Water Policy 23 (2021) 274–290

Optimization of water productivity in Bhagwanpur distributary command of India employing TLBO and cuckoo search algorithms

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Abstract

Efficient and judicious use of land and water is the need of the hour. In other words, evolving a cropping pattern, which optimizes productivity or net return considering prevailing constraints is quite useful to farmers, because such a cropping pattern is expected to be better than the existing cropping pattern in terms of yielding optimum productivity or net return. A single objective problem consisting of an objective function of optimization of water productivity with prevailing constraints was formulated and three optimization algorithms, namely (i) LINPROG, (ii) teaching learning based optimization (TLBO) and (iii) cuckoo search (CS) were employed to compute optimum water productivity corresponding to various affinity levels. It was observed that all three approaches yielded exactly the same values of water productivity at different affinity levels. TLBO showed better convergence capability as it reached the optimum value of objective function at a lower number of iterations than CS technique. Optimum water productivity at 20% affinity level seems quite practical and reasonable to be recommended in this distributary command for adoption because water productivity value is 2.57 times higher with 98.25 ha less cropped area as compared to the value of water productivity for the existing cropping pattern.

Keywords: Cropping pattern; Cuckoo search algorithm; Optimization; Teaching learning based optimization; Water productivity

Highlights

- Water productivity is an indicator which can point out hot spots where net return can be improved with less water consuming crops.
- A single objective function problem of optimization of water productivity was formulated and solved by three optimization algorithms: (i) LINPROG, (ii) TLBO, (iii) Cuckoo search.
- It was observed that all three approaches yielded exactly same values of water productivity at different affinity levels.

doi: 10.2166/wp.2021.083

Introduction

Land and water are two important finite natural resources, which are diminishing at a faster pace due to indiscriminate and unscrupulous exploitation. Increased population pressure and sinking natural resources are matters of deep concern and present a challenge among planners and policy-makers to produce more from limited natural resources to feed the ever-increasing population. There is immense pressure on water available for agriculture and it can be gauged from the fact that due to increased demand and supply of water towards industrial, urban and domestic sectors, allocation of water for agriculture is expected to be reduced drastically in future. Under such a situation, the only feasible way is to realize the importance of water and plan its efficient use in crop production. In other words, those beneficial, as well as feasible options, which enhance water productivity are required to be explored. Molden *et al.* (2010) defined water productivity as net return per unit of water used and improvement in water productivity could be made possible by producing more food, better income livelihoods and ecosystem services with less water. Their study showed that levels of water productivity varied by commodity and scope for improvement existed. Two possible methods for enhancing water productivity are: (i) either increase agricultural production without allowing water consumption to increase, or (ii) sustain crop production and reduce water consumption (Upadhyaya & Sikka, 2015). Kang *et al.* (2017) presented two successful cases of improving agricultural water productivity in China. In the first case, crop water use efficiency was improved by applying a novel irrigation method based on crop physiological responses and in the second case, regional water productivity was improved by integrative methods in the Shiyang River basin of Northwest China. A scientific study, which determines maximum net return per unit of water, i.e, water productivity by allocating land under different crops, keeping in view the existing constraints of farmers as well as different scenarios of canal and groundwater use, may be quite helpful to farmers in planning and decision-making about efficient use of water as well as obtaining better production and net return. Optimization techniques are quite helpful in analysis and evolving a better plan of maximizing net return per unit of water (water productivity) under the prevailing constraints.

One of the most primitive optimization techniques to solve single objective function problem is linear programming (LP), which was employed by Hall & Dracup (1970) to maximize net return and select an optimum cropping pattern. Later on, Matanga & Marino (1979) determined the cropping pattern yielding maximum profit under limiting water supply employing the simplex method of linear programming. To determine the optimal storage in a reservoir to facilitate more intensive cropping for Mayurakshi project in India, Maji & Heady (1980) used a linear programming model considering chance constrained situation. Various other researchers, such as Yaron & Dinar (1982), Panda *et al.* (1996), Singh *et al.* (2001), El-Awar *et al.* (2001), Tanko *et al.* (2006), Igwe *et al.* (2011), Singh & Panda (2012), Majeke (2013), Singh (2014) and Bamiro *et al.* (2015) employed a linear programming model to determine optimal cropping pattern with a single objective of maximization of net return or farm income. Garg & Dadhich (2014) developed a non-linear programming model and determined optimal water releases and cropping pattern with maximization of net financial return under deficit irrigation for Khairpur East canal command of the lower Indus basin. They reported improvement in net financial return by 92.5% and increase in cropped area by 109.7% under deficit irrigation. Etedali *et al.* (2019) employed the linear programming technique to compute the optimal cultivated area for cereals in order to maximize the total national water footprint volume in irrigated and rainfed lands.

