocation amount for each crop cultivated is focussed on the availability of surface water through the canal network of agricultural area.

$$\sum_{i=1}^{n} CWR_{i,m,s} \times A_{is} \le {b_{jm}}^{P_{jm}} \times \gamma \ - CU_p - R_{jm} \tag{4}$$

Where CWR i,m,s denotes crop water requirement for the month m and season s and crop i; γ is the irrigation efficiency; $b_{jm}^{P_{jm}}$ is the surface water supply for the month m and risk constraint j (Mm^3); A_{is} is the area allocated to each crop in season s

$$R_{jm} = \varnothing \times b_{jm}^{P_{jm}} \tag{5}$$

Where R_{jm} is the EFR for a particular month m, risk constraint j and φ denotes the percentage release

$$CU_p = \frac{CWR_{p,m,s}}{\gamma} \times (A_{total} - A_r) \tag{6}$$

Where, A_{total} is the total land irrigated with the available water, A_r is the remaining area after preference crop cultivation; CU_p is the gross water use of preference crop; CWR $_{p,m,s}$ denotes crop water requirement for the month m and season s and crop p

$$\sum_{i=1}^{n} CWR_{i,m,s} \times A_{is} \le F^{-1}(P_{jm}) \ \ \forall i, \forall m \tag{7}$$

$$F(I_m) = P_{jm} \ or \ F^{-1}(P_{jm}) = I_m \tag{8}$$

Where F is the cumulative distribution function; P_{jm} is the risk probability for risk constraint j and month m; I_m is the inflow for month m.

$$Pr\left[\sum_{i=1}^{n} (CWR_{i,m,s} \times A_{is}) + R_m \le I_m\right] \ge 1 - P_{jm} \tag{9}$$

$$Pr\left[I_m \le F^{-1}(P_{jm})\right] = P_{jm} \tag{10}$$

$$Pr\left[I_m \le {b_j}^{(P_j)}\right] = P_j \tag{11}$$

where P_r is the probability distribution of random variable b_j, $P_j \in [0, 1]$ illustrates the decimal form of acceptable risk of constraint j, thus, the constraint j should be satisfied with at least a probability of $1 - P_j$ or exceedance probability of 1- P_j. Therefore, from the Cumulative Distribution Function (CDF) graph of probability distribution, value of any b_j can be determined with some probability and can be written as in Eqs. (9)–(11).

Constraint 2: *Food and nutrition security*. The fundamental motive of food cultivation is to ensure food security of the region, which is also the centre point for deciding the type of crop to be cultivated. The important purpose for human food consumption is to meet the demand for nutrition along with calorie. Grains, pulses and oilseeds are the primary items for calorie intake and to assure food security of the region [27,28]. Other commodities for food security include vegetables as vegetables are protective foods packed with vitamins, micronutrients, and essential compounds necessary to prevent multiple diseases and ailments. Among the vegetables, tomato, onion and potato are the largest cultivated and consumed vegetables in Indian household [29].

The crop yield should be able to meet the region's food demand every year.

$$A_i \bullet Y_i \ge FD_{iy} \tag{12}$$

$$FD_{iy} = A_{pop} \times FD_i^{percapita} \tag{13}$$

Where A_i is the area of crop i, FD_{iy} is the annual food demand for the local population and is obtained by multiplying the area's population (A_{pop}) and food demand per person ($FD_i^{percapita}$) as in Eq (12) and (13).

Constraint 3: *Available land.* Eq. (14) and (15) implements the practice of crop rotations. Similar cereal crops cannot be grown in sequential seasons in the same amount of land area. The total land is the cultivable command area. However sometimes less area is under cultivation due to insufficient water availability for irrigation. The arable land occupied by one crop in season s should be lower than the surface occupied by this crop during the previous season s. The preference crop (i.e., the crop occupying the major area in existing condition) should not occupy a higher than a specific percentage of the total arable land.

$$A_p = \omega \times A_{total} \tag{14}$$

Where, A_p is the preference crop cultivation area and ω is the percentage of area for preference crop cultivation

$$\sum_{i=1}^{n} A_{is} \leq A_r \tag{15}$$

Where, A_r is the remaining area after preference crop cultivation or depending on the amount of water left for irrigation, A_{is} is the area of crop i in season s.

Constraint 4: *Crop diversification.* To achieve crop diversification, the farmer must grow at least one crop from cereal, pulses, oilseeds and vegetables in an arable land. This constraint assigns specific land area to the perishable crops during different seasons [30, 7] as in Eq. (16) and (17).

$$A_{inm} \leq \mu_{is} \times A_r \ \ \forall inm \tag{16}$$

$$A_{ip} \leq \vartheta_{is} \times A_r \ \ \forall ip \tag{17}$$

Where, A_{inm} represents crops with no government support price or non-Minimum Support Price (non-MSP) crops as they are perishable in nature, and A_{ip} represents the higher benefit priced vegetable crop, μ_{is} and ϑ_{is} are the percentage area for perishable vegetable crops and high-priced perishable vegetable crops.

Non-negativity constraint is given as in Eq. 18

$$A_i \geq 0; A_{inm} \geq 0; \ A_{ip} \geq 0 \tag{18}$$

Taking the constraints described above as a basis, we describe four models that manifest the potential strategies that the farmer can follow for crop diversification scheme (Table 1). Model I correspond to the situation where demand for the preferred crop is satisfied fully by the previous season's cultivation and therefore, meeting food demand of other crops only remains as constraint. This means the farmer will not go for the same preferred crop already cultivated in previous season. Model II corresponds to the cultivation of preferred crop, only when the previous season crop failed due to various unexpected climatic events. Finally, Models III and IV simulate the plan of allowing the farmers to select crop diversification along with preference crops. While Model III goes with the 10% and 20% less EFR flows, Model IV is for the existing condition. To avoid monocropping with preferred crop, cultivation of preferred crop for Model III and Model IV has been restricted by limiting percentage of summer rice to 20%, 40% and 60%. These are named as Scenario-A, B and C respectively under Model III and IV. With advanced optimization packages, LP models can efficiently solve innumerable decision variables and constraints on a standard computer.

2.1.3. Solution method

This section aims to provide the solution method for the IFEC model. The developed model was solved using Microsoft Excel Solver software. The inputs for the software are target cell, changing cell, constraints and the output are the values of area of per crop selected. In addition, maximum runtime, iterations, constraint precisions, tolerance, and convergence for the objective function are also considered.

Table 1
Details of the model types.

