A MODEL FOR OPTIMUM WATER ALLOCATION WITH ADEQUATE AND LIMITED WATER SUPPLIES

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ABSTRACT-Opportunities for the significant capture of new water are now limited. Efficient use of water in agriculture and to increase productivity of limited water resources is the only solution therefore, it is especially important to introduce better management practices.

The model consists of three levels. The first level involves production functions for each crop under different farm size groups. The second level deals with a non-linear programming model for optimum allocation of water resource among various crops on farm level. The third level concerns a dynamic planning of water distribution plan at a maximum level between seven different size farms under a tertiary channel for adequate and limited water supply conditions. Current water allocation practices among farmers also evaluated in order to indicate the performance of dynamic modeling.

After the examination of NLP and dynamic model solutions, small, medium and large farm incomes are 8486, 25459, 59405 € for adequate water supply conditions, respectively. Hence, an irrigation unit with limited water supply can obtain higher income when distributions of water among farms are equal. Moreover, more farmers may benefit from water supply. These results indicate that irrigating more land with available water supply, delivering water equally to farms on deficit irrigation are essential.

KEYWORDS: Non-linear programming, dynamic programming, deficit irrigation, allocation of water resources, irrigation scheduling, limited water supply, optimization

Introduction

Water scarcity in semi-arid and arid areas is a well-known and alarming problem. Today the issue is of increasing concern to national governments and research institutions. Increasing water scarcity is threatening the economic development and the stability. At present, agriculture accounts for over 75% of the total consumption of water. However, with rapidly growing demand, it is certain that water will increasingly be reallocated away from agriculture to other sectors. Moreover, opportunities for the significant capture of new water are now limited. Only solution to this problem is to make efficient use of water in agriculture and to increase productivity of limited water resources (Shangguan et al. 2002). Therefore, efficient management of water resources is especially important to introduce better management practices.

Scientists are searching for ways to overcome this problem and a number of options for utilizing the existing resources more efficiently have been explored. Much work has been done in;

i. optimized irrigation scheduling for different crops,
ii. optimized crop patterns for farms and
iii. efficient water allocation for irrigation network.

Kumar et al. (1998) formulated a non-linear programming problem for identifying an optimal cropping pattern as well as optimal deficit irrigation schedule. Carvallo et al. (1998) have developed a non-linear optimization problem for the determining optimal cropping patterns. Gulati and Murty (1979) have developed a model for optimal distribution of water in the canal command area. Shangguan et al. (2002) formulated a recurrence control model for regional optimal allocation of irrigation water resources, aiming at overall maximum efficiency. Mujumdar (2002) presented some mathematical tools for irrigation system operation, crop water allocations. Benli and Kodal (2003) have developed a non-linear model for the determination of optimum cropping pattern, water amount and farm income under adequate and limited water supply conditions.

Decision making for water allocation involves many subtle considerations such as the nature and timing of the crop being irrigated, its stage of growth, competition among crops for a limited amount of available water and the effect of a deficit water supply on the crop yield (Mujumdar, 2002). Dynamic programming is one way to preview strategies and to test decisions on a seasonal basis. It is a multistage optimising scheme that involves the choice of discrete quantities of irrigation water distribution among the farms over the course of the growing season that will maximize the sum of the contributions to net returns for the growing season (Epperson et al. 1993).

Main objective of this paper is to develop an allocation model which optimizes the use of water resources (adequate and limited), among an irrigation unit under a tertiary channel.

Basic characteristics of the region

As a test the model applied to a semi-arid region in Central Anatolia Plateau, Ankara Sogulca irrigation project in Turkey (39° 36` N; 32° 40`E, elev. 1050 m.). The reservoir's available water storage capacity is 3.8 million m^3 with a watershed of 59 km^2. The irrigation district is around 555 ha and 100 farmers are going to utilize the reservoir as a water resource for irrigation. Irrigation network is still under construction, and the area has not been opened to irrigation yet, so that the actual crop pattern is 50% cereal and 50% fallow. An irrigation unit with seven farms from different scales such as: four small scale (5 ha), two medium scale (15 ha) and one large scale (35 ha), were chosen for determining optimum water allocation among them in this research (Fig 1).