One of the important early contributions in fuzzy linear programming (FLP) was provided by Zimmermann (1976) and in detail by Zimmermann (2001). Chanas (1989) proposed a fuzzy programming in multi-objective linear programming (MOLP) problem and it was solved by a parametric approach. Czyzak (1989) applied a FLP method for solving multi-criteria agricultural planning problems under uncertainty. Lai & Hawng (1992) considered a MOLP problem with all parameters, having a triangular possibility distribution. Sakawa & Sawada (1994) presented an interactive fuzzy satisfying method for large-scale multi-objective fuzzy linear programming (MOFLP) problems with the block angular structure. Saad (1995) suggested a procedure for solving MOFLP problems and some basic stability notions have been characterized for MOFLP problems. Chang *et al.* (1997) explained the advantage of fuzzy multi-objective optimization over deterministic approach. The study considered the above aspects in the multi-objective FLP framework by incorporating three objectives, net benefits, crop production and labour employment, for selection of the compromised irrigation plan. Slowinski (1998) studied uncertainty and vagueness effect in agricultural production. Sakawa & Nishizaki (2001) presented an interactive fuzzy approach for multi-objective linear programming problems. Stanciulescu *et al.* (2003) proposed a new methodology that considers fuzzy decision variables for solving MOFLP problems. Sahoo *et al.* (2006) developed fuzzy multi-objective and LP-based management models in order to optimally plan and manage land, water and crop system in Mahanadi Kathajodi delta in eastern India. The crisp MOLP problems have been solved using the global criterion method and the distance functions method was proposed by Iskander (2008). In agricultural development planning, Peidro *et al.* (2009) proposed fuzzy optimization for supply chain planning under supply, demand and process uncertainties. Zeng *et al.* (2010) also applied a MOFLP model to crop area planning of Liang Zhouregion, Gansu province of northwest China, and then obtained the optimal cropping patterns under different water saving levels and satisfaction grades for water resources availability of decision-makers. Veeramani *et al.* (2011) studied MOFLP problems in which both technological coefficient and resources were considered fuzzy with linear membership function and discussed the method through an example. Behera & Rana (2013) applied the multi-objective fuzzy linear programming (MOFLP) technique to study various integrated farming system scenarios.

Li *et al.* (2017) developed an inexact multi-objective fuzzy programming (IMOLP) model considering the three objectives of maximizing benefits, minimizing evapotranspiration (ET) and maximizing water productivity and applied to solve the problem of crop area planning in Wiwei city in China. Results indicated that economic benefit, water productivity and water production efficiency of planting in the region increased by 7.05–16.65%, 25.68–33.15% and 39.22–47.59%, respectively, and ET reduced by 20.96–23.10%. The IMOLP model was advantageous over MOLP in effectively reflecting uncertainties expressed as discrete intervals and can provide reasonable solutions and more stable decision alternatives. An optimum land allocation plan with a view to improve farm productivity at ICAR-RCER, Patna, India was developed by Upadhyaya (2017) employing the simplex method of LP and the existing practice was found less profitable as compared to the proposed one. Similarly, the simplex method of LP was employed by Upadhyaya & Roy (2018) in the command of Bhagwanpur distributary of Vaishali Branch Canal under Gandak irrigation scheme in Bihar, India with a single objective of maximizing net return and optimum land allocation plan under different crops. Upadhyaya (2019) employed simplex LP method and MOFLP method in the command of Bhagwanpur distributary of Vaishali Branch Canal under Gandak irrigation scheme in Bihar, India considering three objective functions, i.e., maximization of net return, maximization of agricultural production and minimization of labour required under defined constraints. MOFLP was considered as one of the best methods capable of providing a compromise solution, which could fulfil all the objectives at a time.

In the recent past, some new algorithms such as swarm intelligence-based algorithms and evolutionary algorithms have also gained in popularity and give good results compared to traditional optimization methods (Varade & Patel, 2019). However, their algorithm-specific control parameters require proper tuning, which affects the performance of the algorithm and leads to either an increase in computation effort or reaching a local optimal solution. The teaching learning based optimization (TLBO) algorithm, developed by Rao *et al*. (2011), requires only common control parameters like population size and number of generations for its working. Rao (2015) mentioned the application of TLBO in a number of fields of engineering and computer science by optimization researchers. Aruna & Kalra (2017) reviewed the TLBO algorithm and its potential. They concluded that since TLBO does not require any algorithm-specific parameter, algorithm efficiency improves and error caused due to improper tuning of the specific parameters is removed.