	Model I	Model II	Model III	Model IV
Description	Not to meet the preference Arable land <27705 ha At all release	To fulfill the preference as food demand Arable land <27705 ha At all release	To fulfill the preference and environmental flow Arable land 11082–22164 ha Available water 70%, 80% released downstream	To fulfill the preference at the existing release Arable land 11082–22164 ha
Model	Max [f(x)] s.t. all constraints 4–13,15-18	Max[f(x)] s.t. constraint 4–13,15-18	Max[f(x)] s.t. constraint 4-18	Max[f(x)] s.t. constraint 4-18

f is the objective function which represents the net present value and continuous variables x represent the surface of a crop in the arable land in a specific region.

2.2. Environmental footprint family quantification of food products

The "environment footprint family" consists of water, carbon, ecological and material footprints. These modules present an input-output relationship and help to understand better the performance of the above optimization in the face of changing climate and declining resources. Thus, it allows policymakers to ensure environmentally sustainable production and management of resources. Some of the footprints are discussed below and are used in this study. The footprint unit used is expressed in per unit calorie of the product.

2.2.1. Water footprint

The footprint for water (WF) includes blue (irrigation water), green (rainfall), and grey (polluted water) [31]. The study uses the term blue water footprint only, as the effective rainfall during the non-monsoon period is negligible for yield stability. The unit of WF is m^3cal^{-1}.

2.2.2. Carbon footprint

The footprint for carbon (CF) includes all types of carbon emissions from agricultural inputs such as fertilizers, pesticides applied, petrol or diesel consumed, and electricity used. They are expressed as carbon equivalent (CE) [32]. The calculation was performed based on methods, described in Pandey and Agrawal, [33]. Wherever possible region-specific data was used and the unit for CF was kg CE cal^{-1}.

2.2.3. Material footprint

The footprint for material (MF) includes all the input demand for production. Primarily it is the consumption-based indicator for material use [34]. Here in this study, we have considered N, P, and K raw material flows to produce food crops, as because, fertilizer input is one of the vital inputs for crop production. The unit for MF was kg cal^{-1}.

3. Case study

3.1. Study area

The constructed model was applied to the Jamuna command area (JCA), a potential agricultural area in Assam, India. The study area is located in the rainshadow region of Khasi Jayantia -Barail hill ranges, extending from 25°40′N 92°50′E to 26°20′N 93°40′E. The command area fed by Jamuna River, is a sub-tributary of the mighty Brahmaputra River of Assam, India. The study area covers two districts of Assam; Nagaon and Karbianglong. There are 120 villages in the command area. The study area location map is shown in Fig. 3. As per the Jamuna Command area Development Division report, around 90% of the water is released downstream for environmental flows as EFR. Water is diverted through a diversion weir at Bakuliaghat to irrigate a command area of 27,705 ha through main canal, distributaries, minor and sub minor canals.

The study area, receives a relatively lesser average annual precipitation of 117 cm as compared to state average. 80% of rain occurs from June to September while November to February shows drought-like conditions. The annual normal temperature in the command area varies from 27 °C to 33 °C in summer while in winter the temperature varies from 16 °C to 24 °C in winter. The monthly average pan evaporation data is 63 mm. Soils of command area is mainly lateritic soil having fine loamy texture mostly, named by Typic Haplaquepts in the Food and Agricultural Organization-World Reference Base for soil Resources, 4th edition (FAO-WRB) classification

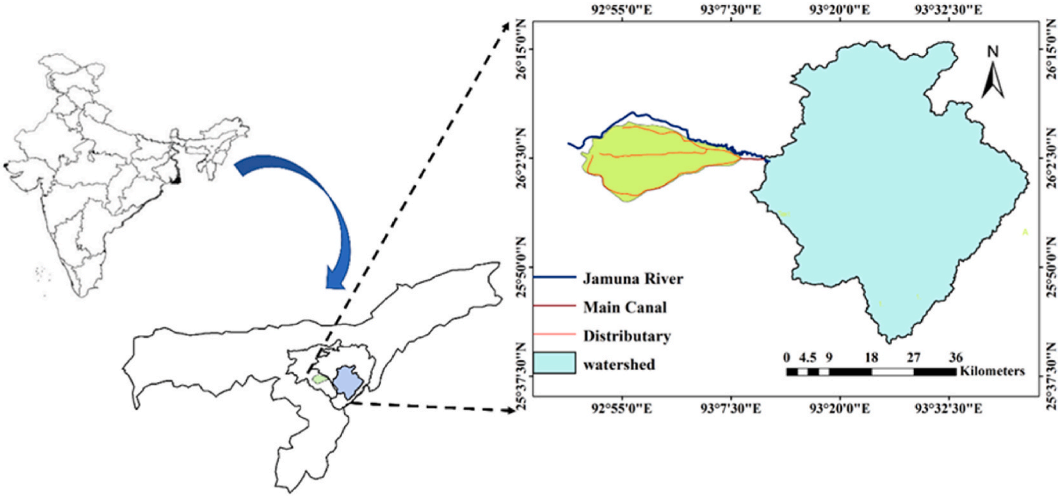


Fig. 3. Location map of study area.

and are deficient in nitrogen, potash and phosphorus supply [35]. Also, there are coarse loamy texture in a few areas (Typic Udifluvents in the FAO-WRB classification). As reported in the Jamuna Irrigation Project report, winter rice is cultivated during kharif season, and land remains fallow in winter and summer after the rice harvest. Farmers apply N, P and K fertilizers for proper growth of rice. With ample water, the government of Assam is encouraged to improve both the land and water productivity through sustainable crop intensification while increasing producers' profit. The study area experiences drought-like conditions and faces water crises occasionally. Therefore, it is mandatory to allocate water in the area to curb water shortage and thus promote intensive agriculture in the rice-fallow cropping system.

3.2. Data collection and processing

3.2.1. Data

3.2.1.1. Water related data. This work considers both the agricultural water demand and environmental flow options. We considered uncertainty in water available for irrigation at the barrage from the expected monthly river flows at 10%, 50%, 80% and 90% probability of exceedance (Fig. S1). The monthly crop water requirement is as shown in (Table S1) at 100% irrigation efficiency [36]. Moreover, as the effective rainfall is insignificant during the rabi season, the crop water requirement is the irrigation water requirement. Further, the irrigation efficiency of the command area is assumed to be 35% [37].

3.2.1.2. Food demand. Foods and water provide the major proportion of humans' total daily intake of trace elements. Household food consumption patterns included mainly carbohydrates, protein, fats, vitamins and minerals. Food items considered in the study are shown in Table 2, and its per capita consumption is shown in Table 3 [38]. In addition to this, rice is the widely grown cereal crop as a source of carbohydrates, covering over 70 % of the total cultivable area of Assam during the kharif season. However, among the four categories of rice viz. Ahu, Sali, Boro and Bao, Boro rice has gained more attention in the last decade because of its superior yield potential and area extension due to potential irrigation facilities in flood plains of the Brahmaputra River during the non-monsoon period [39].

