Hybrid optimization model for conjunctive use of surface and groundwater resources in water deficit irrigation system

Karthikeyan Moothampalayam Sampathkumar*, Saravanan Ramasamy, Balamurugan Ramasubbu, Saravanan Karuppanan and Balaji Lakshminarayanan
Centre for Water Resources, Anna University, Chennai, India
*Corresponding author. E-mail: mskerode@gmail.com, msk@annauniv.edu

ABSTRACT

The increasing demand for food production with limited available water resources poses a threat to agricultural activities. Conventional optimization algorithm increases the processing stage and it performed with in the space, which is allocated from user. Therefore, the proposed work is utilized to design with better performance results. The conjunctive allocation of water resources maximizes the net benefit of farmers. In this study, a novel hybrid optimization model developed is first of its kind to resolve the sharing of water resources conflict among different reaches based on a genetic algorithm (GA), bacterial foraging optimization (BFO) and ant colony optimization (ACO) to maximize the net benefit of the water deficit Sathanur reservoir command. The GA-based optimization model considered crop-related physical and economic parameters to derive optimal cropping patterns for three different conjunctive use policies and further allocation of surface and groundwater for different crops are enhanced with the BFO. The allocation of surface and groundwater for the head, middle and tail reaches obtained from BFO is considered as an input to the ACO as a guiding mechanism to attain an optimal cropping pattern. Comparing the average productivity values, Policy 3 (3.665 Rs/m³) has better values relating to Policy 1 (3.662 Rs/m³) and Policy 2 (3.440 Rs/m³). Thus, developed novel hybrid optimization model (GA-BFO-ACO) is very promising for enhancing farmer’s net income and can be replicated in other irrigated regions to overcome chronic water problems. The productivity value of policy 3 was 6.54% greater than that of policy 2, whereas that of policy 1 was 6.45% greater. Overall, the comparison shows the better performance analysis of various optimization is done successfully.

Key words: ant colony optimization, bacterial foraging optimization, conjunctive use, cropping pattern, genetic algorithm, hybrid optimization, productivity

HIGHLIGHTS

- Conjunctive use.
- Cropping pattern.
- Genetic algorithm.
- Bacterial foraging optimization.
- Ant colony optimization.
- Hybrid optimization.
- Productivity.

INTRODUCTION

Population increase and demand for food resources impose a serious threat to water resources, as a 60% increase in food requirements is expected in 2050 (Yearbook F. A. O. S 2013). Climate change increases rainfall intensity and reduces the number of rainy days in a year, which leads to floods and droughts without proper management of available rainfall, which poses a risk to human lives (Jongman et al. 2014). In many developing nations, 90% of water withdrawn for irrigation purposes and extraction of groundwater of approximately 15–35% for irrigation are assessed as unsustainable (World business council for sustainable development 2006). Nutrient poor- soil, water stress and deteriorating water resources are among the cognitive factors to low crop productivity (Araya et al. 2021). Conjunctive use of surface and groundwater in an irrigation system should be taken up to avoid drawdown of groundwater levels and to avoid water stress. The main purpose of the conjunctive use of available water resources is to increase the yield and reliability without compromising supply (Singh et al. 2016).
The key benefits of conjunctive use are maximizing the net return by minimizing the water stress of the crop. It is necessary to use a suitable cropping pattern that maximizes the net profit for the available conjunctive water. The optimal allocation of surface and groundwater resources in different cropping seasons of the year is crucial for conjunctive planning (Singh 2014). Different programming methods have been used in the optimization of the conjunctive use of surface and groundwater for irrigation planning and have been discussed extensively in (Singh et al. 2016). Previous studies that examined different programming techniques in the optimization of conjunctive use are linear programming (Tyagi & Narayana 1984; Khare et al. 2007), non-linear programming (Matsukawa et al. 1992; Vedula et al. 2005), and dynamic programming (Benedini 1988; Karamouz et al. 2004). However, the inability to attain a global solution and handle nonlinear non-convex problems requires a heuristic approach. This research contributes to increase the performance of hybrid optimization over traditional optimization. The convergence speed of optimization is improved on the global search and major function of swarm.

Genetic algorithms (GAs) have been used in several studies to solve the non-convex problem to attain a global optimal solution in conjunctive use. Some of the key studies that employed a heuristic approach in the optimization of conjunctive resources for maximize net benefit are listed in Table 1.

However, as discussed in the literature, much of the early work centers around the comparison of meta-heuristic algorithm performance in the optimization of cropping patterns that maximize the net benefits of farmers. In this study, a novel hybrid optimization approach was employed for the conjunctive use of surface and groundwater to maximize economic benefits by optimizing cropping patterns. Considering the effectiveness of meta-heuristic algorithms, a hybrid optimization model

| Citation                  | Optimization Method/Algorithm                                      | Inference                                                                                                                                                                                                                                                                                                                                 |
|---------------------------|-------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Varade & Patel (2018)     | Jaya algorithm and Particle swarm optimization                    | Net annual returns improved by 76 and 78% for PSO and Jaya algorithm respectively from the existing cropping pattern also water allocation reduced by 39% for PSO and Jaya algorithm.                                                                                                                                                                                                 |
| Kumar & Yadav (2019)      | Elitist Jaya algorithm (EJA) and Elitist teaching learning-based optimization (ETLBO) | EJA was found to be a better algorithm when compared with ETLBO, JA, TLBO, and Linear programming (LP). For maximum cropping pattern net benefit results of EJA perform better than LP, ETLBO, TLBO, and JA as 8.33%, 0.04%, 0.58%, and 0.002% respectively.                                                                                                                                 |
| Kumar & Yadav (2020)      | Self-adaptive multi-population Jaya algorithm (SAMP-JA)           | SAMP-JA was compared with PSO, DE, JWO, FA, TLBO, JA, elitist-JA and elitist-TLBO. Net annual benefits were found the same for SAMP-JA and EJA. The rate of convergence was found better in SAMP-JA than EJA.                                                                                                                                                                                                 |
| Rath et al. (2019)        | Cuckoo Search algorithm                                          | The cropping pattern suggested by cuckoo search increase the net benefits by 33% and LINDO provides a 21% increment than the existing cropping pattern.                                                                                                                                                                                                                                                                  |
| Rath & Swain (2018)       | Linear programming (LP), Genetic algorithm (GA), Cuckoo search (CS) and Particle swarm optimization (PSO). | The maximum net return found by PSO optimized cropping pattern results in 230.120 billion rupees whereas GA, CS and LP produce 210.19 billion rupees, 229.895 billion rupees and 199.271 billion rupees respectively. The optimized cropping produced from swarm techniques results in 97.92 billion rupees more than the existing cropping pattern.                                                                                                                                 |
| Mohammadrezapour et al. (2019) | Cuckoo optimization algorithm (COA) and Genetic algorithm (GA) | COA algorithm performs better than GA in terms of net benefit and low water consumption. The net profit increased by 1.48%, 1.27%, 2.6%, 6.2% respectively in hot-dry, dry, normal and wet conditions.                                                                                                                                                                                                 |
| Safavi & Falsafioun (2017) | Genetic algorithm (GA)                                           | Conjunctive use of surface and groundwater resources is optimized using a genetic algorithm (GA) for two scenarios. For scenario – I, 24 MCM of water was saved with a reduction in net financial return by 22%. For scenario- II, the net revenue increased in dry years when compared with normal and wet years.                                                                                                                                               |
comprising a genetic algorithm (GA), bacterial foraging optimization (BFO) and ant colony optimization (ACO) was developed. Major objective is to improve the convergence speed of optimization in various application specific design. The developed model would maximize the farmers’ net benefit by conjunctively using the surface water from reservoir release and groundwater resources at the head, middle and tail reaches of the Sathanur reservoir command for three different cropping seasons. The developed model comprises three stages: i) cropping area optimization based on a genetic algorithm, ii) optimization of surface and groundwater allocation conjunctively using BFO and iii) maximizing the net benefit of farmers using ACO.

