IRRIGATION AND DRAINAGE
Irrig. and Drain. **58**: 38–49 (2009)
Published online 6 June 2008 in Wiley InterScience (www.interscience.wiley.com) **DOI**: 10.1002/ird.381

OPTIMAL CULTIVATION RULES IN MULTI-CROP IRRIGATION AREAS†

O. BOZORG HADDAD[1]*, M. MORADI-JALAL[2], M. MIRMOMENI[3], M. KH. KHOLGHI[1] AND M. A. MARIÑO[4]

[1]*Department of Irrigation & Reclamation, Faculty of Soil and Water Engineering, College of Agriculture and Natural Resources, University of Tehran, Karaj, Tehran, Iran*
[2]*Department of Civil Engineering, University of Toronto, Toronto, Canada*
[3]*Abadgaran Construction Company, Tehran, Iran*
[4]*Hydrology Program, Department of Civil and Environmental Engineering, and Department of Biological and Agricultural Engineering, University of California, Davis, California, USA*

ABSTRACT

A linear programming model is developed for annual cultivation rules of multi-crop irrigation areas in a reservoir–irrigation system. The objective is to maximize the annual benefit of the system by assigning annual irrigation areas as well as monthly irrigation schedules over the planning horizon. The annual irrigation areas are considered to be a linear function of both total volume of storage at the end of the last operating year and the average inflow rate of the current year. The methodology is applied to a previously analyzed problem, without considering operational rules. Results are compared with those of a linearized modeling of the problem and the advantages of the proposed approach are discussed. Furthermore, results indicate that although there is a 40% decrease in the value of the objective function when using cultivation rules, the model is nonetheless a helpful tool for planners and/or stakeholders to decide at the beginning of each year how much and which type of product should be cultivated. This has been verified by applying the extracted rules with a generated five-year inflow time series. Results show the robustness of the rules facing the uncertainty of model parameters. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: optimization; cultivation rules; reservoir operation; multi-crop pattern; irrigation schedule; linear programming

Received 12 July 2007; Revised 31 October 2007; Accepted 3 December 2007

RÉSUMÉ

Un modèle de programmation linéaire est développé pour optimiser les assolements annuels dans des secteurs de polyculture irriguée par réservoir. L'objectif est de maximiser le bénéfice annuel du système par l'assolement et les dotations d'eau mensuelles. Les surfaces irriguées annuelles sont considérés comme une fonction linéaire du volume stocké à la fin de la précédente campagne et du taux moyen d'apport de l'année en cours. La méthodologie est appliquée à un problème précédemment analysé, sans considérer les règles opérationnelles. Les résultats sont comparés à ceux du modèle linéaire et les avantages de l'approche proposée sont discutés. Les résultats montrent que malgré la diminution de 40% de la valeur de la fonction objectif en utilisant les règles opérationnelles, le modèle est néanmoins un outil utile pour des planificateurs et/ou les partenaires pour décider en début de campagne combien et quel type de culture devrait être engagée. Ceci a été vérifié en appliquant les règles extraites à une série d'apport générée sur cinq ans. Les résultats montrent la robustesse des règles face à l'incertitude des paramètres du modèle. Copyright © 2008 John Wiley & Sons, Ltd.

* Correspondence to: Dr O. Bozorg Haddad, Assistant Professor, Department of Irrigation & Reclamation, Faculty of Soil & Water Engineering, College of Agriculture & Natural Resources, University of Tehran, Karaj, Tehran, Iran. E-mail: obhaddad@ut.ac.ir
†Optimisation des assolements dans des régions de polyculture irriguée.

MOTS CLÉS: optimisation; règles de culture; gestion de réservoir; assolement de polyculture; programme d'irrigation; programmation linéaire

INTRODUCTION

One of the efficient strategies to reduce water deficits is to optimize the irrigation systems of existing areas and improve water resource allocation by establishing suitable multi-crop patterns and irrigation schedules. Extracting the optimal cultivation rule for reservoir–irrigation systems is a complex decision-making process. The most important aspects in irrigation scheduling are to determine the best time to irrigate and how much of each product must be irrigated. The main purpose of this paper is to formulate a linear programming (LP) model to assign optimal annual multi-crop irrigation areas in a reservoir-irrigation system as well as to determine the optimum reservoir operation and irrigation scheduling. This information facilitates consultation and contribution of authorities, farmers, and researchers to make a decision, with better performance in evaluation of integrated reservoir operation–irrigation scheduling systems.

The goal is to optimize overall efficiencies of the reservoir–irrigation system, which can be either maximizing the total benefits of the system by allocating the released water for different purposes such as irrigation, energy production, etc., or minimizing deficit costs of spills and losses. Various constraints, which influence the operation of the irrigation reservoirs, must be satisfied. In all reservoirs, water can be either released for beneficial activities or retained in the reservoir for possible enhanced applications in the future. This simple criterion becomes extremely complex when future inflows are uncertain and economic benefits of released water are not deterministic and constant (Shih and ReVelle, 1994). In most cases, uncertainty is a significant factor in the decision-making process and considerable risks are involved in the decision policies. Considering uncertainty in reservoir modeling by identifying, predicting, and quantifying sources of uncertainty in reservoir and/or river conditions, may result in better management. It can lead operators and managers to develop current and future operational guidelines. Thus, management of irrigation reservoirs requires creating a set of operational procedures, rules, schedules and plans which best meet a set of objectives and constraints.