3.2.1.3. Yield related data. Statistics on the production and yield of crops for each year for 17 years (from 2000 to 2016) were obtained from the Directorate of Economics and Statistics, Department of Agriculture & Cooperation, Government of India.

3.2.1.4. Fertilizer data and residual fertilizer. After rice harvest, in November 2016, the residual storage of nutrients was quantified after the cropping season. Total Kjeldahl Nitrogen (TKN) and Available Phosphorus (P_{av}) were measured from the plots after the rice harvest. 13 random villages were chosen in the command area for soil sample collection for N and P fertilizer effect. For each village, three samples were collected and a total of 39 samples were taken. Point soil samples were collected after scrapping away surface litter. Initial N, P status before the cultivation of rice and soil organic carbon percentage after rice harvest are provided in Table S2. A questionnaire survey was conducted for the fertilization management practices by farmers of the respective villages during the year 2016. There are four levels of N and P from the fertilizer input data obtained and from the amounts of N and P present in the Urea and DAP fertilizer. Urea contains 46% of N and DAP constitute 18% of N, 20.2% of P. Accordingly, applied N and P doses were ranked (from rank 1 = low to rank 4 = Very high). Low, medium, high and very high doses for N are 40–60, 61–80, 81–100, 101 kg ha^{-1} and above, respectively, while for P are 0–4, 5–9, 10–19, 20 kg ha^{-1} and above respectively. Field observation was made to validate the information provided by the farmers for the input fertilizer amount. Three soil samples were collected from each village's field at 0–10 cm and 10–20 cm. Samples were air-dried, ground using a wooden pestle and mortar and then passed through a 2 mm sieve to analyze plant-available nutrients. TKN was measured by Kjeldahl method. The Bray and Kurtz method was used to measure P_{av} [40]. Fertilizer data in the form of N, P and K was obtained Department of Agriculture, Government of Assam (Table 4).

In the upper 0–10 cm soil layer, the available N concentration lowered with increased doses up to high doses. It ranged from 54.88 kg ha^{-1} yr^{-1} to 72.03 kg ha^{-1} yr^{-1} for both the layers. For P, the soil nutrient for 0–10 cm and 10–20 cm soil layer ranged from 1.43 kg ha^{-1} to 0.59 kg ha^{-1} and 1.41 kg ha^{-1} to 1.15 kg ha^{-1} respectively. On averaging across two sample depth and thirteen villages, result showed that the value for TKN and P_{av} are 62.14 kg ha^{-1} and 1.13 kg ha^{-1} respectively. Overall, N and P fertilizer application decreased total soil N and available soil P status after rice harvest, however with organic carbon ranging from 1.55% to 0.37%, indicating good soil health (Tables S3) [41]. This soil residual nutrient is deducted from the required N, P amount. The subsidized price of nutrient-based fertilizer for 2015-16 is collected from the Department of Chemicals and Fertilizers, Government of India.

Table 2
Food items considered in the study.

Crops considered	Food Items
Summer rice	bhoja bora chaul, komal chaul (soft rice), hurum, korai, sandah guri, puffed rice, popped rice and flaked rice
Wheat	Broken wheat, flour, chapati
Maize	Corn, yellow corn grains, baby corn, popped maize
Lentil/pulses	Beans (moong bean, chickpea, peas)
Mustard/Oilseeds	Mustard (fresh leafy vegetable, dry seed, seed powder), sunflower,
Vegetables	Tomato, onion, potato, other vegetables

Table 3
Per capita various food consumption in Assam.

Sampled commodity	Average Consumption (g/week)
Rice	2436
Wheat	92
Maize	10
Lentil/pulses	59
Mustard/Oilseeds	44
Tomato	77
Onion	115
Potato	384

Notes: Food demand is calculated using the consumption and population of the JCA.
The population of JCA is as per the census of the villages lying in the command area.
Sources: (Borthakur et al., 2016)

Table 4
Amount of N, P required for crop growth in kg ha^{-1}.

Crops	N	P	K
Wheat	60	20	35
Maize	80	18	33
Lentil	15	15	12
Mustard	60	17	33
Tomato	75	26	50
Onion	120	36	68
Potato	60	44	83

3.2.1.5. Economic data. The net return of the farmers from various crops is obtained by deducting the cost of cultivation of the crops from the gross benefit received by selling the produce (Table S1). The average price prevailing in the nearby mandi (Lanka) market is collected from Agricultural marketing board, Government of Assam. As, horticultural crops, including vegetables, spices, and fruits, are yet to receive the minimum support price; hence, these crops' prices fluctuate according to the market demand. However, for cereal and many other non-perishable crops, a Minimum Support Price (MSP) is fixed yearly by the Commission for Agricultural Costs and Prices (CACP) based on the agricultural production cost. MSP assures farmers fair price to farmers; in case the market price falls below the threshold. MSP, market price and cost of cultivation of crops were obtained for 2015–2016. The cost of cultivation was obtained from Department of Agriculture and Farmers Welfare, Government of India.

Table 5
The results of net economic benefit for various models and Scenarios in million (M) ₹

Probability	Release	Model I	Model II	Model III			Model IV		
				Scenario A	Scenario B	Scenario C	Scenario A	Scenario B	Scenario C
0.1	70%	5986.80	5677.90	4803.45	3620.62	2437.56			
	80%	5986.80	5677.90	4803.45	3620.62	2437.56			
	90%	5986.80	5677.90				4803.45	3560.64	–
0.5	70%	5986.80	5677.90	4803.45	3620.62	2437.56			
	80%	5986.80	5677.90	4803.45	3620.62	–			
	90%	5986.80	–				4707.21	–	–
0.8	70%	5986.80	5677.90	4803.45	3620.62	2437.56			
	80%	5986.80	5677.90	4803.45	3620.62	–			
	90%	5986.80	–				4007.31	–	–
0.9	70%	5986.80	5677.90	4803.45	3620.62	2437.56			
	80%	5986.80	5677.90	4803.45	3620.62	–			
	90%	5881.37	–				3231.23	–	–

Notes: -*Denotes insufficient water for crop diversification water demand.
a Model I denotes not to cultivate preference crop.
b Model II denotes to fulfill the preference crop as food demand.
c Model III denotes to fulfill the preference crop and environmental flow.
d Model IV denotes to fulfil the preference crop at existing release.

4. Results and discussion

4.1. Model solution

The IFEC Model I have 7 decision variables and 240 equations, whereas Models II, III and IV each contain 8 decision variables while 272, 180 and 60 equations respectively. Solution time for each models varied according to the instance being solved.