MATERIALS AND METHODS

Study area

The Sathanur reservoir command located in Tiruvannamalai district, Tamil Nadu, India, was selected for this study, which lies between the coordinates of 11° 55’N and 12° 05’N latitude and 78° 55’E and 79° 00’E longitude. The geographical area covers approximately 18,200 ha of land. The Sathanur Reservoir has a capacity of 207.3 Mm$^3$ and the catchment area is 10,835 km$^2$. The total cultivable area under the Sathanur command is divided into the Sathanur Left Bank Canal (SLBC) and Right Bank Canal (SRBC), with an extent of 10,200 ha and 8,000 ha, respectively; the command area’s average topographical gradient is 2.5 m per the annual average rainfall of the study area is 1,040 mm and the climate is tropical, with a temperature range between maximum (29.5 °C to 38.4 °C) and minimum (20.4 °C to 26.5 °C) (Kannan 2012). Red loamy is the predominant soil formation in the study area and geological formations comprise charnockites and gneiss. Paddy, sugarcane, pulses and groundnuts are the major crops cultivated in the Sathanur command area.

Paddy is the main crop grown in the irrigation command area for Season-1 (August-November). During Season-2 (December-March), groundnuts, maize, and grains were grown. In Season-3 (April-July), paddy, groundnuts, and pulses were grown. Sugarcane was grown in the command area. These are the cropping patterns followed in the Sathanur command area. Cropping plans, present reservoir capacity, and profit/ha for various crops were obtained from the Public Works Department and Agricultural Department, Thiruvannamalai District, Tamil Nadu, India. Daily rainfall data and ground water level from 14 pumping wells for 15 years (2002–2017) were collected from Water resources Department and Central Ground Water Board respectively. Climate data (Maximum and minimum temperature, Wind speed, Sunshine -Hours & Humidity) was obtained from Data Centre, Tharamani, Chennai, Tamil Nadu, India. A map of the study area is shown in Figure 1.

Methodology

Figure 2 shows a flowchart that depicting the detailed methodology proposed in this work.

After modeling the water irrigation process, the optimization is applied for cropping pattern generation. With the use of hybrid optimizations, the conditions are satisfied to get better performance and it achieves the result of cropping pattern.

Irrigation water requirements

The net irrigation requirement (NIR) is defined as the amount of water required by a crop to augment the rainfall to meet the crop evapotranspiration ($ETc$) without compromising crop yield. Several techniques are available to compute the reference crop evapotranspiration ($ET_0$) and crop evapotranspiration ($ETc$) of crops. (Allen et al. 1988; Jensen et al. 1990):

$$ETc = K_c \times ET_0$$  \hspace{1cm} (1)

where $ETc$ represents crop evapotranspiration in mm/day, and $K_c$ and $ET_0$ represent the crop coefficient and reference evapotranspiration in mm/day, respectively. The following equation given by (Smajstrla & Zazueta 1998) is used to calculate the NIR of a crop:

$$NIR = ETc – ER$$  \hspace{1cm} (2)

where $NIR$ is measured in mm/month and $ER$ is the measurement of effective rainfall in mm/month.

CROPWAT is an effective decision tool proposed by the FAO (Smith 1992) for irrigation planning and management based on the daily water balance. It is used to compute $ET_0$ and the required data are the duration of various crop growth stages, crop coefficients, date of sowing or planting, initial and final root depths, and crop yield response factors. In the case of paddy
Figure 1 | Sathanur Command Area Map.

Figure 2 | Flowchart of the proposed work.
fields, the depth of water required for land preparation and puddling must be specified (Islam & Talukdar 2014). Climatic data (monthly average) of crop and soil data were used to estimate the ETc values and NIR of crops in the command area.

**Estimation of surface and ground water potential**

The prediction of surface water volume for the rainfall depth from any catchment is possible using a well-established method called the Soil Conservation Service Curve Number (SCS-CN). The SCS-CN technique was proposed in 1964 by the USDA, who determined that a single CN accounts for numerous factors that affect runoff (USDA S 1964). (Mishra & Singh 2003) suggests that the SCS-CN technique is a very useful method for estimating precipitation excess (runoff) by considering cumulative precipitation, antecedent soil moisture conditions, land use, and land cover. The groundwater level fluctuation method recommended by the groundwater estimation committee (Methodology G. R. E 1997) is widely used in the Indian context to calculate the net groundwater recharge for the command area during the monsoon season. Source (Scanlon et al. 2002) suggested that the groundwater level fluctuation method is useful in estimating the net groundwater recharge using the observed fluctuations in the groundwater level from 14 wells for a period of 15 years (2004–2018).

**Optimization model**

The main objective is to formulate an optimization model for maximum net returns by optimally utilizing the surface and groundwater resources (total water) for the crops that are grown (farmer preference constraints) in the command area. The most important part of the optimization model is to assign non-negative constraints to achieve the global optimum for the objective function. The non-negative constraints are incorporated because decision variables should not produce a negative value and the smallest value is zero.