There has been extensive application of optimization methods in irrigation planning, scheduling, and operation. Various studies have addressed scheduling of irrigation areas planted with a single crop, whereas most irrigation areas are concerned with several crops grown at the same time. Allocation of both areas and irrigation water under a multi-crop pattern in a season should be considered simultaneously.

Solution of optimization models for irrigation reservoirs is challenging because of the fact that they are dynamic and large-scale. In addition, unexpected inflows, evaporation losses, hydrologic parameters, system demands, and economic parameters which are treated as stochastic variables associated with different uncertainties, convert the problem to a complex, large-scale, and stochastic optimization one. Consideration of uncertainty in reservoir modeling can lead to better management of reservoir–irrigation systems.

Irrigation programs with distinct dates and depths of irrigation, for three crops and the determination of a cropping pattern for them, were developed by Matanga and Mariño (1979a). The linear area-allocation model maximized gross margin from yields of crops under consideration subject to total water supply, maximum available water for irrigation purposes on any date of irrigation, and irrigation labour. Matanga and Mariño (1979b) developed a stochastic interseasonal model for a finite or infinite planning horizon to determine irrigation policy considering leaching and seasonal irrigation depths. The information provided by the interseasonal model was used in an area-allocation model that allocates acreage available for planning among the crops for unlimited and limited water supplies. A generalized LP model for optimizing agricultural production systems by evaluating the time-varying competition between crops for land, labour, and machinery was proposed by Bender *et al*. (1984). Chávez-Morales *et al*. (1992) provide a simulation model for planning the conjunctive use of irrigation water in a reservoir–aquifer system with a single multipurpose reservoir and an aquifer, and the allocation of cropped areas within an irrigation district. Optimal seasonal multi-crop irrigation water allocation and optimal stochastic intraseasonal irrigation scheduling for maximizing total benefits of several crops were carried out by Sunantara and Ramirez (1997). Their objective was to obtain both optimal seasonal water and irrigation area allocation among crops using deterministic dynamic programming. Ibañez-Castillo *et al*. (1997) used a combination of LP and

DOI: 10.1002/ird

simulation models for planning the operation of an irrigation system with two reservoirs, two irrigation districts, and water transfer capabilities between reservoirs. Mujumdar and Ramesh (1997) developed a short-term reservoir operation model for irrigation. The model consists of two components including an operating policy model and a crop water allocation model that were formulated using deterministic dynamic programming (DP).

Malek-Mohammadi (1998) presented a mixed integer linear optimization model for planning an irrigation system considering surface reservoir capacity, groundwater and spring withdrawal, delivery system capacities, area of developing regions, and cropping patterns as intersecting parts of the system. A nonlinear optimization model for determining optimal cropping patterns in irrigated agriculture was developed by Carvallo *et al*. (1998). Teixeira and Mariño (2002) developed a DP model to solve the problem of two reservoirs in parallel supplying water for irrigation districts. In the model, forecast information including crop evapotranspiration, reservoir evaporation and inflows is updated, which allowed application of the model for real-time reservoir operation and generation of a more precise irrigation schedule. Vedula *et al*. (2005) presented an integrated conjunctive decision-making model and developed a stable operating policy for optimal allocation of surface and groundwaters for multi-crop irrigation in a canal command area to maximize the sum of annual relative yields of crops in a normal year. Nagesh-Kumar *et al*. (2006) used genetic algorithms for proposing an irrigation allocation model to determine relative yield from a specified cropping pattern for various states of reservoir inflows and rainfall in the irrigated area.

This paper extracts the optimal cultivation rules and presents the optimization of irrigation areas assigned with appropriate multi-cropping patterns along with proper reservoir operation and irrigation scheduling in a reservoir–irrigation system. Irrigation areas for crops and fruits, reservoir evaporation, operational policies for supplying irrigation water, and surplus water which spills from the reservoir are considered as interacting parts of the system. LP is used to optimize the reservoir–irrigation system by providing optimal annual irrigation areas for multi-cropping patterns as well as the optimum reservoir operation in the system simultaneously. The extracted rule is then verified by applying it in monthly five-year generated inflow, which also reflects the sensitivity of the system performance to the variations of inflow time series.

MATHEMATICAL MODEL

The total production benefit over the planning horizon is maximized through integration of reservoir operation policies and allocation of irrigation areas to optimal multi-cropping patterns. Three sets of constraints are considered for the objective function: (1) mass balance of the reservoir in the case of reservoir evaporation loss; (2) crop and fruit allocation area limitations; and (3) physical restrictions of the reservoir capacity.

The two main characteristics of the system are: (1) annual irrigation areas; and (2) monthly reservoir releases. Monthly inflow is the model input, and the optimal irrigated areas by water released from the reservoir are considered as the output parameters. The monthly released water from the reservoir consists of two parts: (1) when the reservoir is not full but monthly release of the system is greater than monthly irrigation water demand, in which the water demand is initially supplied for the irrigation system and the surplus water diverted through the downstream using the irrigation intake of the system. Hence, the spill is the volume of released water when the monthly water demand for crops and fruits is less than what should be released from the reservoir, and (2) when the stored water violates the reservoir capacity which occurs when the monthly inflow to the system is high enough so that the reservoir is full and the excess water should be spilled from the reservoir. Therefore, in order to maintain the normal storage volume for the reservoir, the surplus water is spilled from the spillway crest, making the total volume of monthly inflow plus the previous month's storage equal to the total capacity of the reservoir.

The principal decision variables in a reservoir–irrigation system are classified into two main categories: (1) optimal operation rules of the reservoir considering reservoir operation and irrigation scheduling, and (2) suitable multi-cropping patterns and allocated irrigation areas for each crop/fruit.