The optimization model was executed by considering area variations in the non-MSP priced or vegetable or perishable crop cultivation area such as 10 %, 20 %, and 50 %. Accordingly, vegetable crops area ranges from 20 % to 90 % and high-priced vegetable crop (tomato) ranges from 10 % to 55 %. As, for, fulfilling food demand which is the principal aim of each model, the farmer requires only 1.25 % of the area to be cultivated for non-MSP priced crops. Apart from this, allowable mining for surface water for irrigation, after allowing for 80 %, 70 % EFR, more from existing release, was executed. These deviations were considered around the existing to create a more practical model. Further, all these deviations were made after the considerable area is utilized for the cultivation of preference crop. It implies growing summer rice every year in a part of the area, summer rice as a food crop (summer rice demand as food intake in the command area), and when no summer rice is cultivated (rice demand as food intake in the command area is already met by winter rice). Such consideration will help decide the amount of surface water that could be utilized for irrigating the crops.

The solution of each CCLP optimization model is given by an optimal cropping plan that maximizes the farmer's net benefit in the command area. Additionally, water, as a source of natural capital, provides for human basic needs and development activities. Therefore, the solution to the model in a way also helps to maintain the riverine stability, health, and productivity. The optimal cropping plan is when the local farmers also meet the farmers' preference for food crops in the rabi season. The resulting total net returns for the command area in each scheme are shown in Table 5. As observed in Table 5, the farmer's net economic return varies for each model and scenario. Further, the optimal cropping plans under different risk probabilities and EFRs for each model are detailed in Table 6 and Table S4-S6. Among all the models, farmers' net benefit is largest in Model I in all releases followed by Model II except at existing releases at even 0.5 probability (Table 5). This is because more profitable crops occupy the larger area in Model I, with the available water in the command area than in the other models. In other models except Model I, some part of the area is fixed for cultivating the summer rice. Cultivating summer rice in some fixed part of the arable land, gives lesser profit and more water consumption. Among the models, Model II shows that vegetable crops occupy a major area of 27% after summer rice due to higher revenue generated from the crop. And least benefit was observed for Model IV Scenario C (IVC) as 60% of the area is allocated for less benefit, summer rice crop. This suggests that the preference crop introduced in the command area might not be economically sustainable. Overconsumption of water leads to no-water- left for other crop cultivation even if land is available. This is in line with the report by Ref. [42] which showed that crop diversification reduced irrigation amount by 43%. Hence, the farmer's economic net return per hectare is more prominent in Model I, suggesting that not cultivating the preferred crop at all, is the best one. Also in Model II, due to more than 35% of the area under summer rice and higher water consumption by summer rice, insufficient water prevailed in most probabilities of water level except in high flow levels.

Also, in case of deviation in EFR, Model III Scenario C (IIIC) shows scarce water for irrigation, even at 80 % EFR. On the other hand, Model IV, which is at 90% EFR, Scenario B and Scenario C, shows insufficient water except at high flows for Scenario B. However, for Scenario A, water is sufficient even at the current EFR of 90%. It is important to note that the above solution differs due to the amount of water that is left after cultivation of summer rice. Initially the water available for irrigating the command area is same for all models and scenarios. This suggests that choosing Scenario A is ideal for irrigation of the command area under existing condition, at all exceedance probabilities, which has 20% of agricultural area under summer rice.

As shown in Table 6 and Fig. 4(a and b), no area (Model I) or only food demand area (36.6%) (Model II) is under summer rice cultivation in the cropping plan. In Model I, lentil, mustard, and onion occupy 3, 2 and 0.3 % respectively, for different exceedance probabilities and all EFR except under 0.9 probability and 90% EFR. The area for wheat and maize changes to 27 % and 18.5 % from 1.5 % to 44 %. Also, with a declining water level at 80% EFR and 0.5 probability, area under tomato and potato slightly reduces from

Table 6
Cropping pattern at 80% exceedance probability and 80% and existing release in ha.

Crops	Model I	Existing	Model II	Existing	Model III			Model IV (existing)		
				–	I	II	III	I	II	III
Rice			10150	–	5541	11082	16623	5541	11082	16623
wheat	415	415	415	–	415	415	–	415	–	–
maize	12145	12145	1995	–	9375	6604	–	32	–	–
lentil	797	797	797	–	797	797	–	797	–	–
Mustard	495	495	495	–	495	495	–	495	–	–
Tomato	6927	6927	6927	–	5541	4156	–	5269	–	–
Onion	86	86	86	–	86	86	–	86	–	–
Potato	6840	6840	6840	–	5455	4070	–	4187	–	–

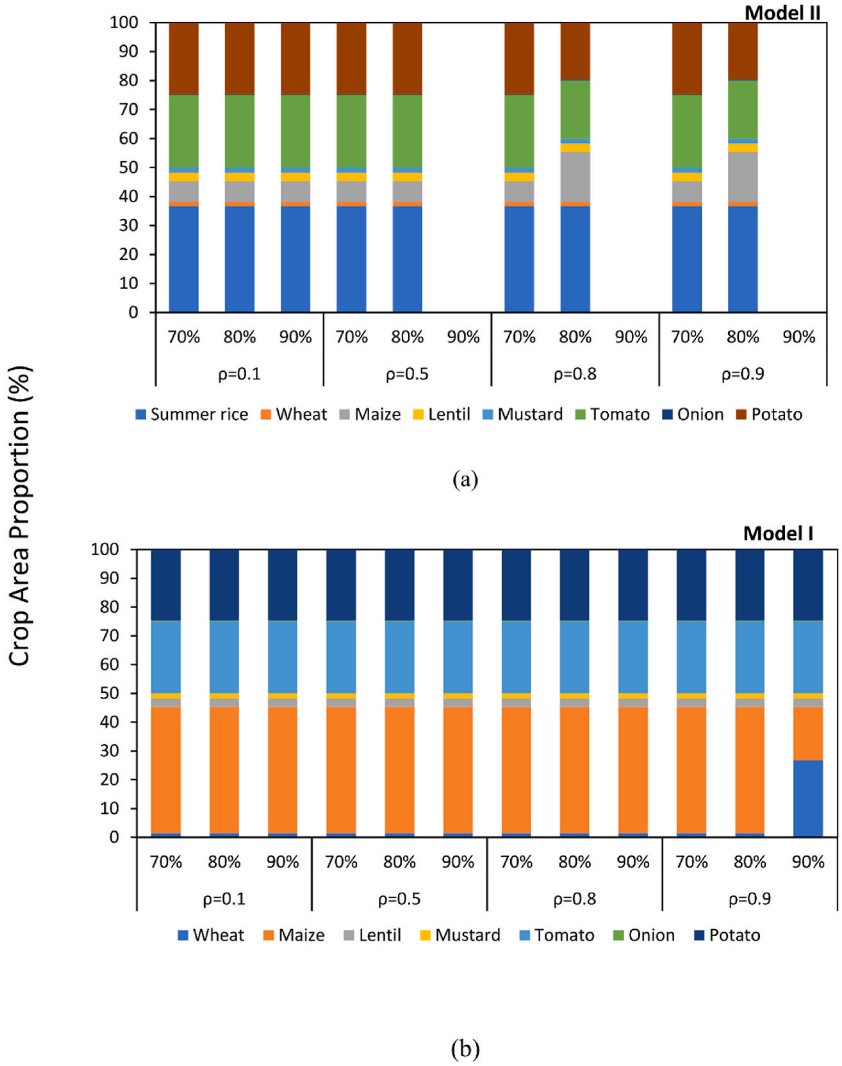
Notes: -*Denotes insufficient water for crop diversification water demand.