Maximize $Z = \sum_{j=1}^{n} A_j \times P$  \hspace{1cm} (3)

Subject to

$\sum_{j=1}^{n} A_j W_j \leq TWR$  \hspace{1cm} (4)

$\sum_{j=1}^{n} A_j \leq TCA$  \hspace{1cm} (5)

$\sum TCA, TWR, A_j \geq 0$  \hspace{1cm} (6)

where $A_j$ and $P$ is the area under irrigation and net return for the $j^{th}$ crop, respectively. $W_j$ is the water requirement for the $j^{th}$ crop, $TWR$ is the total water (surface and groundwater) resources available and $TCA$ is the total cultivable area under irrigation.

The developed model comprises of three stages i) Cropping area optimization based on genetic algorithm ii) Optimization of surface and groundwater allocation conjunctively using BFO iii) Maximizing the net benefit of farmers using ACO. Cropping pattern optimization is discussed in (Lina et al. 2018; Bhavana et al. 2021).

**Genetic algorithm**

Genetic algorithms (GAs) belong to a class of search algorithms used in function optimization (Holland 1992). The algorithms imitate the natural evaluation and survival of the fittest criteria in human beings. These types of algorithms are inspired by various conditions of selection, mutation, and crossover. The GA is an appropriate function optimizer because of its global characteristics and flexibility. The GA process consists of initialization, evaluation, selection, crossover, mutation, convergence, and stochastic operators (Whitley 1994). The schematic procedure of the GA proposed in this study is shown in Figure 3.

Several parameters are required to execute a genetic algorithm. The GA algorithm uses an iterative technique to create an optimal solution to a given problem by appropriately adjusting the ideal parameter (Dobslaw 2010). The optimization process using a genetic algorithm was performed using a soft computing technique (Sahoo et al. 2012). Source (Ghosh & Dehuri...
2004) used an elitist strategy for obtain the optimal solution using GA. The parameters used in the GA are population size, crossover, and mutation rates of 500, 0.9, and 0.01, respectively to obtain the optimal solution. The elitist selection procedure with a generation gap of 0.98, is adopted.

The main function of the GA is to arrive at an optimal cropping area of the Sathanur command with constraints such as the type of crop, crop water requirement, and available surface and groundwater resources. The output of the GA is used as an input to bacterial foraging optimization (BFO) for optimizing the source (surface and groundwater) allocation for the conjunctive use of water.

**Bacterial foraging optimization (BFO) algorithm**

In the Bacterial foraging optimization technique presented in (Passino 2002), a set of bacteria attempts to accomplish the optimum threshold value by involving stages of chemotaxis, swarming, reproduction, elimination and dispersal. The main idea of BFO is to imitate the chemotactic movement of virtual bacteria in the search domain. Each bacterium generates a set of best possible parameter values iteratively. Progressively, all bacteria congregate to the global optimum threshold value. The bacteria have a choice either to tumble by a tumble or a tumble, followed by a run/swim in the chemotaxis stage. In the process of swarming, each bacterium signals other bacteria to swarm together via attractants. To keep the swarm size constant, the least healthy bacteria die and the healthier bacteria are asexually split into two bacteria, which are then placed in the same location in the reproduction stage. In the final stage, any bacterium is either eliminated or dispersed from the set to a random space during the process of optimization. This stage mainly helps the bacteria attain the global optimum solution. If \( i \) represents the bacterium position and \( J(i) \) is the objective function, then \( J(i) < 0 \), nutrient rich, \( J(i) = 0 \), neutral, and \( J(i) > 0 \); toxic. Bacteria attempt to increase the concentration of nutrients to obtain the minor values of \( J(i) \). In addition, they try to find ways out of neutral media and avoid toxic substances. The BFO algorithm was modified to determine the optimal allocation of surface and groundwater resources.

**Bacterial foraging optimization algorithm for the proposed study**

The control parameters proposed in this study are (i) number of bacteria \( (S) = 50 \), (ii) maximum number of steps \( (N_s) = 4 \), (iii) number of chemotactic steps \( (N_c) = 100 \), (iv) number of reproduction steps \( (N_re) = 4 \), (v) number of elimination-dispersal steps \( (N_{ed}) = 2 \), (vi) Probability \( (P_{ed}) = 0.25 \) and (vii) Step size \( C(i) = 0.1 \).

**Step 1:** \( S, N_c, N_n, N_re, N_{ed}, P_{ed} \) (Intializing the Parameters) and \( C(i), (i = 1, 2..., S) \).

Choose the initial value for the control variable \( (\theta^i) \) cropping area. The control variables \( (\theta^i) \) were randomly distributed across the search space. Once \( \theta^i \) is computed, the \( P \) value is updated automatically and reaches the terminates when it reaches the maximum specified iterations.

**Step 2:** \( 1 = 1 + 1 \) (Elimination-Dispersal loop)
Step 3: \( k = k + 1 \) (Reproduction loop)
Step 4: \( j = j + 1 \) (Chemo taxis loop)

(a) Chemo-tactic step for bacterium ‘\( i = 1,2,\ldots,S \)’ as follows:
(b) Let \( J(i,j,k,l) \) be the compute water allocation.
(c) \( J(i,j,k,l) = J(i,j,k,l) + J_{cc}(\theta(i,j,k,l),P(j,k,l)) \).
(d) To find a better surface and groundwater allocation, \( J_{last} = J(i,j,k,l) \)
(e) Tumble: \( \Delta(i) \in \mathbb{R}^p \) with each element generating a random vector, and \( R \) is a real number. Generate a random number on \([0,1]\) for steps \( \Delta_{m}(i) \), \( m = 1, 2, \ldots, p \).
(f) Modification of water source allocation

\[
\theta(i + 1, k, l) = \theta(i, k, l) + C(i) \frac{\Delta(i)}{\sqrt{\Delta^T(i) \Delta(i)}}
\]

This depicts step size \( C(i) \) for bacterium \( i \) in the direction of the tumble

(vii) Compute the updated water allocation \( J(i,j + 1,k,l) \)
(viii) Swim.

The Swim function is to allocate the positive increment of cropping area until it satisfies the surface and groundwater availability.