According to the Thornthwaite (1948) classification system, Ankara is in a semi-arid climate zone with dry summers. Long term (25 years) climate values as mean average temperature is 9.5ºC, average annual relative humidity is 65%, average annual rainfall is 385 mm and the average wind speed at 2 m is 2.1 m/s.

Many cropping alternatives are available to producers in this area. Eleven crops were chosen on the basis of climate and market conditions for this research. For the study irrigated crops include barley, wheat, sunflower, sugarbeet, corn, tomato, pepper, onion, melon, chickpea and vetch. Rainfed crops include wheat, barley, sunflower, melon, chickpea and vetch.

The predominant soil type in the area is brown loam soil that holds about 120mm of available water per meter of soil depth. The basic infiltration rate is 20 mm/h.

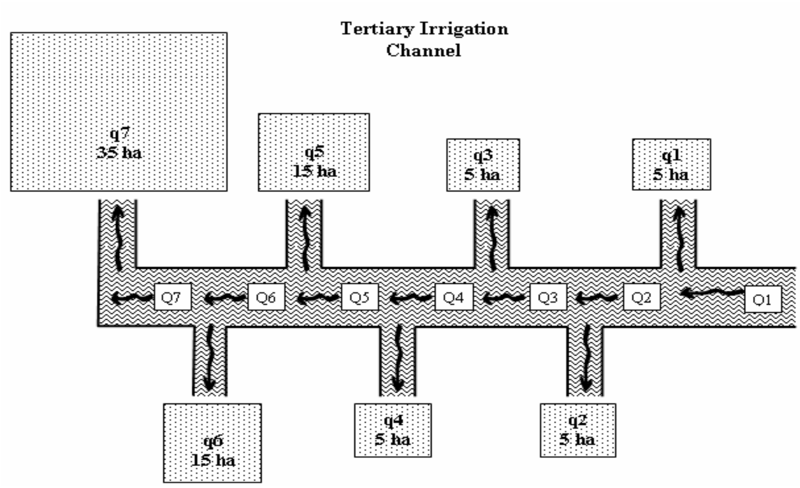

Fig 1. Irrigation unit under a tertiary channel with different farm sizes.

Methodology

The main purpose of the methodology is to establish optimum water allocation and maximum income. The flow chart of the methodology in the study is shown in Fig 2. The model consists of three levels. The first level involves production functions for each crop under different farm size groups. The second level deals with a non-linear programming model for optimum allocation of water resource among various crops on farm level. The third level concerns a dynamic planning for water distribution plan at a maximum level between seven different size farms. A brief description of each of the levels is as follows:

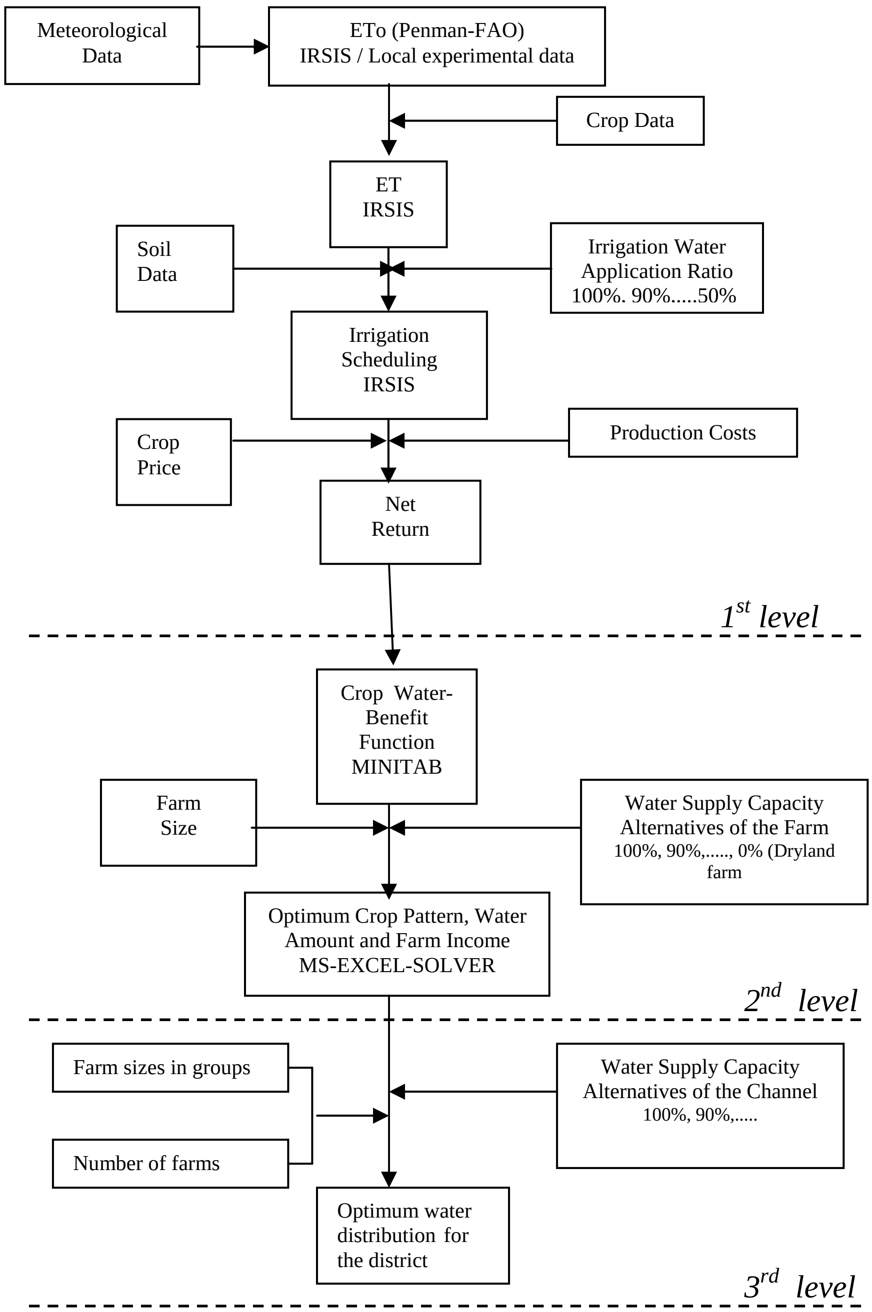

Fig 2. Flow chart of the model.

Level 1: Production functions for each crop

The production functions for the selected crops were developed using the data on climate, crop, soil, irrigation scheduling, crop price, production costs for the region under consideration. The IRSIS software (Raes et al. 1988) was used to schedule irrigations for each combination of crop and irrigation application level. Exploitations in the irrigation union are in different scales. Family labour force capacity and labour force requirement were calculated for each farm type, considering the social form of the region, and expenses added to the production costs.

The relationship between the irrigation water and net return has been accepted and solved as in non-linear form. Non-linear (second degree polynomial) crop production functions have been generated from the net return values obtained from various quantities of irrigation water applied for each crop.

Level 2: Non-linear programming model for optimum crop pattern and water levels

A non linear model (Benli and Kodal 2003), has utilized for the optimal allocation of a given amount of water among different crops based upon water production functions of the selected crops. For the purpose of generating the model, crops in the exploitation were grouped as shown in Table 1

Table 1. Index groups of crops

Index	Explanation	Crops
i	All crops	Barley, wheat,sugarbeet, maize, sunflower, tomato, pepper, chickpea, melon, vetch, onion, rainfed wheat, rainfed barley, rainfed sunflower, rainfed melon, rainfed chickpea, rainfed vetch.
iw	Winter crops	Barley, wheat, rainfed wheat, rainfed barley,.
is	Summer crops	Sugarbeet, maize, sunflower, tomato, pepper, chickpea, melon, vetch, onion, rainfed sunflower, rainfed melon, rainfed chickpea, rainfed vetch.