a Model I denotes not to cultivate preference crop.

b Model II denotes to fulfill the preference crop as food demand.

c Model III denotes to fulfill the preference crop and environmental flow.

d Model IV denotes to fulfil the preference crop at existing release.



(a)

(b)

Fig. 4. Optimal cropping plan in percentage in JCA for arable land under different releases for all probabilities in (a) Model I (no summer rice) and (b) Model II (summer rice as food demand) Note: ρ denotes exceedance probability.

25 to 20 %, 24.7 to 19.7 %, respectively. Results showed that vegetable crops that require less water and have more profit, occupied a largest area of cultivation than the vegetable food demand area of the arable land [43]. Thus, along with variation in available water, crop area would vary. Such changes would mainly occur in vegetable and cereal crops especially wheat, which have similar features with higher yield and relatively less crop water requirement as compared to maize. Zhong et al. [44] reported in his study that production of maize during monsoon season and fallowing the winter would save a significant amount of water and prevent groundwater depletion. The whole arable land dedicated to producing crops for the food security of the command area year (0.15% cultivated with tomato and 0.78% potato) can be grown in much excess, provided there is import of such crops by the government.

The optimal cropping plans in the command area for Scenario A, Scenario B and Scenario C are shown in Fig. 5(a–c). In all these models, the optimal cropping pattern for scenarios A, B and C include planting of summer rice fixed at 20 %, 40 % and 60 % of the area. As observed in Fig. 4, the cropping plan maximizes more cereal and vegetable crops. However, cropping plan is changed at existing condition, for Scenario A, due to insufficient water even at 0.5 exceedance probability. Mustard and wheat crop is planted at 17 % and 8 % compared to 1.5 % and 1.8 % in other EFR. Further, at the existing condition for Scenario A, with further decline in water level at 0.8 probability, area of these crops is devoted mainly to satisfying the local food demand. It is worth noting that, optimal use of cultivating area by models is dependent on the yield and its corresponding irrigation water required to first meet the food demand of localities. Hence, the rest of the arable land remains fallow due to water insufficiency. Practical implementation of this suggested optimization results could be obtained primarily through improving and expanding water infrastructure and land management for increased efficiency. For increasing field irrigation efficiency, techniques such as border irrigation and surface levelling, must be adopted for maximum usage of available water. For instance, as the extent of boro rice/summer rice cultivation area increases, the

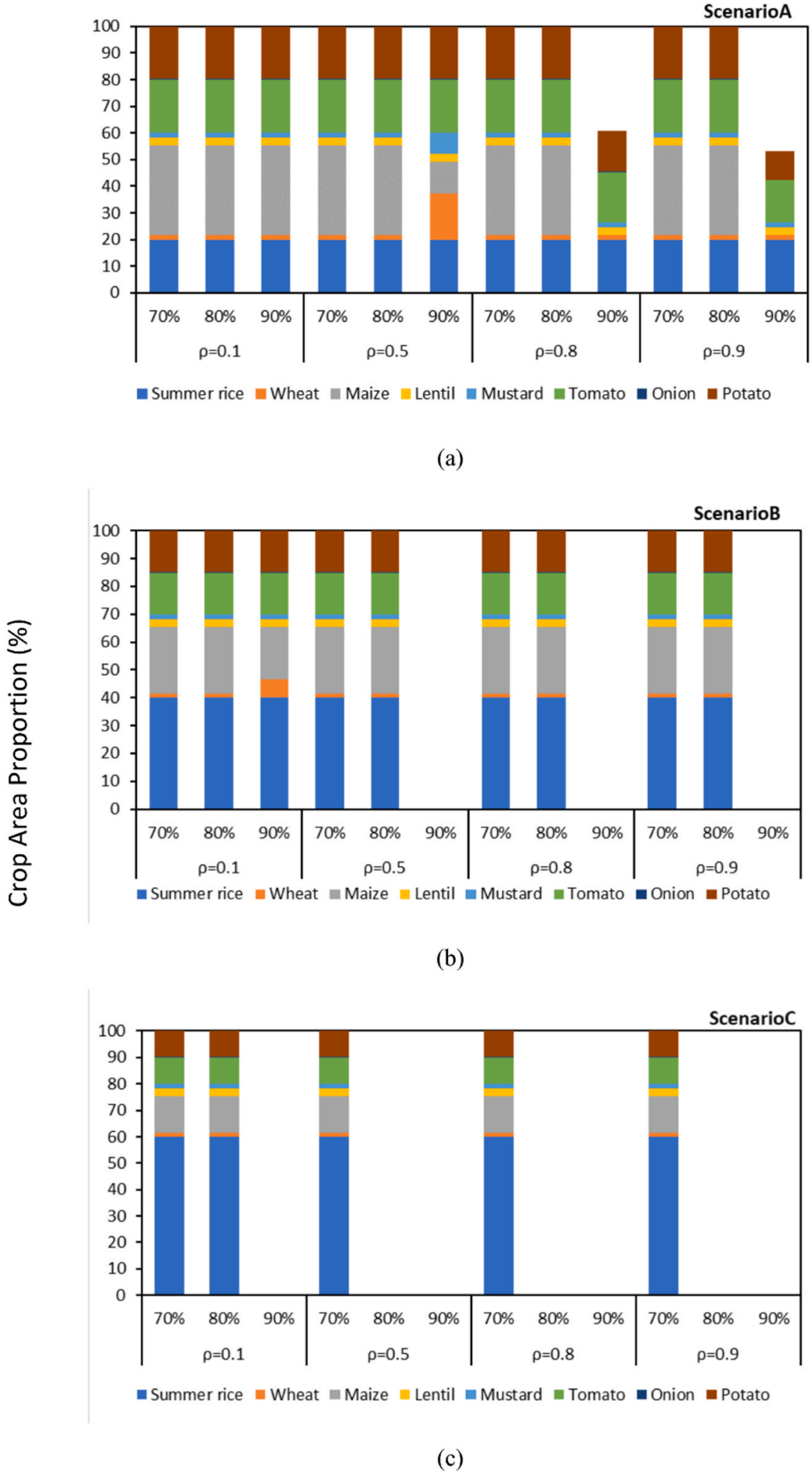


Fig. 5. Optimal cropping plan in percentage at JCA for Model III and Model IV under different releases for all probabilities for (a) Scenario A (Summer rice area = 20%) (b) Scenario B (Summer rice area = 40%) and Scenario C (Summer rice area = 60%). Note: ρ denotes exceedance probability.