Yang & Deb (2009) developed a meta-heuristic optimization algorithm known as cuckoo search (CS) and Yang (2010) discussed its applications in engineering optimization. The CS algorithm is a recently developed meta-heuristic optimization algorithm, which is suitable for solving optimization problems. Valian *et al*. (2013) enhanced the accuracy and convergence rate of the CS algorithm by tuning the cuckoo search parameters. According to them, improving the CS algorithm can successfully be applied to a wide range of optimization problems. Mohammadrezapour *et al*. (2017) described a case study of Qazvin plain, Iran, using cuckoo optimization algorithm for crop planning and concluded that this algorithm is quite promising in cultivation area of crops' optimization problem because of its simple structure, excellent search efficiency and strong robustness. Rath *et al*. (2019) formulated a cropping model for Hirakud command area in Odisha, India to optimize the cropping pattern by using the CS technique to maximize the net annual benefit. The processes of crop planning and crop rotation were given more emphasis, considering optimal allocation of scarce water resources highly necessary. The results indicated that the farmers were getting benefits of 0.975 million USD. The cropping pattern suggested by LINDO and CS technique yielded a net benefit of 1.07 million and 1.296 million USD per year, respectively. Boindala & Arunachalam (2019) reviewed the applicability of self-adaptive cuckoo search in the field of reservoir optimization and reported that the proposed algorithm was found to be working well. According to them, even with 80% dependable inflows, the reservoir could perform efficiently and could provide an annual net benefit of 1,770.3 million rupees. The above-mentioned review suggests that recent optimization algorithms like TLBO and CS are better than the primitive simplex method of linear programming optimization. This encouraged study of the comparative performance of these optimization algorithms when applied to maximize water productivity of a distributary command.

Keeping this in view, the study conducted in Bhagwanpur distributary of Vaishali Branch Canal in Gandak Canal command area, Bihar, as reported by Upadhyaya & Roy (2018), was revisited with the following objectives:

1. To formulate a single objective function problem of optimization of water productivity in terms of Rs./m^3 with allocation of distributary command area under different crops and solve by employing three algorithms, i.e. (i) LINPROG for simplex method of LP, (ii) TLBO and (iii) CS.
2. To study the comparative performance of all three optimization algorithms.
3. To determine improvement in water productivity over the water productivity of current cropping pattern.

Study area

Bhagwanpur distributary, which branches off from the Vaishali Branch Canal in Gandak command area is the project site and is shown in Figure 1 (Source: Gandak Command Area Development Authority, Muzaffarpur). The command area of Bhagwanpur distributary lies in the latitude between 25° 52′30″ and 26°3′0″N and longitude between 85°7′30″ and 85°15′0″ E and comprises Saraiya block of Muzaffarpur district and Vaishali block of Vaishali district. It runs through nine villages of Muzaffarpur district having 2,157 households and 16 villages of Vaishali district having 7,290 households,

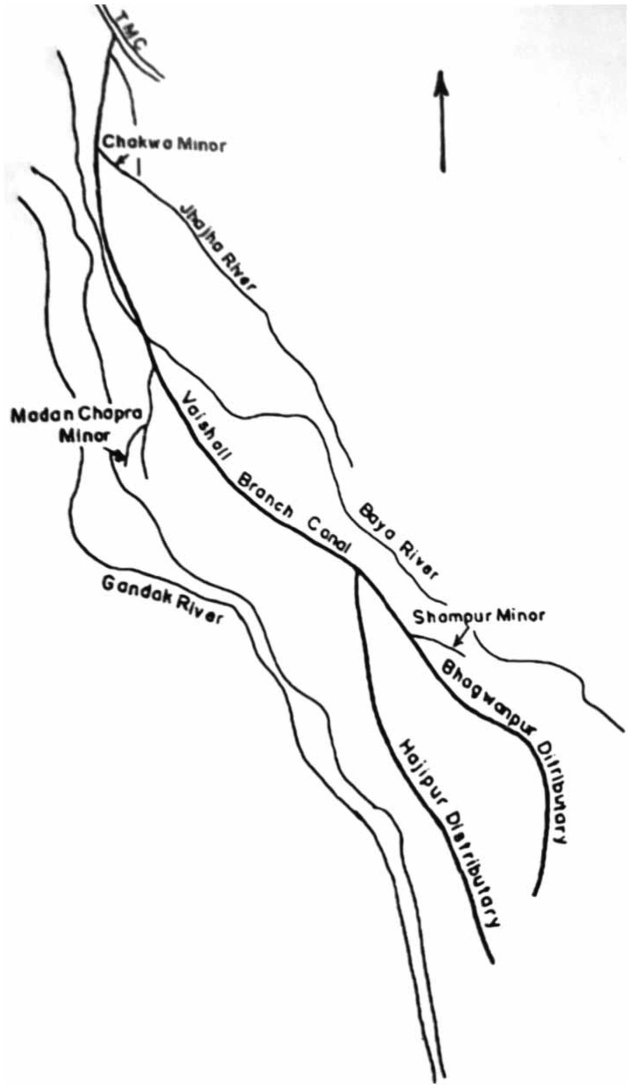

Fig. 1. Vaishali Branch Canal command area.

respectively. The total population in the command area is 50,975 persons. If the available labour force in the command area and annual average man-days for each labour are assumed as 20% and 200 man-days, respectively, there is no scarcity of labour in the area. State Agriculture Department reports indicated that the total cultivable command area (CCA) is 1,841 ha and the gross command area is 2,250 ha. The major crop was rice in 70% of the area followed by maize crop in the rest of the area during *kharif* (monsoon) season; wheat as the major crop in 60% of the area, followed by lentil in 30% area and potato in 10% during *rabi* (non-monsoon) season; and green gram in a limited area (30%) during the summer season. About 89% of the total rainfall (945 mm) occurs during mid June to the end of September and very little during summer and winter seasons. In the summer season, the temperature varies between 35 °C and 42 °C, whereas in the winter season temperature remains between 15 °C and 30 °C.