(ix) Take the next bacterium \((i + 1)\) if \( i \neq S \) (i.e., possibility of increment in area allocation for surface water and groundwater simultaneously)

Step 5: If \( j < N_c \), repeat step 3. The chemotaxis process continues until all the surface and groundwater sources are allocated for each crop.

Step 6:
(a) \( J_{health}(i) \) is the total allocation of water resources. Compute for the given \( k \) and \( l \), and for each \( i = 1, 2, \ldots, S \),

\[
J_{health} = \sum_{j=1}^{N_c+1} J(i, j, k, l)
\]

(b) The \( S_r \) bacterium (allocated surface and groundwater) with the lowest productivity \( J_{health} \) values die and the healthy \( (S_h) \) bacteria with the best values split.

Step 7: If \( k < N_{re} \), proceed to Step 2. However, the specified reproduction steps have not been reached.

Step 8: Elimination-Dispersal
For \( i = 1, 2, \ldots, S \) with probability \( P_{ed} \), to eliminate and disperse each bacterium in random space in the optimization domain.
If \( l < N_{ed} \), go to step 1; else, end.

The BFO algorithm results in an optimal allocation of surface and groundwater resources considering the input from the Genetic algorithm as the optimum cropping pattern and the result of the BFO is the input for the Ant Colony optimization (ACO)-guided search algorithm to distribute resources to the head, middle and tail command areas to obtain the maximum net profit.

**Ant colony optimization (ACO) for optimal conjunctive use of surface and groundwater**

The ant colony optimization system (Meuleau & Dorigo 2002) was first developed by the behavior of ants to find the shortest route between food and nest. ACO is a branch of swarm intelligence and a group of ants with its social behavior used to solve optimization problems. While traveling ants deposit pheromones, the other ants follow in their trial. Each trial of an ant is followed by a pheromone deposit along a possible path. The pheromone density during each trial was indirect communication and reinforcement learning.

In this study, an ACO algorithm was developed to maximize the net profit from the distribution of surface and groundwater to the head, middle and tail reaches of the command area for different crop seasons. The developed method is a mathematical
optimization approach that uses a guided search technique. The search domain was flexible between the available surface and groundwater. The cropping area was discretised and assigned as ants for the search domain. The ants are allowed to move in the reaches of the head, middle and tail. The different sources of water (surface water and groundwater) were obtained from the BFO and were used for maximize the net profit for the entire cropping season. Each ant will explore the possibility of maximizing the net profit through the area allocated in the head, middle and tail reaches with the available surface water and groundwater.

The objective function of ACO for the net profit maximization and is given:

$$\text{Maximize}(Z) = \sum_{i=1}^{\text{seasons}} \sum_{m=1}^{\text{reaches}} \sum_{k=1}^{\text{sources}} C_A(i, j, k, cp) \times \text{NP}(cp, k)$$

Subject to

$$\sum_{i=1}^{3} C_{Ai} \leq A \quad \text{(Area Constraints)}$$

$$\sum_{i=1}^{3} IWR_{sj} \leq \text{Total Surface Water Availability} \quad \text{(Surface Water Constraints)}$$

$$\sum_{i=1}^{3} IWR_{gj} \leq \text{Total Ground Water Availability} \quad \text{(Ground Water Constraints)}$$

where $Z$ is the net profit function, $C_A$ is the area of the individual crop, NP is the net profit, IWR is the irrigation water requirement: i is the season varies from 1 to 3, j is the reaches (head, middle and tail), k is the source of water supply (surface water and groundwater) and cp is the cropping pattern area (paddy, sugarcane, groundnut, maize, grains and pulses).

The crop area is divided into a segment of varieties, such as paddy, sugarcane, groundnut, maize, grains and pulses. These crop areas are commanded in the reaches of the head, middle and tail in the form of discretized quantities. To facilitate the search by each ant, the surface and groundwater distribution for the different seasons is proportional to the head, middle and tail reaches for the different crops. Three different policies are considered for the distribution of surface and groundwater and the details are listed in Table 2.

The possibility of visits made by an individual ant is based on the cropping pattern in the head, middle and tail reach and the source of water (surface water and groundwater). Thus, each ant may have a different visiting order from the other ants. Each ant must visit all possible sources of water (surface water and groundwater).

| Policy – 1 | Surface Water Quantity (Mm$^3$) | % of SW | Groundwater Quantity (Mm$^3$) | % of GW | Total Quantity (Mm$^3$) |
|------------|---------------------------------|---------|-------------------------------|---------|-------------------------|
| Season-1   | 207.67                          | 100     | 0                             | 0       | 207.67                  |
| Season-2   | 0                               | 0       | 79.74                         | 50      | 79.74                   |
| Season-3   | 0                               | 0       | 79.74                         | 50      | 79.74                   |

| Policy – 2 | Surface Water Quantity (Mm$^3$) | % of SW | Groundwater Quantity (Mm$^3$) | % of GW | Total Quantity (Mm$^3$) |
|------------|---------------------------------|---------|-------------------------------|---------|-------------------------|
| Season-1   | 103.84                          | 50      | 0                             | 0       | 103.84                  |
| Season-2   | 103.84                          | 50      | 0                             | 0       | 103.84                  |
| Season-3   | 0                               | 0       | 159.48                        | 100     | 159.48                  |

| Policy – 3 | Surface Water Quantity (Mm$^3$) | % of SW | Groundwater Quantity (Mm$^3$) | % of GW | Total Quantity (Mm$^3$) |
|------------|---------------------------------|---------|-------------------------------|---------|-------------------------|
| Season-1   | 124.60                          | 60      | 15.95                         | 10      | 140.55                  |
| Season-2   | 62.30                           | 50      | 63.79                         | 40      | 126.09                  |
| Season-3   | 20.77                           | 10      | 79.74                         | 50      | 100.51                  |
The initial network of the ACO algorithm consists of several parameters, such as i, j and k representing the starting node, next node and ant, respectively. Each ant in starting node i is an agent who places pheromone on a visited path, and then chooses to visit the next node j with a probability that is a function of the net profit and the pheromone density. \( \tau_{ij} \) represents the pheromone on edge (i, j) at iteration t. This is updated according to the following equation:

\[
\tau_{ij}(t) = (1 - \rho) \tau_{ij}(t) + \Delta \tau_{ij} + \sum_{k=1}^{m} \Delta \tau_{ij}^{k}
\]

(10)

where \((1 - \rho)\) represents the decay of pheromone between iterations t and \(t + 1\), and

\[
\Delta \tau_{ij} = \sum_{k=1}^{m} \Delta \tau_{ij}^{k}
\]

(11)

\[
\Delta \tau_{ij}^{k} = \begin{cases} 
Q/L_k & \text{if ant k uses edge (i, j) in the iteration t} \\
0 & \text{else}
\end{cases}
\]

(12)

where \(\Delta \tau_{ij}^{k}\) is the pheromone change by ant k at j, and m refers to the total number of ants. The quantity \(\Delta \tau_{ij}^{k}\) is given as.