planting area of other crops decreases with more water consumed for growing summer rice crop. For example, tomato and potato crop in Scenario A, Scenario B and Scenario C decrease as 20 %, 15 % and 10 %; 19.7 %,14.7 % and 9.7 % respectively. Further, the area of maize also reduces 33.8 %, 23.8 % and 13.8 % respectively for Scenario A, Scenario B and Scenario C. It is to be further noted that at 0.9 probability, it includes 10% risk for water supply for irrigating the crops. Hence, in the situation of chronic water scarcity problem, a decision maker would choose the cropping pattern according to this scenario though the economic benefit would be lesser. Therefore, to achieve more profit a decision maker would ultimately select for probability 0.5 or up to 50% risk. However, an optimistic one would choose more larger risk depending on the local condition and preference prevailing.

4.2. Water allocation and EFR sensitivity analysis

In field conditions, water usage in most systems in India varies between 30 and 40 % [45]. With better irrigation systems, India can dent the water demand surge by almost 70 %. Further by increasing irrigation efficiency, the total water demand by 2050 can be 8% lower than the current water withdrawals recorded for India [46]. The result clearly demonstrates the amount of water used for irrigation considering land and water available. Except for 70 %, the water used for all other releases is 522 Mm^3 and covers only 60 % of land due to water unavailability on account of overconsumption, in Scenario C. To further elucidate these results, the maximum possible annual water use of 593.4 Mm^3 for Scenario C was calculated for the command area as the sum product of cultivated crops and water used per ha for each crop selected in the scheme. Moreover, the least water used for the Model I considered, uses only 10–20 % of the water available whereas Scenario C would use highest of 30–64 % at 70 % EFR. Similarly for Scenario A at existing condition, all water is used for satisfying food demand and rest of the area remains fallow due to insufficient water. At the existing release, Model I consume 185 to 167 Mm^3 while for Model II, water available at the existing condition is insufficient even at 0.5 exceedance probability. Model IV Scenario A consumes 321 to 239 Mm^3 while water is inadequate for Scenario B and C except at 0.1 exceedance probability or high flows, for Scenario B. From the results it can also be suggested that identification of the potential groundwater resources is essential for irrigation adequacy in such a canal command area along with increasing efficiency by various techniques [47].

In the present condition, EFR is 90 % of the river flow. Reduction in EFR by 10 % and 20 % from the present condition for each exceedance probability showed that the net benefit would many times increase. For high flows, however, the benefit was the same for each release for Scenario A. The benefit at the existing release for Scenario A and B increased with an increase in water availability. The R^2 value was 0.75 and 0.77 respectively for Scenario A and B respectively. On average benefit was less by around ₹ 3265 M for Scenario B as compared to Scenario A. Complying with the preference rules up to 60 % area would decrease the profit up to 49% as compared to 20% area in existing condition at even 10% risk (Fig. 6). However, in other models and scenarios, except Scenario C, the benefit was same for 70 % and 80 % EFR. This reduction in EFR from the existing condition would increase the profit ranging from ₹ 3577 M to ₹ 96 M in various models and scenarios. The model selects the cropping area of each crop keeping in view water availability in such a way to satisfy the model constraints while maximizing the total benefit of the farmers. Adequate water for cultivation and more irrigated area coverage provides greater profit. Lesser EFR, compared to existing conditions, results in more crop area and more profit for farmers. It was also reported by Jägermeyr et al. [23], that, globally 41 % of irrigation water consumption occurs at the cost of EFRs, meanwhile, water use stakeholders for irrigation supply found that the increasing environmental flows would reduce the area of irrigated agriculture and its farm income.

4.3. Crop diversification under various perishable horticultural crop area

We executed the IFEC model with fixation in perishable horticultural crops area ranging from 20 % to 90 % and high-priced vegetable crop (tomato) from 10 % to 55 %. In Model I, the tomato crop is the largest cultivated crop with 25 % of the area. In Model I, if no area constraint is applied for high priced vegetables and other horticultural crops, the benefit is estimated to be maximum around ₹14027 M. However, as the area constraint is given there is a loss. And the loss increases from approximately 23 %–79 % for all releases and risk probabilities. Similarly, for Scenario A when sufficient water is available the profit is more as more area is available for vegetable cropping.

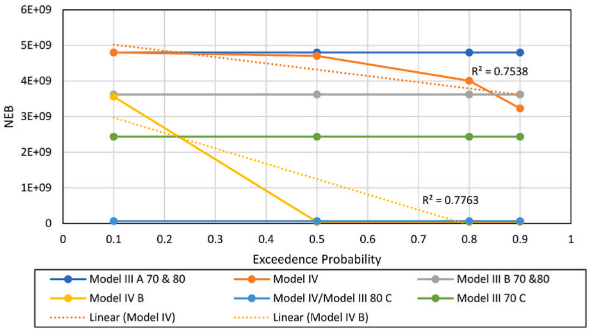
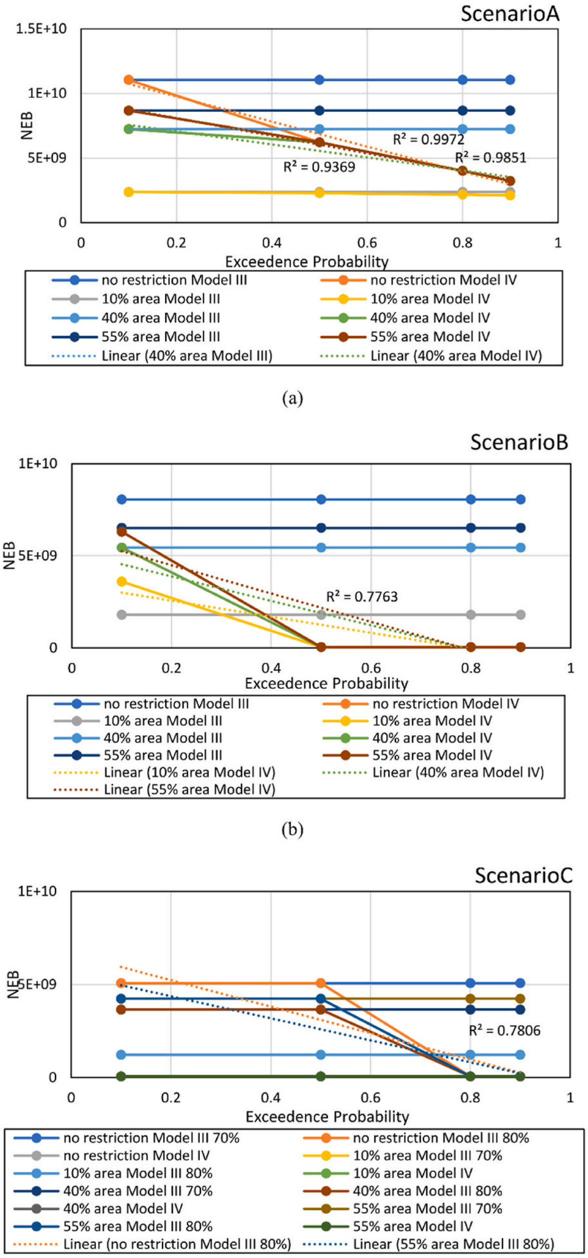