Methodology

Field survey

Data about inputs applied (like seeds, fertilizer, insecticides/pesticides, land preparation, farm implements, water and labour) and outputs produced (like main product and by-product), along with cost were collected through a developed questionnaire (Supplementary Material, Annexure 1) from 100 randomly selected farmers representing the whole command of Bhagwanpur distributary. Meteorological data for 30 years were collected from Muzzafarpur and Vaishali district from IMD, Patna. Data about canal water and groundwater availability and supply were also collected. The discharge of some representative tube wells was measured by filling a tank of 500 litre capacity and dividing it by time required to fill the tank. A total of 971 tube wells of shallow to medium depth, mostly diesel operated, were found in the project area. The average discharge of tube wells and average annual operation hours were estimated at 54 $m^3\ h^{-1}$ and 87 h, respectively. The total groundwater resources availability was estimated to be 456.17 ha-m. The canal water availability during different months was collected from Divisional Office of Water Resources Department, Sarraiya and the total canal water availability was estimated to be 466.74 ha-m. Same data of crop water requirement, irrigation requirement and labour requirement, cost of input, income from output and net return, as mentioned by Upadhyaya & Roy (2018), were used and are mentioned in Tables 1 and 2 for ready reference.

Table 1. Average yield, crop water requirement, irrigation requirement and labour requirement of various crops.

Sl. No.	Crop	Average yield (kg)	Crop water requirement (mm)	Net irrigation requirement (mm)	Labour requirement (man days ha^{-1})
1.	Rice	4,500	1,182	698	164
2.	Maize	4,000	336	132	84
3.	Wheat	3,500	267	222	75
4.	Lentil	2,000	240	193	62
5.	Potato	25,000	193	135	88
6.	Green gram	1,500	253	211	40

Table 2. Cost of input, income from output ant return of different crops.

Sl. No.	Crop	Cost of input (Rs.)	Income from output (Rs.)	Net return (Rs.)
1.	Rice	45,120	70,500	25,380
2.	Maize	25,960	60,250	34,290
3.	Wheat	38,430	60,500	22,070
4.	Lentil	33,695	73,000	39,305
5.	Potato	87,000	250,000	163,000
6.	Green gram	24,870	72,750	47,880

It was also realized during the field survey that farmers have a special affinity with the rice crop during *kharif* season and wheat crop during *rabi* season. Since rice and wheat are staple crops, farmers want to reserve some area under these crops as per their need and affinity. In this study, affinity level for rice and wheat crops varying between 10 and 40% at an interval of 10% was considered. Similarly, another affinity of farmers was to sow lentil and green gram in more than 30% of the net sown area and farmers do not want to sow green gram in more than 50% of the net sown area in the summer season.

Problem formulation

Based on the collected data and interactions with farmers of the project area, the problem consisting of single objective function and inequality constraints was considered and is discussed below.

Objective function: maximization of water productivity (Z_{WP})

$$\text{Max}\, Z_{WP} = \left[\sum_{i=1}^{3} \sum_{j=1}^{6} \frac{1}{IA_{ij}} [A_{ij}(Y_{ij}\, P_{ij} + YB_{ij}\, PB_{ij} - CP_{ij}) - \sum_{i=1}^{3} PCW_i \times A_i - PGW \times NH] \right] \quad (1)$$

where Z_{WP} is net annual return from all the crops of the command per unit of irrigation water applied (Rs.-ha/m^3); i = index for crop season (i = 1 for monsoon or *kharif* season, 2 for non-monsoon or *rabi* season and 3 for summer season); j = index for crop name (1 for rice, 2 for maize in monsoon season; 3 for wheat, 4 for lentil, 5 for potato in non-monsoon season; and 6 for green gram in summer season); A_{ij} = area to be allocated (ha) in season i for crop j; IA_{ij} = irrigation applied in season i for crop j (m^3); Y_{ij} = yield of crop j grown in season i (kg/ha); P_{ij} = current market price of crop j in season i (Rs./kg); YB_{ij} = yield of by-product of crop j grown in season i (kg/ha); PB_{ij} = current market price of by-product of crop j in season i (Rs./kg); CP_{ij} = cost of production (excluding irrigation water price) of crop j grown in season i (Rs./ha); PCW_i = price for canal water paid (Rs./ha); A_i is area covered by crops during monsoon, non-monsoon and summer season; PGW = price paid for groundwater applied (Rs./hr); NH = number of hours of operation in providing irrigation.