To implement the cultivation rule functions, annual irrigation area for candidate crops and fruits is as follows:

$$A_{i,n} = a_i I_n - b_i S_{n-1,T} - c_i \quad \text{for } I = 1, .., C \text{ and } n = 1, .., Y \tag{1}$$

$$A_j = a_j I_Y - b_j S_{0,0} - c_j \quad \text{for } j = 1, .., F \tag{2}$$

DOI: 10.1002/ird

where $A_{i,n}$, the annual irrigation area for candidate crops, is considered as a linear function of the volume of storage at the end (T) of the previous operating year ($S_{n\text{-}1,T}$) and the total inflow volume to the system in the current year (I_n). Furthermore, A_j, annual irrigation area for candidate fruits, is also a linear function of the volume of storage at the first month of the first year of the planning horizon ($S_{0,0}$) and the total inflow volume to the system in the entire planning horizon (I_Y). Note that $a_{,i}$, $b_{,i}$, $c_{,i}$, a_j, b_j, and c_j are constant coefficients which act as the decision variables of the system. Y is the number of years in planning horizon, and T is the number of monthly operational periods in each year.

The reservoir evaporation volume depends on the average free surface area of the reservoir at the start of the planning horizon and at the beginning of each month, while the free surface area itself is a function of reservoir storage. The reservoir area–volume relationship curve is applied to obtain the reservoir free surface area in the planning horizon, and the monthly evaporation volume is obtained by considering the corresponding monthly evaporation depth value. By linear averaging of the free surface area at the beginning and end of each month the evaporation of the model is calculated as

$$\mathrm{AREA}_{n,t} = \alpha S_{n,t} - \beta \text{ for } n = 1, .., Y \text{ and } t = 1, .., T \tag{3}$$

where $AREA_{n,t}$ = free surface area of reservoir storage in the tth month of the nth year and $S_{n,t}$ = volume of storage water at the end of the tth month of the nth year. It should be noted that α and β can be achieved from the regression of original area–volume relationship curve of the reservoir.

The objective function is to maximize the annual benefit of the reservoir–irrigation system over the planning horizon (Y). The total benefit of the system profits from cultivation of agricultural crops (wheat, bean, etc.) and gardening fruit productions (apple, almond, etc.). These two activities must be considered separately because of the fact that the allocated areas for fruit production cannot be changed as fast as the agricultural crop areas during the planning horizon. Therefore, the objective function is presented as

$$\text{Max.} \sum_{i=1}^{C}\sum_{n=1}^{Y} B_i A_{i,n} + Y\sum_{j=1}^{F} B_j A_j \tag{4}$$

where B = unit benefit of crops and/or fruit; A = area of crop cultivation and/or fruit production; C = number of crop production; i = type of crop; n = year of cultivation; F = number of fruit production; and j = type of fruit. Moreover, Equation (4) is subject to some other constraints due to physical and operational limitations.

The mass balance equation is applied to all monthly operation rules of the system:

$$\sum_{i=1}^{C} D_{i,t} A_{i,n} + \sum_{j=1}^{F} D_{j,t} A_j + \mathrm{EV}_{n,t} + S_{n,t} = S_{n,t-1} + I_{n,t} \quad \text{for } n = 1, \ldots, Y \text{ and } t = 1, \ldots, T \tag{5}$$

where $D_{i,\mathrm{t}}$ = water demand for unit area of ith crop production; $D_{j,t}$ = water demand for unit area of jth fruit production; $\mathrm{EV}_{n,t}$ = volume of reservoir evaporation in the tth month of the nth year, and $I_{n,t}$ = volume of inflow in the tth month of the nth year.

The other constraint of the system deals with the limitation of the total area of agricultural activities:

$$\sum_{i=1}^{C} A_{i,n} \le A_C \quad \text{for } n = 1, \ldots, Y \tag{6}$$

where A_C = maximum accessible area of agricultural activities. The allocated area of agriculture is limited over the planning horizon.

Similarly, another constraint of the system deals with the limitation of the total area of gardening activities:

$$\sum_{j=1}^{F} A_j \le A_F \tag{7}$$

where A_F = maximum accessible area of gardening activities.

DOI: 10.1002/ird

The other constraint of the system is subject to the reservoir capacity:

$$S_{n,t} \leq S_{\max} \quad \text{for } n = 1, .., Y \text{ and } t = 1, .., T \tag{8}$$

where $S_{\max}$ = reservoir capacity.

There is a physical restraint on the allocated gardening areas for all type of gardening activities and fruit production. This constraint implies that the allocated area for all gardening activities must be constant over the planning horizon and it is impossible to change the allocated areas for gardening activities during that horizon:

$$(A_j)_{n,T} = (A_j)_{n+1,1} \quad \text{for } j = 1, .., F \text{ and } n = 1, .., Y \tag{9}$$

Finally, to fix the storage at the beginning and end of the planning horizon so as to prevent reservoir carryover storage, it is assumed that the initial volume of the storage water should be equal to the final volume of storage at the end of the planning horizon:

$$S_{0,0} = S_{Y,T} \tag{10}$$

Application

A reservoir–irrigation system located in Iran is considered where a new reservoir dam is soon to be constructed. Figure 1 shows a schematic diagram of the reservoir–irrigation system. Irrigation water supply for downstream agricultural areas in terms of optimal irrigation planning of the system by allocating cultivation areas and appropriate reservoir operation as well as irrigation scheduling is the main purpose of the system. It is necessary to specify all the required data and constraints of the system in both current and future conditions in order to find the optimal policy for system operation.