Fig. 6. Plots showing the benefit obtained for Model III and Model IV under different releases for all probabilities and Scenarios.



(a)

(b)

(c)

Fig. 7. The plot depicts the benefit obtained due to variation in high priced vegetable crop (tomato) for (a) Scenario A (b) Scenario B (c) Scenario C at JCA for Model III and Model IV under different releases for all probabilities.

For example, at 0.8 exceedance probability and 80 % EFR, for Scenario A as shown in Fig. 7(a), around 21 %–79 % loss is incurred as the area of high-priced vegetables reduces from 55 % to 10 %. Also, for Model IV loss is maximum for 0.5 exceedance probability which is up to 64 % as the area under high priced vegetable crop reduces. For Scenario B, depending on water availability loss ranges from 10 % to 76 % at 0.8 exceedance probability of 70 % and 80 % EFR. For scenario C at 70 % EFR release and 0.9 exceedance probability loss ranges from 17 % to 77 % (Fig. 7(a–c)). At existing condition, the R^2 value between water availability risk and benefit is 0.95, 0.78, 0.78 respectively for Scenario A, B and C. In general, as the cultivation of preference crop area increases, the area for vegetable cropping reduces and further reduction occurs when the water availability is less. Studies showed that because of the dearth of irrigation systems in dry tropics cultivation of horticultural crops is reduced during the dry season due to water unavailability to fulfil the water requirement [48,49]. Therefore, the inclusion of vegetable crops for crop rotations involves not only appropriate farm land management to improve the sustainability of agriculture for maximum water utilization [50] but also provides higher benefit to farmers. Thus, this strategy benefits the producer, in the face of water stress under climate change and population growth [9]. An increased cultivation of vegetable crops rather than subsequent cereal mono-cropping, saves water for more area to be cultivated along with increase in yield of perishable, non-MSP priced crop and benefit of farmers., It is also worth noting that, human food consumption globally not only demands for quantity but quality as well. Vegetables are protective foods packed with vitamins, micronutrients, and essential compounds necessary to prevent multiple diseases and ailments. Despite, all of the advantages, this fact cannot be denied that, vegetable crops are more sensitive to soil and environmental factors such as soil type temperature, humidity and their cultivation involves lot of risk for farmers [51]. Further even after a good yield by outweighing the risk, surplus production might lead to the wastage of crops due to lack of minimum support price and proper market access. In addition to this vegetable marketing facility is subjected to fluctuation depending on supply-demand ratio. This attracts less attention of farmers for vegetable cultivation. Kumar et al. [52], reported that 92.5 % of the farmers avoid vegetable cultivation due to the lack of proper product marketing facilities. Thus, it can be noted that this multiple cropping with major area covered under vegetable crops can only be achieved if the government fixed a yearly minimum price or other financial support for such type of crops.

4.4. Footprint analysis and comparison with NEB

For the footprint measurement, Indian specific data was used. Full details for CF measurement are provided in Sah and Devakumar, [53]. The range is 2.3-1.1 kg $\text{cal}^{-1}*10^{-3}$, 580.6–167 $\text{m}^3\ \text{cal}^{-1}$,445.3-174.3 kg CE cal^{-1} for MF, WF and CF respectively for the various optimal cropping patterns under each circumstance. Results showed that when profit was more, WF was found to be least whereas CF was highest, and MF was somewhat more (Fig. 8). This is because, the crops, tomato and maize show high CF and MF (Table S7). For instance, in Model I at existing condition the profit was ₹ 5881 M, the MF is 1.8 kg $\text{cal}^{-1}*10^{-3}$, whereas for Model IV Scenario B (IVB), the profit is least of ₹ 43 M, as water is insufficient for other crop cultivation except summer rice, the MF and CF is also least at 1.08 kg $\text{cal}^{-1}*10^{-3}$ and 174.33 kg CE cal^{-1} but WF was up to 339 $\text{m}^3\ \text{cal}^{-1}$. This implies rice requires more water giving less benefit to farmers. Model III Scenario C (IIIC), shows significantly less profit of ₹ 2437 M even after crop diversification and highest WF and MF of 581 $\text{m}^3\ \text{cal}^{-1}$ and 2.3 kg $\text{cal}^{-1}*10^{-3}$ respectively. CF is 439.5 kg CE cal^{-1}. Similarly, lentil is a carbon-intensive and less profitable crop. However, with a positive note, legume–cereal rotations are also known to enhance soil fertility in subsequent cereal crops [54]. Furthermore, though onion is a profitable crop, it is a water-intensive crop. Lastly, the overall environment footprint analysis result of other studies indicated that water, economy and carbon trade-offs must be addressed for sustainable multiple crop cultivation [55,56].

Based on the analysis performed, the developed IFEC model has shown positive and crucial impact on the overall agricultural sustainability. The model developed can beneficially utilize the fallow land resources after rice harvest for local food and nutrition security and maximize the economic benefit of farmers while lowering the fertilizer cost, which has more advantages over the work by previous researchers. However, command area consists of fragmented land holdings and majority of the farmers are marginal or smallholder who cannot invest in improved seed or fertilizer. Further, the practical implementation of irrigated farming in any command area depends on the farming community's participation with irrigation water suppliers. The sowing and harvesting time of the crops in whole command area is compatible for equitable distribution of water. Further, automation of the components of the irrigation system helps to avoid any discrepancies in water release at various water demand stages of crops. In addition to this, as we do not have appropriate information on the market demand of perishable crops, it is assumed that all the harvested will be completely sold or transferred to cold storage areas to be finally sold in local market.