Constraints related to area:

$$\text{Constraint 1:}\quad A_R \geq 10\,\text{to}\,40\%\,\text{of CCA} \tag{2}$$

$$\text{Constraint 2:}\quad A_R + A_{Ma} \leq \text{CCA} \tag{3}$$

$$\text{Constraint 3:}\quad A_W + A_L + A_P \leq \text{CCA} \tag{4}$$

$$\text{Constraint 4:}\quad A_L + A_{Gg} \geq 30\%\,\text{of CCA} \tag{5}$$

$$\text{Constraint 5:}\quad A_{Gg} \leq 50\%\,\text{of CCA} \tag{6}$$

$$\text{Constraint 6:}\quad A_W \geq 10\,\text{to}\,40\%\,\text{of CCA} \tag{7}$$

Constraint related to labour:

Assuming 20% of the total population of the command, i.e., 50,975 persons and maximum 200 man-days each year, the maximum man-days available for agricultural operations are estimated at 2,039,000. Thus this constraint is expressed as:

$$\text{Constraint 7:}\quad 164A_R + 84A_{Ma} + 75A_W + 62A_L + 88A_P + 40A_{Gg} \leq 2{,}039{,}000 \tag{8}$$

Constraint related to canal and groundwater availability for use by crops:

Canal water was available during *kharif* (monsoon) season. The total canal water availability was estimated as 466.74 ha-m. Thus, net irrigation requirement of rice and maize multiplied by the area to be allocated under these crops should not exceed the total available canal water during the monsoon period in the command. It is expressed as:

$$\text{Constraint 8:}\quad 0.498A_R + 0.132A_{Ma} \leq 466.74\,\text{ha} - \text{m} \tag{9}$$

Groundwater availability was estimated as 456.17 ha-m, which was obtained by counting the number of tube wells in the command (971) and multiplying it with average discharge (54 m^3/h) as well as average hours of operation in a year (87 h). Thus, the net irrigation depth required to be met by groundwater, partially for rice during the monsoon period and for all other crops during the non-monsoon period should not exceed the total available groundwater. It is expressed as:

$$\text{Constraint 9:}\quad 0.2A_R + 0.222A_W + 0.193A_L + 0.135A_P + 0.211A_{Gg} \leq 456.17 \tag{10}$$

Here, A_R, A_{Ma}, A_W, A_L, A_P and A_{Gg} are area in ha to be allocated under rice, maize, wheat, lentil, potato and green gram, respectively.

TLBO algorithm

The TLBO technique is motivated by the process of sharing knowledge in the classroom, where students first learn from a teacher and then share knowledge among themselves through discussion. It is a population-based technique in which a batch of students is considered as the population. The student of a group represents a realizable solution of the problem, various subjects given to the group of students are defined as design parameters of the problem and the result of the student is considered as the fitness value (the value of objective function) of the realizable solution of the problem. The areas of different crops in this case are the parameters of the problem, which are subjects of the students. This algorithm comprises two phases: the first phase is the teacher phase and the second is student phase. In this research, TLBO was used to find the areas to be allocated under different crops, which optimize the objective function taking various constraints mentioned above into consideration. For this problem the population size for the TLBO algorithm was taken to be 50 and the value of maximum number of generations was 6,000.

Cuckoo search

Cuckoo search is an optimization technique formulated by Yang & Deb (2009). It is influenced by the breeding characteristics of a few cuckoo birds, laying their eggs in the nests of birds of different species. When some host birds realize that the eggs are not their own, then either they will destroy the unfamiliar egg or simply desert their nest and construct a new nest somewhere else. A cuckoo might follow the shape, colour and size of the host eggs to save it from being detected, while some cuckoos might throw other local eggs from the host nest to enhance the probability of hatching of their own eggs and a hatched egg will remove other eggs to improve their nourishment. This technique works on the concept of breeding behaviour of cuckoos by evaluating the solutions for a problem i.e., the value of fitness function as alien cuckoo eggs in nests of different birds, the search starts with a predetermined number of nests which contains the candidate solution which is the value of areas in this case to develop an initial set of solutions; the generated solution advances from one iteration to the next while a number of solutions will be discarded and substituted by a new solution to develop the concept of unfamiliar egg detection in the cuckoo world.

This technique depends upon the Lévy flight as the random walk to generate new solutions from the present solution according to the given equation:

$$cuckoo_j^{(u+1)} = cuckoo_j^{(u)} + \alpha \oplus \text{Lévy}(\lambda) \tag{11}$$

where $cuckoo_j^{(u+1)}$ is the value of the j^{th} cuckoo at instance u, α: step size, generally chosen to be equal to one, λ: Lévy distribution coefficient ($1 < \lambda < 3$). A few new solutions are created from the best present solutions by Lévy walks; this gives cuckoo search the potential of local search along with the capability of self-improvement as in memetic algorithms. In cuckoo search we chose the parameters given in Table 3.