Where Q is the crop area related to the quantity of trails made by ants, and \(L_k\) is the productivity (Rs/m\(^3\)) for each ant k. The third part is the elitist ant strategy, where \(e\) is the elitist pheromone coefficient and \(\Delta \tau_{ij}^{e}\) is the pheromone laid by the best ant at each \(\Delta \tau_{ij}^{e} = Q/L_e\), where \(L_e\) is the total tour length of an elitist ant. This leads to the best solution with a higher probability.

Next, the ant can decide the next node j from i by the transition rule using the following equation:

\[
P_{ij}^{k}(t) = \frac{[\tau_{ij}(t)]^{\alpha} (\eta_{ij})^{\beta}}{\sum_{k \in \text{allowed}} [\tau_{ij}(t)]^{\alpha} (\eta_{ij})^{\beta}}
\]

(12)

where defines the visibility, and \(\eta_{ij}\) is the ratio of water supplied and productivity. \(\alpha\) is the relative importance of the pheromone and \(\beta\) is the visibility that controls the relative importance. The translation probability is a tradeoff between visibility, which is a greedy heuristic strategy, and the pheromone.

The above steps are repeated for each set of cropping seasons to achieve the maximum net profit with the conjunctive use of surface and groundwater. All the mentioned computational experiments were coded in C++ using Microsoft Visual Studio 2015 platform.

**RESULTS**

This section summarizes and discusses the main findings of this work. To optimize the net profit of the Sathanur command area, a hybrid optimization model was developed. The net return of each crop, total water availability and Net Irrigation requirement were calculated and given as input parameters.

| Crops   | Crop Evapotranspiration (ET\(_c\)) (mm/day) | Crop Water Requirement (m) | Irrigation water Requirement (mm) |
|---------|------------------------------------------|-----------------------------|----------------------------------|
| Paddy   | 0.29–2.91                                | 1.2                         | 702.7                            |
| Sugarcane | 1.12–3.57                                | 2.0                         | 333.8                            |
| Groundnut | 0.38–2.61                                | 0.42                        | 140.7                            |
| Maize   | 1.04–3.61                                | 0.3                         | 91.8                             |
| Grains  | 1.04–3.00                                | 0.2                         | 85.7                             |
| Pulses  | 1.26–2.56                                | 0.187                       | 62.2                             |
Net return of crops

The net profit of crops per hectare was estimated by including the market price of crops, crop yield and cost of production. The major crop expenses, such as seed, land preparation, and labor costs, were obtained from the Tamil Nadu Agriculture University and Agricultural Marketing Information Center (directorate of marketing and inspection), Thiruvannamalai Dis-

Table 4 | Optimal cropping area from GA

| Policy – 1 | Total Area (ha.) | Paddy | Sugarcane | Groundnut | Maize | Grains | Pulses | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) |
|---|---|---|---|---|---|---|---|---|---|
| Season-1 | 11,000 | 300 | 4,900 | 900 | 700 | 400 | 3,638.82 | 5.09 |
| Season-2 | 2,800 | 300 | 6,300 | 4,800 | 1,600 | 2,400 | 3,751.72 | 5.25 |
| Season-3 | 0 | 300 | 17,000 | 300 | 300 | 300 | 4,400.66 | 6.16 |
| Policy – 2 | Season-1 | 1,000 | 300 | 10,000 | 3,100 | 3,000 | 800 | 2,969.16 | 4.16 |
| Season-2 | 1,500 | 300 | 9,550 | 3,050 | 3,000 | 800 | 2,986.83 | 4.18 |
| Season-3 | 0 | 300 | 17,000 | 300 | 300 | 300 | 4,400.66 | 6.16 |
| Policy – 3 | Season-1 | 4,300 | 1,600 | 9,000 | 1,700 | 900 | 300 | 3,403.38 | 4.76 |
| Season-2 | 5,200 | 1,600 | 8,900 | 1,100 | 800 | 600 | 3,978.24 | 5.57 |
| Season-3 | 0 | 1,600 | 14,400 | 1,000 | 600 | 600 | 4,017.31 | 5.62 |

1 INR = 0.014 USD.

Table 5 | Optimal water allocation for Policy 1

| Crop Type | Area (ha.) | Water Supplied (Mm³) | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) |
|---|---|---|---|---|
| Water Supplied (Mm³) | Surface Water | Groundwater | | |
| Policy – 1 Season -1 | | | | |
| Paddy | 2,808.04 | 55.24 | 0 | 622.15 | 0.87 |
| Sugarcane | 3,080.33 | 33.23 | 0 | 369.64 | 0.52 |
| Groundnut | 3,420.32 | 22.43 | 0 | 654.51 | 0.92 |
| Maize | 3,040.29 | 14.95 | 0 | 425.64 | 0.60 |
| Grains | 2,660.25 | 8.72 | 0 | 266.03 | 0.37 |
| Pulses | 3,116.16 | 9.55 | 0 | 249.29 | 0.35 |
| Policy – 1 Season -2 | | | | |
| Paddy | 5,050.30 | 0 | 33.23 | 787.85 | 1.10 |
| Sugarcane | 3,080.33 | 0 | 12.32 | 766.29 | 1.07 |
| Groundnut | 2,226 | 0 | 8.90 | 553.76 | 0.78 |
| Maize | 2,491 | 0 | 7.47 | 453.36 | 0.63 |
| Grains | 2,623.50 | 0 | 5.25 | 341.06 | 0.48 |
| Pulses | 2,720.86 | 0 | 5.09 | 282.97 | 0.40 |
| Policy – 1 Season -3 | | | | |
| Paddy | 0 | 0 | 0 | 0 | 0.00 |
| Sugarcane | 3,080.33 | 0 | 12.94 | 766.29 | 1.07 |
| Groundnut | 6,057.14 | 0 | 25.44 | 1,506.82 | 2.11 |
| Maize | 2,968 | 0 | 8.90 | 540.18 | 0.76 |
| Grains | 1,987.50 | 0 | 3.975 | 258.38 | 0.36 |
| Pulses | 4,081.28 | 0 | 7.632 | 424.45 | 0.59 |
strict, Tamil Nadu, India. The profit per hectare for paddy, sugarcane, groundnut, maize, pulses and grains are 22,156, 38,000, 19,136, 14,000, 8,000, and 10,000 rupees, respectively.