For downstream irrigation areas two different activities are considered: agricultural crops and gardening fruit production. The total benefit of the system is made up by the combination of their profits. Two main cropping seasons exist in a year: a dry season, from April to October, in which all crops and fruits need to be irrigated, and a wet season. All the information required for allocating irrigation water to candidate products has been presented in Moradi-Jalal *et al*. (2007).

Monthly inflow, a basic parameter of the system, is based on the hydrology records of the corresponding river which are assumed reliable enough to be used as the input parameter of the reservoir–irrigation system. A 35-year hydrological monthly record of river inflow (1965–2000) is considered for the proposed case study. The planning horizon chosen for this study is a five-year period, April 1980 to March 1985, which has been presented in Moradi-Jalal *et al.* (2007). A smooth variation of river inflow is observed in this period.

In order to include the evaporation of the reservoir, using the regression of the area–volume curve, values obtained for α and β are 0.95 and 54 400 respectively.

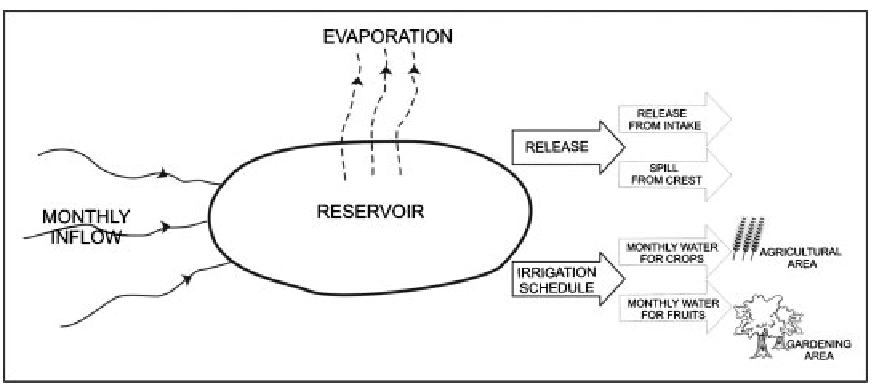

Figure 1. Schematic diagram of the system

DOI: 10.1002/ird

The general input data for the system are: Y = number of planning horizon years, 5; C = number of agricultural crop production, 7 (wheat, barley, onion, bean, potato, cucumber, and watermelon); F = number of gardening fruits produced, 5 (apple, apricot, grape, walnut, and almond); A_C = total area of agricultural crops, 1350 ha; A_F = total area of gardening, 150 ha; and $S_{\max}$ = reservoir capacity, $6.5 \times 10^6\,\mathrm{m}^3$.

This information is used in the proposed optimization model and optimal results are obtained by the LP solver. The results include allocated areas for both agricultural crops and gardening fruits over the planning horizon, associated multi-cropping patterns, monthly operation releases, as well as the total benefit of the system. The monthly coefficient values of the operational rules are listed in Table I. Clearly, all the constant variables are equal to zero. Furthermore, there are no predefined crops that should be cultivated every year and their cultivation rules are completely based on the reservoir storage and inflow characteristics varying from one year to another. It is also implied that fruits are more relevant to the total inflow and among them apple has the largest a_i coefficient and therefore shows the most relevance to inflow. In contrast, crops are more dependent on volume of storage in the planning horizon and barley has a noticeably higher b_i coefficient than the other products. Hence in the case of no predefined crops, barley is certainly the most cultivated product. Optimal annual allocated areas gained from extracted optimal cultivation rules considering their annual benefit value are listed in Table II. Furthermore, Figure 2 illustrates the optimal allocated area for crops over the planning horizon. As is observed, barley is selected as the most beneficial crop since it has the largest allocated area during the planning horizon. It is known that the highest monthly rate of water demand for barley is in May and June, while other products need more water from July to August. Thus, barley is selected as the optimum crop because it is more convenient for the system to supply its water demand while the other crops are not in their highest rate of water consumption.

The optimization model was previously analyzed by Moradi-Jalal *et al.* (2007) as a deterministic model using LP without considering the uncertainties and/or applying the cultivation rule functions to the reservoir–irrigation system. The optimal values of the total annual irrigated areas both in agricultural and gardening activities and their associated benefits obtained from linear cultivation rule functions as well as the total area and annual benefits from results of Moradi-Jalal *et al.* (2007) are also presented in Table II. Obtained values imply that if the monthly inflow is known a priori and there is no uncertainty in the river inflow, the total benefit will increase significantly. But as the

Table I. Coefficients of cultivation rules

Coefficient	Wheat	Barley	Onion	Bean	Potato	Cucumber	Watermelon	Apple	Apricot	Grape	Walnut	Almond
$a_i \times 10^9$	45.6	0.0	142.0	100.0	205.0	34.2	39.9	594.0	562.0	381.0	508.0	408.0
$b_i \times 10^9$	18.0	189 000.0	20.2	67.0	29.2	415.0	15.7	12.8	12.0	8.8	11.2	9.6
$c_i \times 10^9$	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Table II. Optimal results with or without linear cultivation rules

Operating year	Moradi-Jalal *et al.* (2007)		Rules extraction		Rules verification	
	Agricultural area (ha)	Garden area (ha)	Agricultural area (ha)	Garden area (ha)	Agricultural area (ha)	Garden area (ha)
1980–81	63	150	389	118	387	127
1981–82	1345	150	1011	118	507	127
1982–83	1350	150	917	118	897	127
1983–84	1350	150	997	118	982	127
1984–85	808	150	983	118	999	127
Gardening benefit (10^6 US$)		2.4		1.7		1.8
Agricultural benefit (10^6 US$)	7.4		4.3		3.8	
Total benefit (10^6 US$)	9.8		6		5.6	
Average annual benefit (10^6 US$)	2		1.2		1.1	
%	100		60		56	