Results and discussion

Water productivity for the existing cropping pattern in the Bhagwanpur distributary command was computed by dividing net return from all the crops with irrigation water applied and is given below in Table 4.

Table 3. Tuning parameters.

Parameters	Value
Number of nests	40
Lévy exponent	1.5
Maximum iterations	6,000
Number of dimensions	6
Lower bound	[0 0 0 0 0 0]
Upper bound	[1841 1841 1841 1841 1841 1841]
Discovery rate of unfamiliar solutions	0.25

Table 4. Water productivity for existing cropping pattern in Bhagwanpur distributary command.

Existing crops	Area (ha)	Per cent of command area	Value of objective function (Rs.−ha/m^3)	Water productivity (Rs./m^3)
Rice	1,288.7	70	12,854.78	9.98
Maize	552.3	30	24,265.30	43.93
Wheat	1,104.6	60	29,613.22	26.81
Lentil	552.3	30	20,598.58	37.29
Potato	184.1	10	34,093.48	185.20
Green gram	552.3	30	19,045.51	34.48
Total	4,234.3	230	140,470.87	140,470.87/4,234.3 = 33.17

Table 4 shows that according to the existing cropping pattern, 70% of the area is covered by rice and 30% maize during the monsoon season; 60% wheat, 30% lentil and 10% potato during the non-monsoon season and 30% of the area by green gram during the summer season. This gives a total area of 4,234.3 ha, which is 230% of 1,841 ha. In other words, cropping intensity is 230%. The total value of objective function is 140,470.87 Rs.-ha/m^3, which when divided by the total cropped area of 4,234.3 ha gives water productivity value of the command as 33.17 Rs./m^3. This value is quite low and can be improved. The value of water productivity varies from a minimum of 9.98 Rs./m^3 for rice crop to a maximum of 185.19 Rs./m^3 for potato crop. This gives a clue that the area under potato crop should be increased to increase overall water productivity provided water is available.

The single objective function problem along with defined constraints was solved employing TLBO and CS algorithms and results of Z_{WP} as well as area allocated under six crops at different affinity levels varying between 10 and 40% were compared with the results obtained from one of the primitive simplex methods of solving single objective linear programming problem employing LINPROG algorithm. Results for affinity levels varying between 10 and 20% are presented in Tables 5–8, respectively.

It may be observed from Table 5 that all three algorithms estimate exactly the same area under each crop at affinity levels of 10 and 20%. In monsoon season, total cropped area is 1,841 ha, with only a difference of interchange in the area of rice and maize crops at 10 and 20% affinity levels. Similarly, during the non-monsoon period, at 10% affinity level area under potato crop is more and under wheat and lentil crops is less than the area under these crops at 20% affinity level. The area under green gram during the summer season at 10% affinity level is 733.64 ha, which is more the area at 20% affinity level.

Table 5. Area allocated under different crops at 10 and 20% affinity levels as obtained employing TLBO, CS and LINPROG.

	Affinity level 10%			Affinity level 20%		
Area	TLBO	CS	LINPROG	TLBO	CS	LINPROG
A_R	184.10	184.10	184.10	368.20	368.20	368.20
A_{Ma}	1,656.90	1,656.90	1,656.90	1,472.80	1,472.80	1,472.80
A_W	184.10	184.10	184.10	368.20	368.20	368.20
A_L	0.00	0.00	0.00	92.25	92.25	92.25
A_P	1,656.90	1,656.90	1,656.90	1,377.55	1,377.55	1,377.55
A_{Gg}	733.64	733.64	736.64	457.05	457.05	457.05

Table 6. Value of objective function, total area covered by crops in a year and water productivity at 10 and 20% affinity levels as obtained employing TLBO, CS and LINPROG.

	Affinity level 10%			Affinity level 20%		
Item	TLBO	CS	LINPROG	TLBO	CS	LINPROG
Value of objective function (Rs.−ha/m^3)	411,708.03	411,708.03	411,708.03	352,672.64	352,672.64	352,672.64
Total area (ha)	4,415.64	4,415.64	4,415.64	4,136.05	4,136.05	4,136.05
Water productivity (Rs./m^3)	93.24	93.24	93.24	85.27	85.27	85.27

Table 7. Area allocated under different crops at 30 and 40% affinity levels as obtained employing TLBO, CS and LINPROG.

	Affinity level 30%			Affinity level 40%		
Area (ha)	TLBO	CS	LINPROG	TLBO	CS	LINPROG
A_R	552.30	552.30	552.30	736.40	736.40	736.40
A_{Ma}	1,288.70	1,288.70	1,288.70	757.67	757.67	757.67
A_W	552.30	552.30	552.30	736.40	736.40	736.40
A_L	440.59	440.59	440.59	552.30	552.30	552.30
A_P	848.11	848.11	848.11	287.52	287.52	287.52
A_{Gg}	111.71	111.71	111.71	0	0	0

Table 8. Value of objective function, total area covered by crops in a year and water productivity at 30 and 40% affinity levels as obtained employing TLBO, CS and LINPROG.