**Total water availability**

The SCS runoff equation was developed to estimate the total storm runoff. Weighted CN-II was estimated as 86 by taking into consideration the hydrological soil group B (moderately low runoff potential) and cultivated land area. Daily rainfall over 15 years was used to compute the daily runoff.

The total surface water is 282.22 Mm³, which includes the reservoir capacity (207.67 Mm³) and the surface runoff of the command area. The quantity of surface water considered for the optimization model was 207.67 Mm³ (reservoir capacity) and the groundwater quantity was 159.49 Mm³ (obtained via the water table fluctuation method); thus, the total water available is 367.16 Mm³, which is considered for the hybrid optimization model.

**Irrigation water requirement**

To estimate the Irrigation water requirement (IWR) for each crop (paddy, sugarcane, groundnut, maize, grains, and pulses) CROPWAT was used. Climatic data, Rainfall data, Soil data and Crop data were given as inputs. The values of crop water requirements and irrigation water requirements were calculated by considering application efficiency of 70% and given in Table 3. Paddy and sugarcane had the highest IWR compared to the other crops. Water system prerequisite is the total amount of water applied to the land surface in supplement to the water provided through precipitation and soil profile to meet the water needs of harvests for ideal development. Water system wasteful water use is characterized as the volume of water expected to make up for the shortfall between likely evapotranspiration on the one side and powerful precipitation over the harvest developing period and change in soil dampness content on the opposite side.

| Table 6 | Optimal water allocation for Policy 2 |
|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| Crop Type                        | Water Supplied (Mm³) | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) |
|----------------------------------|----------------------|-----------------------------|-----------------------------|
| Policy – 2 Season -1             |                      |                            |                            |
|                                  |                      |                            |                            |
| Paddy                            | 1,936.14             | 38.09                       | 0                           | 428.97                           | 0.60                           |
| Sugarcane                        | 2,801.74             | 30.22                       | 0                           | 336.21                           | 0.47                           |
| Groundnut                        | 2,178.16             | 14.28                       | 0                           | 416.81                           | 0.58                           |
| Maize                            | 2,525.40             | 12.42                       | 0                           | 353.56                           | 0.49                           |
| Grains                           | 2,399.13             | 7.87                        | 0                           | 239.91                           | 0.34                           |
| Pulses                           | 1,958.20             | 6                          | 0                           | 156.66                           | 0.22                           |
| Policy – 2 Season -2             |                      |                            |                            |
|                                  |                      |                            |                            |
| Paddy                            | 1,929.13             | 34.16                       | 0                           | 427.42                           | 0.60                           |
| Sugarcane                        | 2,801.74             | 30.22                       | 0                           | 336.21                           | 0.47                           |
| Groundnut                        | 2,178.16             | 14.28                       | 0                           | 416.81                           | 0.58                           |
| Maize                            | 2,525.40             | 12.42                       | 0                           | 353.56                           | 0.49                           |
| Grains                           | 2,399.13             | 7.87                        | 0                           | 239.91                           | 0.34                           |
| Pulses                           | 1,958.20             | 6                          | 0                           | 156.66                           | 0.22                           |
| Policy – 2 Season -3             |                      |                            |                            |
|                                  |                      |                            |                            |
| Paddy                            | 0                    | 0.000                       | 0.00                        | 0.00                             | 0.00                           |
| Sugarcane                        | 2,801.74             | 18.44                       | 437.07                      | 6.11                             |
| Groundnut                        | 14,961.68            | 62.84                       | 3,721.99                    | 52.1                             |
| Maize                            | 106.33               | 0.32                        | 19.93                       | 0.03                             |
| Grains                           | 159.49               | 0.32                        | 20.73                       | 0.03                             |
| Pulses                           | 170.58               | 0.32                        | 17.74                       | 0.02                             |
Genetic algorithm (GA)

A GA-based model was developed to optimize the cropping area by taking into consideration various constraints. The results of this optimization model reveal that there is a large variation in cropping area compared to the existing cropping pattern and the traditional cropping pattern and the values are depicted in Table 4.

Bacterial foraging optimization (BFO)

The optimized cropping area obtained from the GA-based model for different seasons was given as input to the BFO in order to allocate the surface and groundwater conjunctively. This process involves all three scenarios and the results of the optimized surface and groundwater allocation for the three seasons are shown in Tables 5–7.

This analysis leads to some useful conclusions; most importantly, policy 1 and policy 2 allocations are based on either surface or groundwater. The optimized surface water allocated to season 1 is 144.12 Mm^3 and the corresponding area irrigated is 18,125.4 ha. only and a reduction in net profit. Policy-3 leads to maximum conjunctive utilization of surface and groundwater for all three seasons, through which net profit is increased considerably.

Ant colony optimization (ACO)

The ACO allocates the surface and groundwater for the head, middle and tail reaches by considering the BFO output. To ease the search by each ant, the surface and groundwater distribution for the different seasons is proportional to the head, middle and tail reaches for the different types of crops. The results obtained from each policy for the maximum net profit are tabulated in Tables 8–10.