The profit attainable is represented by the following function:

$$Z_{\max} = \sum_{i=1}^{n} Bf_i . A_i$$

$$B_{fi} = a_0 + a_1 x_i + a_2 x_i^2$$

Where; Z: maximum net return for the farm ($), Bf: Crop water-benefit function per hectare for i^{th} crop, A: surface occupied by each crop (ha), Xi: Net irrigation water for i. crop, mm

The mathematical programming envisages an objective function that maximizes Z, subject to the following constraints, which were considered along with farm water supply capacities:

i. Land Area Constraints

$$\sum_{if=1}^{n_{if}} A_{if} = A_t$$

Where; A_t is total farm area (ha),

ii. Constraints for maximum allowable area

$$A_{if} \leq A_{Maxi}$$

Where; A_{MAXi} is the maximum area available for allocation to crop i. It depends on the market conditions and the machinery capacity of the farm.

iii. Constraints for rotation

$$\sum_{iw=1}^{n_{iw}} A_{iw} \leq \sum_{isum=1}^{n_{isum}} A_{isum}$$

iv. Water allocation constraints

$$\sum_{i=1}^{n} V_i A_i \leq NIV$$

Where; V_i is net available irrigation depth (mm),
NIV is net available irrigation volume for the farm (m^3)

v. Non-negative constraint

$$A_i \geq 0$$

The model solutions were developed for different farm sizes and water supply capacity alternatives. The resolution of the non-linear model was carried out using Solver method that is under the tools of Ms Excel Software. Subtracting the cost of labour from the computed farm income yielded the net benefice.

Level 3: Dynamic planning for water allocation on tertiary channel level

From the point of view of optimum water allocation among the farmers, a dynamic programming model has implied in the integration of the decisions at the tertiary channel level with those at the field level. The recursive equation for the dynamic programming is as fallowing:

$$f_j(Q_j) = r_j(Q_j, q_j) + f^*{}_{j-1}(Q_{j-1})$$

$$f^*{}_j(Q_j) = \max\{f_j(Q_j)\}$$

Where,

f^*_j (Q_j) is maximum income at j level, $r_j(Q_j, q_j)$ is income of the activity, Q is total capacity, Q_j is capacity at j level, q· is decision variable at j level, n is level amount and j is the number of the level

Constraints

$$0 \leq Q_j \leq Q$$

$$0 \leq q_j \leq Q_j$$

$$Q_j = q_j + Q_{j-1}$$

$$q_j \geq 0$$

$$(j = 1,2,....,n)$$

Results and Discussion

Production functions (Irrigation scheduling model results)

Second degree polynomials regression equations were obtained as production functions. Generic functions gross revenue versus applied water are given for the crops that are considered for the model during an average year. The coefficients of the equations are presented in Table 2.

Table 2 . Coefficients of crop-water-benefit functions

Crop	a_0	a_1	a_2
Barley	220.97	2.2175	-0.0076
Wheat	335.63	3.6137	-0.0087
Sugarbeet	-2766.4	14.105	-0.0083
Maize	-1211.2	6.0466	-0.005
Sunflower	-389.37	2.2701	-0.0019
Tomato	-2616.1	14.982	-0.0082
Pepper	-1948.4	24.316	-0.0204
Chickpea	-439.68	4.7765	-0.0047
Melon	-1120	10.68	-0.0142
Vetch	-291.73	6.2249	-0.0065
Onion	-215.21	18.215	-0.0314

Once the profit function for each single crop is known, the model answers the question as to the amount of land and water resources that should be devoted to each crop with the given land and water restrictions (Benli and Kodal, 2003).

Optimum crop pattern (Non-linear model results)

The optimum crop pattern for each water supply capacity and farm type was determined by non-linear programming models. Using the crop production functions, the non-linear model was set up to determine the optimal cropping pattern and farm income for adequate and limited water supplies. The results that were obtained by the model for small (5 ha) size farm are given in Table 3.