DOI: 10.1002/ird

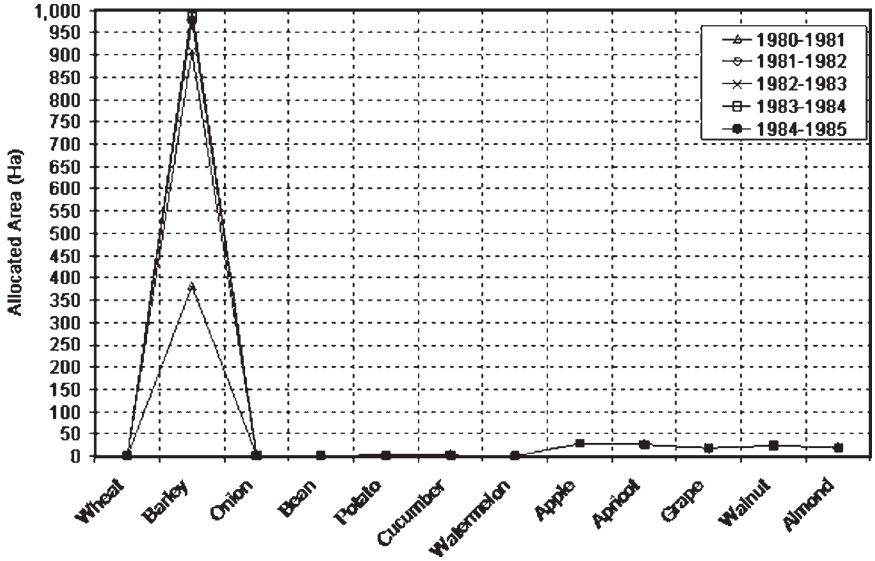

Figure 2. Optimal allocated areas for crops over planning horizon in extracting the rules

inherent behavior of the inflow is involved with unpredicted natural values, the system will reduce its efficiency due to the incorporation of uncertainties in the modeling.

Operation policies of the reservoir for extracted linear cultivation rule functions, which consist of monthly storage, spilled water, and inflow, are shown in Figure 3. As is observed in Figure 3, in the 30th month of the planning horizon, the monthly inflow ($7.7 \times 10^6\,m^3$) is more than the reservoir capacity ($6.5 \times 10^6\,m^3$). Meanwhile, the total volume of the demand is about $0.26 \times 10^6\,m^3$, while most of the inflow is stored in the system in the next month, and the rest is released through the spillway crest. Therefore, the empty storage is completely filled while the surplus water is spilled from the spillway crest. It should be noted that the system has several spills from the crest of the spillway for a linear cultivation rule scenario. This event is repeated, while the maximum annual inflow is repeated, and the system tries to increase the volume of the storage.

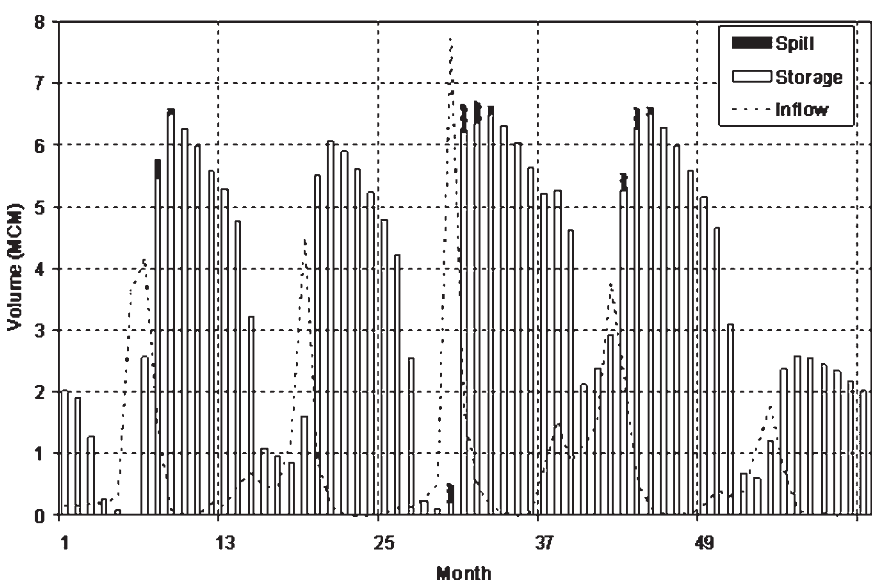

Figure 3. Monthly spill, storage, and inflow in extracting the rules

DOI: 10.1002/ird

Finally, the monthly inflow, release, and water demand for the extracted linear cultivation rule function in the system is depicted in Figure 4. It is also observed that the volume of released water in 7 months during the depicted 60-month planning horizon significantly exceeds the water demand of agricultural and gardening activities. The release from the spillway crest occurs just once as stated earlier. In 7 months of the planning horizon, although the reservoir is not full, the released water exceeds the required irrigation water of the system.

