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Optimal Crop Yield under Limited Water Availability –A Linear Programming Approach

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Abstract—*Water is still a scarce resource in many parts of India, at least during some period in a year or so. Shortage of rainfall coupled with its erratic distribution and infiltration during rainy season causes water deficit both in surface and subsurface water sources. Droughts of different intensity result as an obvious possible outcome. Non-availability of adequate quantity of irrigation water adversely affects crop production as a consequence. Optimal allocation of limited irrigation water available becomes a prerequisite for sustainable development. In this study a model based on linear programming (LP) is developed to tackle such adverse natural calamity with a view to optimize crop yield. The developed mathematical model considers optimal allocation of limited irrigation water in order to maximize crop yield. For illustrative purpose, conditions generally observed in a typical Indian city are considered. The linear programming based optimization model considers optimal allocation of water for five crops at two agricultural units during individual crop's growth stages while satisfying several constraints. Two scenarios of the developed LP model are considered in this study. The developed models are solved using LINGO solver (GAMS/LINGO) developed by GAMS (The General Algebraic Modeling System, USA). Limited results obtained show that the developed LP model has the potential to solve real world problems in order to maximize crop yield under adverse conditions.*

Keywords: *Limited water availability, irrigation water, optimal crop yield, linear programming, crop growth stages, GAMS/LINGO.*

1. INTRODUCTION

Shortage of rainfall causes water deficit both in surface and subsurface water sources. Drought is a natural calamity which may threaten lives of human beings as well animals. Limited availability of irrigation water causes significant reduction in crop production. Such a situation undoubtedly requires proper planning and implementation so that the available irrigation water can be utilized optimally in order to maximize crop yield .On an average, 28 percent of the geographical area in India is vulnerable to droughts. Optimal allocation of available water is the only efficient way to overcome such a water crisis situation during droughts. Various models have been reported in literature where optimal allocation of limited water is suggested for maximizing crop yield in adverse situations. Mohan and Arumugam (1997) and Shangguan et al. (2001) reported 50 percent reductions in water demand during water scarcity using revised irrigation planning and optimization techniques. Rescheduling irrigation by taking into consideration factors, such as available water, growth stages can be more effective in decreasing both water consumption and unnecessary wastages. In case water is supplied to crops according to their growth stage based requirements, wastage of water can be minimized while ascertaining better crop yield.

A review of the literature shows that these factors have hardly been considered for drought management. Yaron and Dinar (1982) presented a recurrence method using linear programming (LP) and dynamic programming (DP) to resolve water allocation across crops. In this paper the optimization model based on linear programming is developed to allocate water optimally considering fives Rabi crops at two different agricultural units. Two scenarios are considered while solving the model. Wastage of water is considered while solving the models.

2. MODEL FORMULATION

Optimization model based on linear programming is developed for optimal allocation of water when there is scarcity of water. The objective is to maximize crop yield.

$$\text{Maximize: } Z = \sum_{i=1}^{N1} \sum_{j=1}^{N2} x_{ij} y_j \tag{1}$$

Subject to:

$$\sum_{j=1}^{N2} x_{ij} \le A_i \text{, for all } i = 1, N1 \tag{2}$$

$$F_1 \sum_{i=1}^{N1} \sum_{j=1}^{N2} c_{ij} x_{ij} \le TMA \tag{3}$$

$$F_2 \sum_{j=1}^{N2} 10^4 x_{ij} m_j \le MAW_i^k \text{ for all i=1 ,N1} \quad (4)$$

$$F_2 \sum_{i=1}^{N1} \sum_{j=1}^{N2} 10^4 x_{ij} m_j \le \sum_{i=1}^{N1} MAW_i^k \quad (5)$$

$$\left(\frac{1}{10}\right) x_{ij} y_j \ge myt_j \text{ , for all i=1, N 1and j=1, N2} \quad (6)$$

$$x_{ij} \ge x_{ij}^L \text{ , for all i=1, N 1and j=1, N2} \quad (7)$$

$$x_{ij} \le x_{ij}^U \text{ , for all i=1, N1 and j=1, N2} \quad (8)$$

Where,

N1: Number of agricultural units;

N2: Number of crops to be cultivated;

x_{ij} *:* Area to be allocated at unit *i* to crop *j* (in hectares);

y_j : Average yield of crop *j* (quintals/hectare);

c_{ij} : Cost of production at unit i for crop *j* (Rupees/hectare);

A_i: Culturable command area at unit *i (hectares);*

TMA: Total money available for production of crops at all units (Rupees);

F_1: Factor for cost escalation with regard to data available for 2003-2004;

m_j: Average monthly water requirements for crop *j* (in meters);

MAW_i^k*:* Monthly available water at unit *i* at month *k* (cubic meters);

F_2: Factor for consideration of wastage of water;

myt_j : Minimum production of crop *j* required (in tons);

x_{ij}^L : Minimum area to be allocated at unit *I* to crop *j* (hectares);

x_{ij}^U: Maximum area to be allocated at unit *I* to crop *j* (hectares);

In the performance analysis of the developed model, N1 is taken to be two while the number of crops, N2, to be cultivated is considered as five. Two scenarios, viz. Case 1 and Case 2 are considered. In Case 1 scenario, it's assumed that water available in a unit is not transferable to the other unit while Case 2 considers mutual transfer possible between units. Solving of Case 1 models, all constraints except constraint (5) are considered. The Case 2 models, however, requires deletion of constraint (4).