The comparative results based on the output of BFO and ACO for all seasons with different policies in terms of net profit are shown in Figure 4. The Results show that the GA-BFO-ACO hybrid model provides maximum net benefits (Rs.33,546.77

Table 7 | Optimal water allocation for Policy 3

| Crop Type | Area (ha.) | Water Supplied (Mm³) | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) |
|-----------|------------|----------------------|----------------------------|-------------------------------|
|           |            | Surface Water | Groundwater | Net Profit (Rs.) | Net Profit (USD) |
| Policy – 3 Season-1 | | | | |
| Paddy | 3,854.71 | 65.97 | 6.02 | 1,362.39 | 1.91 |
| Sugarcane | 2,107.62 | 17.86 | 2.98 | 269.20 | 0.38 |
| Groundnut | 2,064.80 | 9.92 | 2.21 | 426.81 | 0.60 |
| Maize | 2,122.75 | 8.18 | 1.38 | 316.45 | 0.44 |
| Grains | 4,532.56 | 13.39 | 0.90 | 466.70 | 0.65 |
| Pulses | 2,352.26 | 5.95 | 0.77 | 198.04 | 0.28 |
| Policy – 3 Season-2 | | | | |
| Paddy | 4,035.10 | 25.79 | 27.85 | 1,065.40 | 1.49 |
| Sugarcane | 2,102.88 | 6.57 | 9.83 | 306.12 | 0.43 |
| Groundnut | 3,705.21 | 10.04 | 8.69 | 833.81 | 1.17 |
| Maize | 3,142.37 | 7.19 | 5.04 | 510.49 | 0.71 |
| Grains | 2,508.46 | 4.59 | 2.99 | 265.97 | 0.37 |
| Pulses | 2,183.72 | 3.60 | 1.89 | 198.95 | 0.28 |
| Policy – 3 Season-3 | | | | |
| Paddy | 0 | 0 | 0 | 0 | 0.00 |
| Sugarcane | 2,107.62 | 5.24 | 13.64 | 286.59 | 0.40 |
| Groundnut | 9,600 | 6.24 | 40.32 | 2,561.60 | 3.59 |
| Maize | 2,359.33 | 4.80 | 7.07 | 566.04 | 0.79 |
| Grains | 2,205.12 | 1.48 | 5.18 | 313.65 | 0.44 |
| Pulses | 1,889.84 | 2.84 | 3.53 | 283.16 | 0.40 |
lakhs) than the GA-BFO hybrid model (Rs.27,579.6 lakhs) for all three seasons. Various trials were performed for each policy based on the productivity values and the results are illustrated in Figure 5. The performance results are majorly compared with net profit, and productivity. Depends on the three policy (policy 1, policy 2, & policy 3), the net profit is compared for GA with BFO and GA, BFO and ACO approaches. The productivity is calculated based on iteration level of three policies. It reveals that the maximum net profit is obtained from policy 3 through the conjunctive use of surface and groundwater with maximum productivity compared to other policies. The average productivity values from policies are 3.662 Rs/m³ (Policy 1), 3.440 Rs/m³ (Policy 2), and 3.665 Rs/m³ (Policy 3). Hence, the developed hybrid optimization is useful for changing the cropping pattern, which in turn fetches more profit for the farmers of the Sathanur command area with conjunctive use of water.

**DISCUSSION**

Currently, the farmers in the command area are not getting enough net benefits from the existing cropping pattern for the following reasons: (i) Conjunctively not utilizing the available water resources and (ii) traditional cropping pattern. Sathanur reservoir was designed for the cultivation of ID crops, currently, most of the command area is being cultivated with paddy and sugarcane, due to increased profit. This change in cropping patterns causes a higher demand for water, which is met by the conjunctive use of surface and groundwater. This necessitated the equitable distribution of surface and groundwater conjunctively in the head, middle and tail reach of the command area. The present study develops a framework for the optimal conjunctive use of water resources to maximize the net returns in a Sathanur command area. There are only a few studies on Sathanur reservoir command especially on reservoir re-lease plan using heuristic optimization. So far only one study by (Ramakrishnan et al. 2010) attempted to revise the starting period of the crop calendar for the water deficit Sathanur

Table 8 | Optimal cropping pattern for Policy 1

| Crop Type | Area (ha.) | Water Supplied (Mm³) | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) | Productivity Rs/m³ |
|-----------|-----------|----------------------|-----------------------------|--------------------------------|--------------------|
|           | Head | Middle | Tail | Surface Water | Groundwater |                   |                       |                       |                   |
| Policy – 1 Season-1 | | | | | | | | | |
| Paddy | 7,200 | 3,600 | 200 | 171.14 | 0 | 2,437.16 | 3.41 | 1.42 |
| Sugarcane | 100 | 100 | 100 | 3.19 | 0 | 36 | 0.05 | 1.13 |
| Groundnut | 3,700 | 900 | 300 | 25.27 | 0 | 937.66 | 1.31 | 3.71 |
| Maize | 300 | 300 | 300 | 4.37 | 0 | 126 | 0.18 | 2.89 |
| Grains | 300 | 200 | 200 | 2.17 | 0 | 70 | 0.10 | 3.22 |
| Pulses | 200 | 100 | 100 | 1.13 | 0 | 32 | 0.04 | 2.85 |
| Policy – 1 Season-2 | | | | | | | | | |
| Paddy | 900 | 900 | 1,000 | 0 | 30.24 | 806.48 | 1.13 | 2.67 |
| Sugarcane | 100 | 100 | 100 | 1.97 | 0 | 46.80 | 0.07 | 2.37 |
| Groundnut | 2,100 | 2,100 | 2,100 | 25.20 | 0 | 1,567.24 | 2.19 | 6.22 |
| Maize | 1,700 | 1,600 | 1,500 | 14.40 | 0 | 873.60 | 1.22 | 6.07 |
| Grains | 600 | 600 | 400 | 3.20 | 0 | 208 | 0.29 | 6.50 |
| Pulses | 800 | 800 | 800 | 4.49 | 0 | 249.60 | 0.35 | 5.56 |
| Policy – 1 Season-3 | | | | | | | | | |
| Paddy | 0 | 0 | 0 | 0 | 0 | 0 | 0.00 | 0 |
| Sugarcane | 100 | 100 | 100 | 1.974 | 0 | 46.80 | 0.07 | 2.37 |
| Groundnut | 5,700 | 5,700 | 5,600 | 71.400 | 0 | 4,229.06 | 5.92 | 5.92 |
| Maize | 100 | 100 | 100 | 0.900 | 0 | 54.60 | 0.08 | 6.07 |
| Grains | 100 | 100 | 100 | 0.600 | 0 | 39 | 0.05 | 6.50 |
| Pulses | 100 | 100 | 100 | 0.561 | 0 | 31.20 | 0.04 | 5.56 |
irrigation system and the author concluded that surface and groundwater should be used conjunctively to maximize the net benefit without any water stress. Furthermore, the results also agreed with previous studies (Varade & Patel 2018; Rath et al. 2019) that the hybridization of meta-heuristic algorithms provides maximum net benefits.