On the other hand, in real-world problems, river flow is not stable and complex problem. Hence allocation of irrigation water is a tough problem. The developed model can solve such problem by focusing on the risk associated with varying flows in river. It has an influential effect on the irrigation supply and agricultural sustainability of Jamuna command area, which has a drought problem. The developed model is integrated with CCP to capture the flow uncertainty of the river. A series of optimal cropping pattern schemes were generated using the model under the different extent of risk associated with the availability of water for supply of irrigation water using the IFEC model. Thereby it will provide the decision-makers to visualize the schemes and make robust decision in selecting the cropping pattern for irrigation in dry season. Therefore, IFEC model is a precise tool for decision making process to ensure livelihood to the farmers and regional food security of the similar command area facing drought-like conditions.

5. Conclusions

This study developed an IFEC model that optimizes cropping patterns under different risk probabilities, maintain EFRs and preference crop cultivation area, along with maximizing the net return for the fallow period in rice-fallow cropping system. Our model allows for decision support for intensive cultivation while considering the residual fertilizer from the antecedent cultivation. This study evaluated three preference crop area (Scenario A, Scenario B, and Scenario C) for the best cropping plan. Higher profit shows the best cropping choice under available water. Hence, a suitable optimization approach must be chosen by water managers based on the nature of the problem to get an optimal solution. The proposed optimization model was optimized incorporating cropping area variation of perishable and high-priced vegetables ranging from 10 % to 55 % and 20%–90%. Further the EFR reduction of 10 % and 20 % was considered during the optimization process. The experimental results showed that increasing the vegetable cultivation area and decreasing the area of summer rice increases the crop net return along with sustainable use of surface water resources. Expanding the existing system is necessary to improve the operational management of the irrigation system while establishing an adequate infrastructure to ensure sufficient water among farmers. For each model and scenario, a profitable crop area cultivation was determined, making the preference crop cultivation practically less appealing. The study highlighted the need that, governments should take the opportunity for specific subsidies to be defined for marketing of vegetable crops and ensure agricultural practices by farmers that

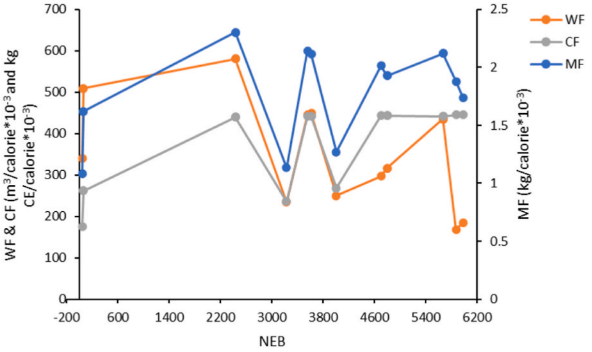


Fig. 8. Impact of water, carbon, and fertilizer availability on NEB. *Note: NEB means Net Economic Benefit, WF means Water Footprint, CF means Carbon Footprint and MF means Material Footprint.

would foster adaptation and mitigation under changing environments while maintaining the country's rural household food security and economic growth. By allowing the smallholder farmers to be aware of the benefits associated with each water availability risk scenario, they can accordingly plan to avail the crop insurance themselves. Environmental footprint analysis also showed higher profit with less water footprint of vegetables. Tradeoffs between water, economy, and carbon emission for crop cultivation can be addressed and accordingly, crop diversification can be modified suitably to sustain food production under changing environments.

The development of such an optimization model allows for managing socio-economic requirements efficiently and ensures the sustainable supply of water. The proposed model applies to different areas with similar problems of rice-fallow by calibrating the model for new locations. However, the solution provided is based on the water availability explicitly and not on other factors such as the availability of quality seed, fertilizer, fencing from stray cattle, and the risk associated with them. Also, there is no agronomic limitation, to crop diversification, and no work limitation in operating the farm machinery equipment considered. Future studies for the developed IFEC model could consider various scenarios such as minimizing carbon emissions and water use. In addition to this, the model could be extended by the construction of a constraint for the IFEC model that involves environmental footprint and its various pressure indicators, which might give more robustness to the developed model in a changing environment while providing climate change risk assessment to the small farmers.

Funding

The authors did not receive support from any organization for the submitted work.

Data availability statement

The data used in this study are included in article and supplementary.

CRediT authorship contribution statement

Mridusmita Debnath: Writing – original draft, Methodology, Investigation, Data curation. **Arup Kumar Sarma:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Chandan Mahanta:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

We are grateful to the staff members of Jamuna Command Area Development Division for providing the preliminary information regarding the command area for field sampling assistance in the study area and collection of secondary data. We are also grateful to the farmers of the study area for actively participating in this study.

Appendix

List of symbols and abbreviations.

Nomenclature/Symbols

NEB_t	Net Economic Benefit at time t
R_s	Revenues generated at season s
CC_s	Cultivation costs for season s
Y_{is}	Yield of crop i for season s
P_{is}	Price received by the farmer in the market for crop i for season s
A_{is}	Area allocated to each crop in season s
FC_i	Fertilizers cost for each crop i
RF_{s-1}	Residual fertilizer from previous cultivation
$F_{total,i}$	Total fertilizer required for crop i
P_{sub}	Subsidized price of fertilizer
R_m	EFR for month m
P_{jm}	Risk probability associated with inflow for risk constraint j and month m
I_m	Inflow for month m
R_{jm}	EFR for month m and risk constraint j
P_r	Probability distribution of random variable
b_j	Random variable of river inflow
$b_{jm}^{P_{jm}}$	Surface water supply for the month m and risk constraint j
$CWR_{i,m,s}$	Crop water requirement for the month m and season s
R_{jm}	R is the EFR for a particular month m and risk constraint j
γ	Irrigation efficiency
$\varnothing$	Percentage release of EFR
CU_p	Gross water use of preference crop
$CWR_{p,m,s}$	Crop water requirement for the month m and season s and crop p
FD_{iy}	Annual food demand for the local population
$FD_i^{percapita}$	Annual food demand per person
A_{pop}	Area's population
A_{total}	Total agricultural area
A_r	Remaining area after preference crop cultivation
ω	Percentage of area for preference crop cultivation
A_p	Area for preference crop
A_{inm}	Area of crops having no government support price
A_{ipt}	Area of higher priced vegetable crop
μ_{is}	Percentage area for perishable vegetable crop
ϑ_{is}	Percentage area for high-priced perishable vegetable crops
₹	Rupees

List of Abbreviations

IFEC	Irrigation-Food-Environment-Chance-constrained Programming
CCLP	Chance-Constrained Linear Programming
SDG	Sustainable Development Goal
EFR	Environmental Flow Release
WF	Water Footprint
CF	Carbon Footprint
MF	Material Footprint
JCA	Jamuna Command Area
MSP	Minimum Support Price

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.heliyon.2024.e28404.

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