Rules verification

The extracted rules obtained in the previous parts need to be verified to make them applicable to other cases with different inflow time series. So, a five-year inflow set has been generated and applied along with the extracted rules using a standard operation policy (SOP) in the proposed case study. For the reservoir operation, the initial reservoir storage has been considered equal to the reservoir storage obtained in the last period in the case of extracted rules. Applying the rules with generated inflow resulted in an objective function of US$5 575 113, which is just 4% less than those of the extracted rules case. It indicates that even when facing different inflow patterns, the rules are valid and can result in a satisfactory objective function, comparable with those of optimization and extracting the rules. The allocated areas as well as the system benefit obtained for this case are summarized in Table II. Moreover, variation of the allocated area to each crop in each operational year is presented in Figure 5. The reservoir operation indices, such as spill, storage, release, demand, and inflow during the five-year operational period, is illustrated in Figures 6 and 7. These figures show the feasibility of the extracted rules used in this case. Although all the monthly five-year demand has been satisfied during the operational periods, no violation of the reservoir capacity has occurred, which is the interesting aspect of this verification and denotes the robustness of the extracted rules. Furthermore, statistical measures of the reservoir operation parameters during the five-year period for both cases of extracting and verifying the rules as well as the ratio of these parameters are presented in Table III. It should be noted that, although the average inflow considered for verification is 25% less than those of extracting the rules, just a 4% decrease of total benefit has occurred in this case. The ratio of allocated area to each product in the verification case to the extracting case is presented in Table IV. As can be seen from the table, almost all the ratios are around 1. It means that the variation of inflow, as the main source of uncertainty, cannot affect the performance of the model. It also adds to the applicability of the extracted rules in other cases. So, the extracted rules can be applied in any other operational periods and the hydrological uncertainties are less effective in the total benefit of the system, using the extracted rules.

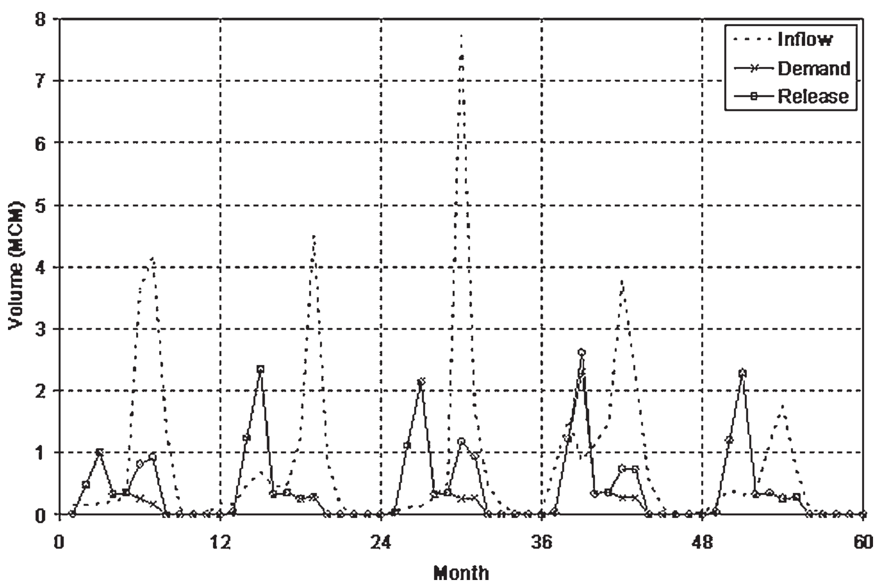

Figure 4. Monthly inflow, release, and demand in extracting the rules

DOI: 10.1002/ird

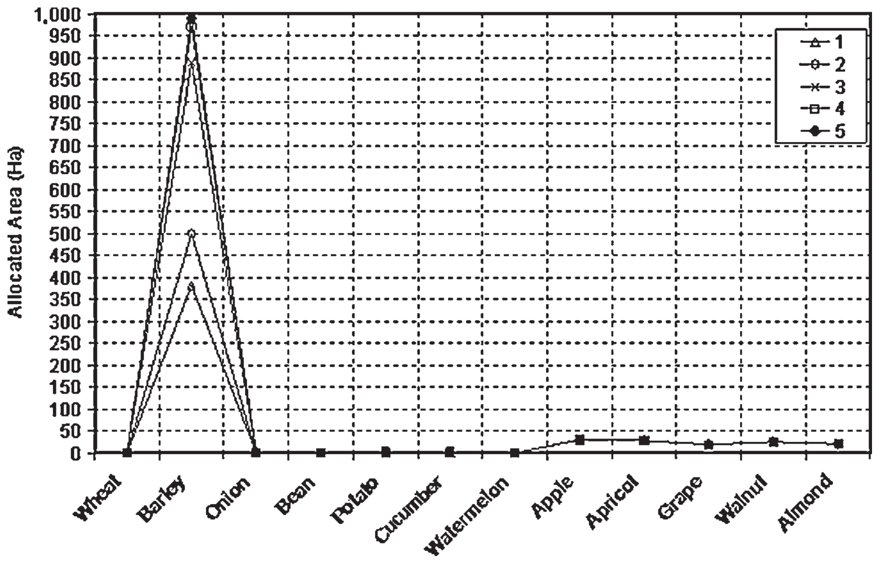

Figure 5. Optimal allocated areas for crops over planning horizon in verifying the rules

CONCLUSIONS

Application of linear programming models can be effective for optimizing operation rules of reservoirs and irrigation schedules in reservoir–irrigation systems. The constraints imposed on the objective function of the model should incorporate the components that are considered user preference to keep the cultivation of different crops under a specified area. The optimization is based on annual crop production functions. The annual crop production functions are obtained using reservoir operation policies, which include irrigation schedules and spilled water as well as the evaporation loss in the model.