CONCLUSION

Thus the design of hybrid optimization in water irrigation system is modeled and obtain the better result of net profit and policy state of irrigation. Unlike previous studies (Karamouz et al. 2004; Rath & Swain 2018), in this study, the hybridization of three meta-heuristic algorithms (GA, BFO and ACO) for optimizing the cropping area, conjunctive water allocation and net returns for different reaches. Net returns from $GA + BFO + ACO$ model was found to be 21.64% higher than $GA + BFO$ model. Thus, the optimal cropping pattern developed in this study by considering conjunctive use is very promising for enhancing farmers’ net income as well as for the conservation of water resources in the command area due to the foraging behavior and guiding mechanism of the developed hybrid optimization model (GA-BFO-ACO). Finally, the hybridization of the meta-heuristic algorithm developed in this study is first of its kind to unravel the sharing of water resources (conjunctive use of surface and groundwater) conflict among different reaches (head, middle and tail) of the reservoir command to maximize the net benefit and can be adopted for other other irrigated regions across the globe to overcome chronic water problems.

ACKNOWLEDGEMENT

The authors are thankful to the Public Works Department and Agriculture Department, Tiruvannamalai and Institute for Water Studies, Chennai for providing the necessary data to carry out this research work.

| Crop Type | Area (ha.) | Water Supplied (Mm$^3$) | Surface Water | Groundwater | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) | Productivity Rs/m$^3$ |
|-----------|------------|-------------------------|---------------|-------------|-----------------------------|--------------------------------|----------------------|
| Paddy     | 500        | 300 200 17.65 0 221.56 0.31 1.26 |
| Sugarcane | 100 100 100 3.19 0 36 0.05 1.13 |
| Groundnut | 4,700 3,300 2,000 59.25 0 1,913.60 2.68 3.23 |
| Maize     | 1,900 900 300 12.68 0 434 0.61 3.42 |
| Grains    | 1,500 1,100 400 8.56 0 300 0.42 3.50 |
| Pulses    | 600 100 100 1.99 0 64 0.09 3.21 |
| Paddy     | 1,050 250 200 21.97 0 332.34 0.47 1.51 |
| Sugarcane | 100 100 100 3.19 0 36 0.05 1.13 |
| Groundnut | 4,800 3,200 1,550 55.20 0 1,827.49 2.56 3.31 |
| Maize     | 1,850 900 300 12.50 0 427 0.60 3.42 |
| Grains    | 1,500 1,100 400 8.56 0 300 0.42 3.5 |
| Pulses    | 600 100 100 1.99 0 64 0.09 3.21 |
| Paddy     | 0 0 0 0 0 0 0.00 0 |
| Sugarcane | 100 100 100 0 1.97 46.80 0.07 2.37 |
| Groundnut | 2,920 1,980 12,100 0 71.40 4,229.06 5.92 5.92 |
| Maize     | 100 100 100 0 0.90 54.60 0.08 6.07 |
| Grains    | 100 100 100 0 0.60 39 0.05 6.50 |
| Pulses    | 100 100 100 0 0.56 31.20 0.04 5.56 |
### Table 10 | Optimal cropping pattern for Policy 3

| Crop Type | Area (ha.) | Water Supplied (Mm³) | Net Profit (Rs.) (in Lakhs) | Net Profit (USD) (in Millions) | Productivity Rs/m³ |
|-----------|------------|----------------------|----------------------------|--------------------------------|-------------------|
|           | Head       | Middle   | Tail   | Surface Water | Groundwater | Net Profit | Net Profit |                   |                  |
| Policy 3 - Season-1 |            |          |        |               |             | (in Lakhs) | (in Millions) |                  |                  |
| Paddy     | 2,700      | 1,100    | 500    | 64.90         | 3.60         | 972.65     | 1.56        | 1.42             |                  |
| Sugarcane | 500        | 500      | 600    | 9.58          | 4.61         | 217.20     | 0.30        | 1.53             |                  |
| Groundnut | 4,900      | 3,200    | 900    | 41.58         | 4.80         | 1,791.13   | 2.51        | 3.86             |                  |
| Maize     | 500        | 800      | 400    | 5.88          | 1.20         | 254.80     | 0.36        | 3.60             |                  |
| Grains    | 300        | 300      | 300    | 1.51          | 0.80         | 102        | 0.14        | 4.42             |                  |
| Pulses    | 200        | 200      | 300    | 0.91          | 0.75         | 65.60      | 0.09        | 3.96             |                  |
| Policy 3 - Season-2 |            |          |        |               |             | (in Lakhs) | (in Millions) |                  |                  |
| Paddy     | 2,700      | 1,900    | 600    | 38.42         | 27           | 1,318.28   | 1.85        | 2.02             |                  |
| Sugarcane | 500        | 500      | 600    | 9.58          | 4.61         | 217.20     | 0.30        | 1.53             |                  |
| Groundnut | 2,900      | 2,800    | 3,200  | 10.77         | 28           | 2,104.96   | 2.95        | 5.43             |                  |
| Maize     | 400        | 400      | 300    | 1.46          | 2.40         | 187.60     | 0.26        | 4.87             |                  |
| Grains    | 200        | 200      | 400    | 0.97          | 1            | 95         | 0.13        | 4.82             |                  |
| Pulses    | 200        | 200      | 200    | 0.91          | 0.56         | 55.20      | 0.08        | 3.76             |                  |
| Policy 3 - Season-3 |            |          |        |               |             | (in Lakhs) | (in Millions) |                  |                  |
| Paddy     | 0          | 0        | 0      | 0             | 0            | 0          | 0.00        | 0                |                  |
| Sugarcane | 500        | 500      | 600    | 9.58          | 4.61         | 217.20     | 0.30        | 1.53             |                  |
| Groundnut | 4,900      | 4,700    | 4,800  | 6.24          | 55.86        | 3,519.11   | 4.93        | 5.67             |                  |
| Maize     | 400        | 400      | 200    | 2.61          | 1.20         | 156.80     | 0.22        | 4.12             |                  |
| Grains    | 200        | 200      | 200    | 0.97          | 0.60         | 69         | 0.10        | 4.39             |                  |
| Pulses    | 200        | 200      | 200    | 0.91          | 0.56         | 55.20      | 0.08        | 3.76             |                  |

### Figure 4 | Comparison of Net Profit values of BFO and ACO for different scenarios.
CONFLICT OF INTEREST
The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT
All relevant data are included in the paper or its Supplementary Information.

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Figure 5 | Productivity values for different scenarios.
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First received 20 April 2021; accepted in revised form 1 July 2021. Available online 15 July 2021