Regarding Table 3, the optimal cropping pattern for the adequate water capacity conditions was to plant 1.65 ha of sugarbeet, 0.5 ha of tomato, 0.5 ha of pepper, 1.25 ha of onion and 1.1 ha of rainfed melon. In the model the maximum allowable area for the vegetables tomato and pepper were limited as 10% and onion as 25% of the total area. As those vegetables are high in profit values, they were always set at their up limits. Sugarbeet, tomato, pepper and onion are the dominant irrigated crops at the water capacity conditions ranging from 100% to 50% where there was a decrease at the area of sugarbeet and increase at rainfed melon. In 80 % capacity, rainfed wheat has entered to the crop pattern and the farm income has decreased by 14%. In 50% water supply capacity, deficit irrigation has been applied to sugarbeet, tomato and onion. In 40% condition, sugarbeet has eliminated from the pattern and fallowing entered with the farm income decreased by 41%. Deficit irrigation has been applied to all crops. When the water supply capacity decreases to 10%, pepper and onion were still in the cropping pattern as irrigated crops. At rainfed conditions, the model has eliminated pepper and onion and chosen rainfed wheat, rainfed melon and fallowing, with the farm income decreased by 96 %. After the examination of NLP solutions, small, medium and large farm incomes are found as 8486, 25459, 59405 € for 100% water capacity conditions, respectively.

Table 3. Summary of output for non-linear model

Combination of crop area and net irrigation water condition	Water Supply Capacity Alternatives										
	100%	90%	80%	70%	60%	50%	40%	30%	20%	10%	Rainfed
Crop pattern											
Sugarbeet											
Area (ha)	1.65	1.41	1.10	0.78	0.47	0.19	-	-	-	-	-
Irrigation (mm)	616.5	598.7	598.7	598.7	598.7	577.3					
Tomato											
Area (ha)	0.50	0.50	0.50	0.50	0.50	0.50	0.49	0.16	-	-	-
Irrigation (mm)	677.5	659.4	659.4	659.4	659.4	637.8	564.8	564.8			
Pepper											
Area (ha)	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.50	0.10	-
Irrigation (mm)	482.6	482.6	482.6	482.6	482.6	482.6	456.4	456.4	379.4	308.1	
Onion											
Area (ha)	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	1.25	-
Irrigation (mm)	228.4	223.7	223.7	223.7	223.7	218.0	198.9	199.0	149.4	125.2	
Fallow	-	-	-	-	-	-	2.6	5.9	7.5	11.5	25.0
Rainfed Wheat	-	-	4.0	7.2	10.3	12.5	12.5	12.5	12.5	12.5	12.5
Rainfed Melon	11.0	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5	12.5
Total Farm Income (€)	12118.38	11343.49	10559.21	9774.52	8989.83	8188.80	7285.04	6208.20	4975.07	2886.63	547.84
Labour Cost	3631.96	3473.12	3239.46	2997.27	2762.65	2507.30	2315.05	1885.48	1609.56	1104.28	224.56
Net Farm Income	**8486.42**	**7870.37**	**7319.75**	**6777.25**	**6227.18**	**5681.50**	**4969.99**	**4322.72**	**3365.51**	**1782.35**	**323.28**

Water allocation (dynamic programming model results)

After obtaining optimum crop patterns with irrigation water ratios for each type of farm size, dynamic programming (DP) model has been applied to the irrigation unit (Fig 1) and exemplary computation results are given in Table 4 in comparison with current practices (CP) of water distribution among farmers in Turkey. We defined irrigation water quantity in a dimensionless parameter called unit; one unit is equal to 1883 m^3 of water, in order to easy understanding and interpretation of water allocation. Regarding Table 4 with the 100% water capacity all the farms are receiving adequate water with their capacity. There is no significance difference in income between DP and CP till the level where water supply capacity decreased to 70%. Moreover, DP distributed the water at equal ratios among the farms where CP decreased the amount of water for the farm only at the downstream, because upstream farms are using all the water available. In 50% condition, under CP, there is no more water available for the downstream farm (q7), where DP allocates water with 50% deficit to all farms. In 20% condition, under CP, only four farms at the upstream can utilize the irrigation water, where DP allocates the same amount of water between all the farmers and provides higher income.

A graphic comparison of the tertiary channel income versus water resource capacity between dynamic programming and current practices is given in Fig 4. As can be seen in Fig 4, the difference between two management alternatives is increasing with the decrease in water resource capacity. With the dynamic programming water allocation, even at the 20% of water resource capacity, tertiary channel income was approximately two times higher then current practices.