	Affinity level 30%			Affinity level 40%		
Item	TLBO	CS	LINPROG	TLBO	CS	LINPROG
Value of objective function (Rs.−ha/m^3)	254,280.63	254,280.63	254,280.63	134,220.64	134,220.64	134,220.64
Total area (ha)	3,793.71	3,793.71	3,793.71	3,070.29	3,070.29	3,070.29
Water productivity (Rs./m^3)	67.03	67.03	67.03	43.72	43.72	43.72

Table 6 shows objective function value (Rs.-ha/m^3), total cropped area (ha) and water productivity (Rs./m^3) at 10 and 20% affinity levels. It may be observed that the value of objective function, total area covered by crops and water productivity values obtained by all three algorithms are exactly the same and there is a decreasing trend. Objective function value reduced from 411,708.03 to 352,672.64, i.e. (14.34%); total area covered under all six crops reduced from 4,415.64 to 4,136.05, i.e. (6.33%); and water productivity reduced from 93.24 to 85.27, i.e. (8.55%), when the affinity level increased from 10% to 20%. This indicates that rice and wheat crops consume relatively more water and give less net return compared to other crops, so when the area under these crops increases, total area covered under the crops as well as water productivity decreases.

Table 7 also shows that the area under each crop at affinity levels of 30 and 40% estimated by all three algorithms is exactly the same. In the monsoon season, total cropped area is 1,841 ha (30% under rice and 70% under maize) and 1,494.07 ha (49.29% under rice and 50.71% under maize) at 30 and 40% affinity levels. Similarly, during the non-monsoon period, the 30% affinity level area under potato crop is 2.95 times higher than the area at 40% affinity level. The area under wheat and lentil crops increased from 552.30 ha to 736.4 ha and 440.59 to 552.30 ha, respectively, on increase in affinity level from 30% to 40%. Area under green gram during the summer season at 30% affinity level is obtained as 111.71 ha, whereas it is nil at 40% affinity level.

Table 8 shows objective function value (Rs.-ha/m^3), total cropped area (ha) and water productivity (Rs./m^3) at 30 and 40% affinity levels. It may be observed that the value of objective function, total area covered by crops and water productivity values obtained by all three algorithms are exactly the same and there is a decreasing trend. Objective function value reduced from 254,280.63 to 134,220.64; total area covered under all six crops reduced from 3,793.71 ha to 3,070.29 ha; and water productivity reduced from 67.03 to 43.72, when the affinity level increased from 30% to 40%. This indicates that rice and wheat crops consume relatively more water than other crops, so when the area under these crops increases, total area covered under all the crops as well as water productivity declines.

It may be noted from Table 9 that the value of objective function reduces by 14.34% for change of affinity level from 10% to 20%; 27.90% for change of affinity level from 20% to 30%; and highest, 47.29% for change of affinity level from 30% to 40%. Similarly, total area covered and water productivity also reduce by 6.33% and 8.55% on shifting of affinity level from 10% to 20%; 8.28% and 21.39% on shifting of affinity level from 20% to 30%; 8.55% and 34.78% on shifting of affinity level from 30% to 40%. It may be inferred from the above that on shifting of affinity level from 10% to 20%, reduction in values of objective function, total area covered and water productivity is less, but on increase in affinity level from 20% to 30% and 30% to 40% there is a sharp decline in values. Although rice and wheat crops are staple crops and essential to fulfil food requirements,

Table 9. Per cent reduction in value of objective function, area covered under crops and water productivity with increase in affinity level.

Per cent reduction	Affinity level from 10% to 20%	Affinity level from 20% to 30%	Affinity level from 30% to 40%
Value of objective function	14.34	27.90	47.29
Total area	6.33	8.28	8.55
Water productivity	8.55	21.39	34.78

allowing more than 20% area under rice and wheat crops in the command does not seem beneficial from the water productivity point of view. Hence, only 20% of area under rice and wheat crops may be recommended.

Figures 2–5 show the convergence abilities of CS and TLBO techniques for 10%, 20%, 30% and 40% affinities, respectively, for 6,000 iterations. In all cases of varying affinities the TLBO technique

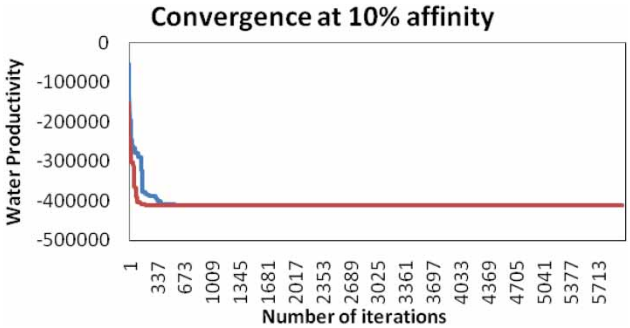

Fig. 2. Convergence graph of CS and TLBO at 10% affinity.