3. RESULTS AND DISCUSSION

Data used for solving the developed models are given in tabular formats. In Table 1, the gross command areas and the culturable command areas for each unit are given. Table 2 contains individual growth stages (in days) for the five crops, viz, wheat, barley, maize, potato, and onion, are detailed. Table 3 contains data of average yield (quintals/hectare) for each of the five crops. In Table 4, the minimum yield (in tons) requirements for each of the crops are mentioned. The costs of cultivation (in Rupees/hectare), based on 2003-2004 statistics, in the two units are given in Table 5. These costs are escalated, by 30 %, 50 %, and 100 %, while solving the models. In Table 6, month wise irrigation water availability (in cubic meter) at each of the two units is detailed. In performance analysis, it's assumed that not more than 25 % of the area at a unit can be allotted to any crop while at least 5 % of the area at a unit must be allotted to each crop. Transportation of water from the source up to the crops at field involves a huge amount of loss of water. In solving these models, wastage varying from 10 % to 20 % is considered. Total money available for production of five crops at both the units is considered to be Rs. 15,000,000. The optimization method used for solving the models is GAMS/LINGO (The LINGO solver under GAMS, the General Algebraic Mathematical Systems, USA.

The performance analyses reported in this study are based on data matching for a typical Indian agricultural area. As a result, the models can be of immense use while dealing with maximizing crop yield under limited water availability while satisfying other constraints. All the crops considered in this study are Rabi crops, generally grown during November to March in India. The results are tabulated in detail in Table 7.

During the performance analysis of unit1 with case 1 scenario when wastage is 20% and cost escalation is 30% total area of the unit 1 is found to be 505.8 hectare .When considered with wastage 20% and cost escalation 100% in case 1 scenario, total area of unit1 is found to be 459.4 hectare. Case2 scenario for unit 1 with wastage 20% and escalation 50% is considered ,total area of unit1 is found to be 504 hectare and again when wastage20% and cost escalation 100% is taken ,total area of unit1 is found to be 459.4 hectare.

While performance analysis of unit2 considering case1 scenario with wastage 20% and cost escalation

30% ,total area of the unit2 is found to be 260 hectare .If considered with wastage 20% and escalation 100% for case1 ,total area of unit 2 found that 100.4 ha . Case 2 scenario with wastage 20% and escalation 50% ,total area of unit 2 is found to be 199 hectare .Finally with wastage 20% and cost escalation 100% for case 2,total area of unit 2 is found to be 100.4 hectare.

Table 1: Area for each units (hectare) (Assumed Data)

Units	Gross Command Area (GCA)	Culturable Command Area (CCA)
1	875	700
2	500	400

Table 2: Individual Growth Stages (Days) for crops in India (F.A.O)

Crops	Vegetative Stage	Flowering Stage	Yield formation Stage	Ripening Stage
Wheat	15	25	50	30
Barley	15	25	50	30
Maize	25	40	45	30
Potato	25	-	45	30
Onion	20	-	20	10

Table 3: Average Yield of Principal crops in India

Crops	Yield (q/ha)
Wheat	25.11
Barley	16.01
Maize	15.54
Potato	166.26
Onion	180.00

Table 4: Minimum Yields Requirement of crops (Tons)

Crops	Minimum Yields
Wheat	125
Barley	100
Maize	150
Potato	2500
Onion	2000

Table 5: Cost of Cultivation per hectare (Rupees) (Data taken from 2003-04 Statistics)

Crops	Units	
	1	2
Wheat	11501	13181
Barley	8195	9639
Maize	6336	7404
Potato	24049	25381
Onion	10174	11599

Table 6: Month wise Water Availability in two units (m3)

Units	Nov	Dec	Jan	Feb	Mar
1	938298	807049	544548	380485	40170
2	535520	460250	310250	216500	40167

Table 7: Area Allocation of different crops (hectare)

Crops	Case1 W=20%, e=30%		Case2 W=20% e=50%		Case1 W=20%, e=100%		Case2 W=20% e=100%	
	Area Allocated		Area Allocated		Area Allocated		Area Allocated	
	Unit 1	Unit 2	Unit 1	Uni t2	Unit 1	Unit 2	Unit 1	Unit2
Wheat	35.0	20.0	35.0	20.0	35.0	20.0	35.0	20.0
Barley	42.5	20.0	42.5	20.0	42.5	20.0	42.5	20.0
Maize	78.3	20.0	76.5	20.0	76.5	20.0	76.5	20.0
Potato	175	100	175	39.8	130.4	20.0	130.4	20.0
Onion	175	100	175	100	175	20.4	175	20.4
Optimal Solution	99130.98		89100.68		64057.26		64057.26	

W :Water wastage while transportation
Case1: Water non-transferable between units
Case2: Water transferrable between units
e: Cost escalation

4. CONCLUSION

The LP based model developed for optimal allocation of areas for maximizing crop yields under water scarcity taking data similar to the ones, generally observed in typical areas of India. Limited results obtained show that the LP model can be a potential tool in tackling such a situation with optimal allocation of water available to the desired crops so as the increase yield. In this study, only five Ravi crops are considered. The number of crops as well as the units can be increased without making any modification in the model. It's obvious that various extension and modifications in the model is possible incorporating constraints that arise in a particular locality. The GAMS/LINGO used for solving the model can be replaced with other optimization methods also. Nonetheless, the limited results obtained are encouraging showing potential applicability of the models in solving real life optimal irrigation problems.

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