Table 4. Summary of water allocation for an irrigation unit (under a tertiary channel) by dynamic programming model

Water Resource			Water Allocation Alternatives	Farm Water Allocation (unit)							Tertiary Channel Income (€)
%	m3	Unit		q1	q2	q3	q4	q5	q6	q7	
100	320110	170	DP	10	10	10	10	30	30	70	144269
	320110	170	CP	10	10	10	10	30	30	70	144269
90	288099	153	DP	5	5	6	7	30	30	70	134691
		153	CP	10	10	10	10	30	30	53	134475
80	256088	136	DP	6	5	5	5	15	30	70	127440
		136	CP	10	10	10	10	30	30	36	125181
70	224077	119	DP	7	7	5	5	30	30	35	115607
		119	CP	10	10	10	10	30	30	19	113209
60	192066	102	DP	7	5	5	5	15	30	35	108351
		102	CP	10	10	10	10	30	30	2	90045
50	160055	85	DP	5	5	5	5	15	15	35	96586
		85	CP	10	10	10	10	30	15	-	76449
40	128044	68	DP	3	4	5	5	15	15	21	85004
		68	CP	10	10	10	10	28	-	-	58173
30	97916	52	DP	3	3	3	3	9	9	21	73486
		52	CP	10	10	10	10	11	-	-	48208
20	64022	34	DP	2	2	2	2	6	6	14	57214
		34	CP	10	10	10	4	-	-	-	30429

DP: Dynamic Programming
CP: Current Practices

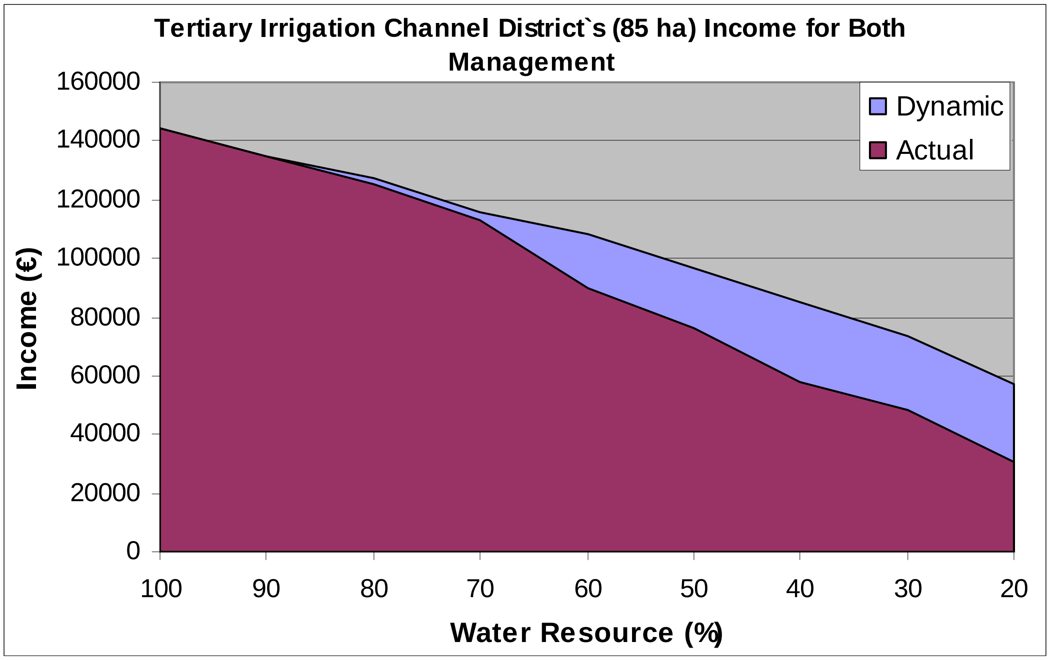

Fig 4. Comparison of the tertiary channel income versus water resource capacity between dynamic programming and current practices

Conclusion

After the examination of NLP and dynamic model solutions, small, medium and large farm incomes are 8486, 25459, 59405 € for adequate water supply conditions, respectively. Hence, an irrigation unit with limited water supply can obtain higher income when distributions of water among farms are equal. Moreover, more farmers may benefit from water supply. These results indicate that irrigating more land with available water supply, delivering water equally to farms and training farmers on deficit irrigation are essential.

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