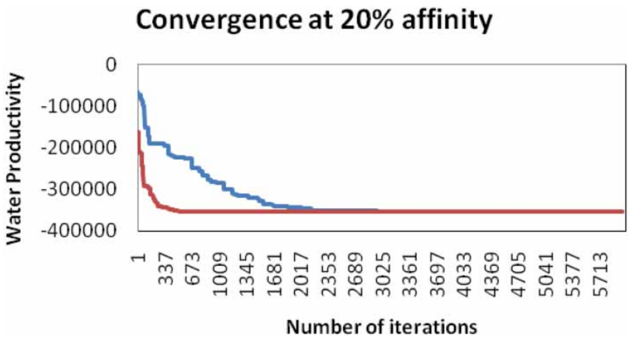

Fig. 3. Convergence graph of CS and TLBO at 20% affinity.

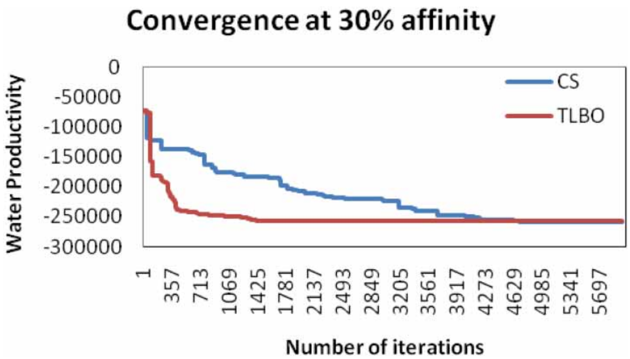

Fig. 4. Convergence graph of CS and TLBO at 30% affinity.

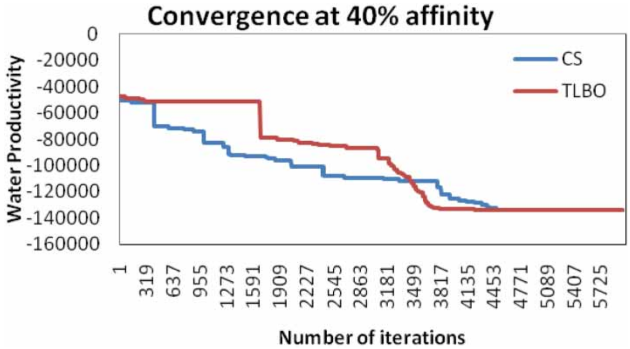

Fig. 5. Convergence graph of CS and TLBO at 40% affinity.

reaches the optimum value of objective function before the CS technique which means that the TLBO algorithm requires less number of iterations and time to converge to the optimum value.

Conclusions

Enhancement in productivity and net return are two indicators that may help planners and decision-makers to select those crops and cropping patterns which are efficient, profitable and encourage farmers to utilize land and water more efficiently and judiciously. Since the availability of land and water to the agriculture sector is expected to decrease in future due to increasing demand in other sectors and pressure to produce more food will rise to feed the ever-increasing population, the only possible pathway is efficient use of land and water leading to enhanced productivity or net return. To get optimum value of water productivity for the crops grown in the command of Bhagwanpur distributary, a single objective problem was formulated and solved through three optimization algorithms, namely, (i) LINPROG, (ii) TLBO and (iii) CS. It was observed that there was no difference in the area allocated under various crops and water productivity at different affinity levels (i.e., % minimum area farmers reserve to produce staple crops rice and wheat varying between 10 and 40%) computed by all three algorithms. The convergence graphs of TLBO and CS algorithms were also given and show that TLBO takes a lesser number of iterations to converge to optimum value of the objective function than CS in all four cases of varying affinities. Water productivity value computed for the existing cropping pattern in the command was the least, 33.17 Rs./m^3 with total cropped area of 4,234.3 ha. The maximum water productivity of 93.24 Rs./m^3 with total cropped area of 4,415.64 ha at 10% affinity level and minimum of 43.72 Rs./m^3 with total cropped area of 3,070.29 ha at 40% affinity level was obtained. Water productivity was found to decline, 8.55%, 21.39% and 34.78%, when affinity levels increased from 10% to 20%, 20% to 30% and 30% to 40%, respectively. There is sharp decline in water productivity values when affinity level shifts from 20% to 30%, which indicates that allocation of more than 20% area of the command under rice and wheat crops may not be beneficial from the water productivity point of view. The water productivity of suggested cropping pattern at 20% affinity level is 85.27 (Rs./m^3), which is 2.57 times higher than the water productivity of the existing cropping pattern. This study is quite helpful in planning and decision-making, as well as convincing farmers about efficient use of land and water by crops, and also suggests the optimum allocation of area under those crops which consume less water but give more net return in the distributary command area.

Data availability statement

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

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Received 8 May 2020; accepted in revised form 23 November 2020. Available online 20 January 2021