A procedure to optimize linear cultivation rules is proposed in this study. A mathematical model (LP) is developed for extracting optimal cultivation rule functions to assign multi-crop irrigation areas so as to maximize the total annual benefit of the multi-crop and fruit productions over a planning horizon. The model considers the

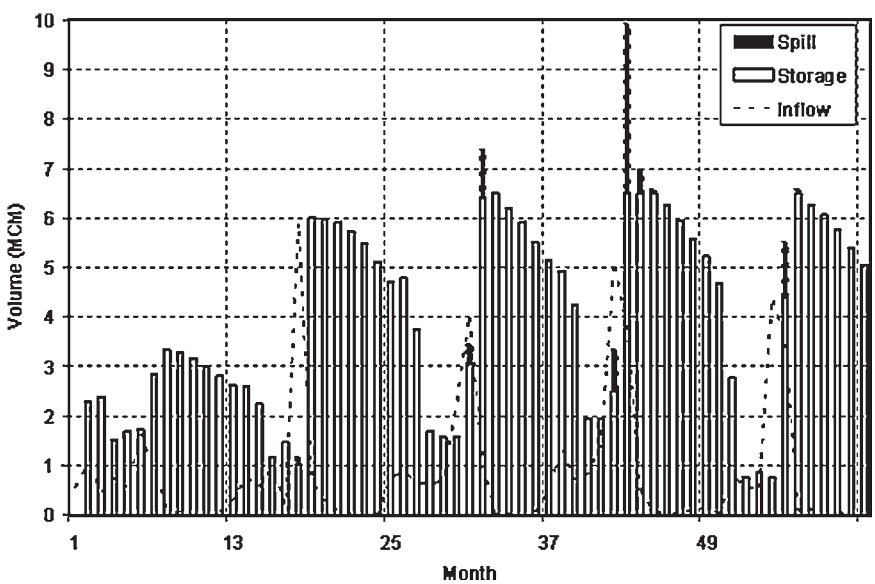

Figure 6. Monthly spill, storage, and inflow in verifying the rules

DOI: 10.1002/ird

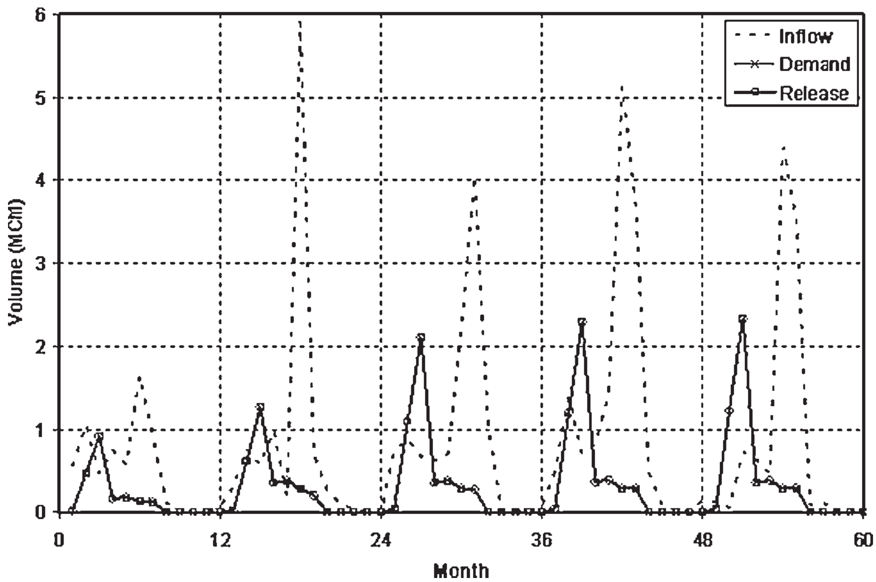

Figure 7. Monthly inflow, release, and demand in verifying the rules

influence of evaporation loss on computing operational policies and then generates the reservoir release rules. The constraint sets are the mass balance of the reservoir considering evaporation loss, and cropping pattern limitations and specifications. These sets of constraints are appropriately linked together by additional constraints. The optimized policies generated by the model suggested a diversified multi-cropping pattern, which would decrease the water requirement and enhance the net benefit per unit irrigation water. Although the obtained rule decreases the benefit of the system by about 40%, the LP model is a reliable tool and prevents extreme losses in dry years.

Table III. Statistical measures of reservoir operation indices

		Extracting the rule	Verifying the rule	Ratio
Inflow	Min.	0.0	0.0	—
	Max.	7.8	5.9	0.8
	Ave.	0.8	0.9	1.1
	Sum.	48.3	51.8	1.1
Demand	Min.	0.0	0.0	—
	Max.	2.3	2.3	1.0
	Ave.	0.4	0.3	0.9
	Sum.	21.6	19.5	0.9
Release	Min.	0.0	0.0	—
	Max.	2.6	2.3	0.9
	Ave.	0.4	0.3	0.8
	Sum.	25.7	19.5	0.8
Storage	Min.	0.0	0.0	—
	Max.	6.5	6.5	1.0
	Ave.	3.7	3.9	1.1
	Sum.	223.5	237.6	1.1
Evaporation	Min.	0.0	0.2	7.7
	Max.	1.0	0.9	0.9
	Ave.	0.4	0.4	1.1
	Sum.	22.6	25.0	1.1
Spill	Min.	0.0	0.0	—
	Max.	0.4	3.4	7.8
	Ave.	0.04	0.1	3.3
	Sum.	2.3	7.5	3.3

DOI: 10.1002/ird

Table IV. Ratio of benefits and allocated areas of products in verification of extraction cases

	1980–81	1981–82	1982–83	1983–84	1984–85	Min.	Max.	Ave.
Wheat	0.6	1.0	0.9	1.1	1.7	0.6	1.7	1.1
Barley	1.0	0.5	0.9	1.0	1.0	0.5	1.0	0.9
Onion	0.6	1.0	0.9	1.1	1.9	0.6	1.9	1.1
Bean	0.6	1.0	0.9	1.1	1.6	0.6	1.6	1.1
Potato	0.6	1.0	0.9	1.1	1.9	0.6	1.9	1.1
Cucumber	0.9	0.6	0.9	1.0	1.1	0.6	1.1	0.9
Watermelon	0.6	1.0	0.9	1.1	1.7	0.6	1.7	1.1
Apple	1.1	1.1	1.0	1.0	1.1	1.1	1.1	1.1
Apricot	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.1
Grape	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.1
Walnut	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.1
Almond	1.1	1.1	1.0	1.0	1.0	1.1	1.1	1.1
Cumulative agriculture area (ha)	1.0	0.5	0.9	1.0	1.0	0.5	1.0	0.9
Cumulative gardening area (ha)	1.1	1.1	1.0	1.0	1.0	1.0	1.1	1.1

To test the performance of the obtained rules, a sensitivity analysis was performed and the model results, which are the extracted rules, were verified. The results, which are the total five-year benefit and the reservoir operation indices, indicated that although a different inflow time series has been used, the objective function only has a slight 10% decrease, which proves the capability of the model and the ability of the extracted rules under different conditions facing inflow variation.

NOTATION

$AREA_{n,t}$ = free surface area of reservoir storage in *t*th month of *n*th year (m^{2})
A = area of cultivation of crops and/or fruit production (ha)
A_F = maximum area of gardening activities (ha)
A_C = maximum area of agriculture (ha)
a_i, b_i, and c_i = constant crop coefficients of the planning horizon
a_j, b_j, and c_j = constant fruit coefficients of the planning horizon
B = unit benefit of crops and/or fruit products (\$ ha^{-1})
C = number of agricultural crop products
$D_{i,t}$ = water demand for unit area of *i*th crop production (m^3)
$D_{j,t}$ = water demand for unit area of *j*th fruit production (m^3)
$EV_{n,t}$ = volume of reservoir evaporation of *t*th month of *n*th year (m^3)
F = number of gardening fruit products
$I_{n,t}$ = volume of input water in *t*th month of *n*th year (m^3)
I = type of agricultural crop
J = type of gardening product
N = year of cultivation
S_{max} = maximum volume of reservoir storage (m^3)
$S_{n,t}$ = volume of storage water in *t*th month of *n*th year (m^3)
T = month of irrigation schedule
Y = number of years in planning horizon
T = number of monthly operational periods in each year
α and β = coefficients of area–volume curve.

DOI: 10.1002/ird

REFERENCES

Bender DA, Peart RM, Doster DH, Barrett JR, Bagby MO. 1984. Energy crop evaluation by linear programming. *Energy in Agriculture* **3**: 199–210.

Carvallo HO, Holzapfel EA, Lopez MA, Mariño MA. 1998. Irrigated cropping optimization. *Journal of Irrigation and Drainage Engineering* **124**(2): 67–72.

Chávez-Morales J, Mariño MA, Holzapfel EA. 1992. Planning simulation model of irrigation district. *Journal of Irrigation and Drainage Engineering* **118**(1): 74–87.

Ibañez-Castillo LA, Chávez-Morales J, Mariño MA. 1997. Planning model of Fuerte-Carrizo irrigation system, Mexico. *Water Resources Managemen* **11**: 165–183.

Malek-Mohammadi E. 1998. Irrigation planning: integrated approach. *Journal of Water Resources Planning and Management* **124**(5): 272–279.

Matanga GB, Mariño MA. 1979a. Irrigation planning, 1, Cropping pattern. *Water Resources Research* **15**(3): 672–678.

Matanga GB, Mariño MA. 1979b. Irrigation planning, 2, Water allocation for leaching and irrigation purposes. *Water Resources Research* **15**(3): 679–683.

Moradi-Jalal M, Bozorg Haddad O, Karney B, Mariño MA. 2007. Optimal reservoir operation in assigning multi-crop irrigation areas. *Agricultural Water Management* **90**: 149–159.

Mujumdar PP, Ramesh TSV. 1997. Real-time reservoir operation for irrigation. *Water Resources Research* **33**(5): 1157–1164.

Nagesh Kumar D, Srinivasa Raju K, Ashok B. 2006. Optimal reservoir operation for irrigation of multiple crops using genetic algorithms. *Journal of Irrigation and Drainage Engineering* **132**(2): 123–129.

Shih JS, ReVelle C. 1994. Water supply operations during drought: continuous hedging rule. *Journal of Water Resources Planning and Management* **120**(5): 613–629.

Sunantara JD, Ramirez JA. 1997. Optimal stochastic multi-crop seasonal and intra-seasonal irrigation control. *Journal of Water Resources Planning and Management* **123**(1): 39–48.

Teixeira AD, Mariño MA. 2002. Coupled reservoir operation-irrigation scheduling by dynamic programming. *Journal of Irrigation and Drainage Engineering* **128**(2): 63–73.

Vedula S, Mujumdar PP, Chandra Sekhar G. 2005. Conjunctive use modeling for multicrop irrigation. *Agricultural Water Management* **73**(3): 193–221.

DOI: 10.1002/ird