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Reservoir operation in assigning optimal multi-crop irrigation areas

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ABSTRACT

A mathematical model is developed for the optimal multi-crop irrigation areas associated with reservoir operation policies in a reservoir-irrigation system. Optimal area allocations are considered by addressing an appropriate mathematical model. The reservoir operations are related to releases policy, monthly water allocations, and occasional reservoir spills in a monthly operating time. The objective is to maximize the annual benefit of the system by supplying irrigation water for a proposed multi-crop pattern over the planning period. Herein, three sets of constraints are applied to the system: achieving monthly balance in the reservoir, covering water demand for crop production, considering evaporation loss from the reservoir, and governing equations for reservoir release and operations. The provided model is formulated with these constraints linked together by appropriate additional constraints as a linear programming model. Sensitivity analysis of inflow and alternative irrigation policies is conducted to investigate their effect on the final results. The methodology is applied to a real case study of a reservoir-irrigation system in Iran to show the applicability of the model.

1. Introduction

Optimization of irrigation systems for existing areas and improvement in water resource allocations by appropriate multi-cropping patterns and irrigation scheduling are the best response to reduce water deficits. Irrigation scheduling deals with two basic questions: when and how much to irrigate?

Because of an ever-increasing demand for irrigation water and the unreliability of stream flow in arid and semi-arid regions, performance evaluation of reservoir operation is important and particularly difficult. Generally, optimal multi-cropping pattern and irrigation areas associated with appropriate reservoir operation and irrigation scheduling are essential for increasing the overall efficiency of reservoir-irrigation systems. The most important aspect of operations is the release of the right quantity of water at the right time to irrigation areas to achieve greater benefits. The most promising aspects that arise in the system monitoring and evaluation

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$A_{i,m}$	free surface area of reservoir in *m*th month of *i*th year (m^2)
A_{frt}	maximum area of fruits and nuts (ha)
A_{arg}	maximum area of agricultural crops (ha)
C	unit benefit of crops and/or fruit productions ($/ha)
$(EV)_{m,i}$	volume of reservoir evaporation of *m*th month of *i*th year (m^3)
f	number of fruit productions
i	year of cultivation
k	number of agricultural crop productions
m	month of irrigation schedule
n	number of years in planning horizon
p	type of agricultural crop
$Q_{m,i}$	inflow discharge of river in *m*th month of *i*th year (m^3)
$S_{i,m}$	volume of stored water at the end of *m*th month of *i*th year (m^3)
u	type of fruit
$(V_{m,i})_p$	unit rate of irrigation water demand for *p*th crop production in *m*th month of *i*th year
$(V_{m,i})_u$	unit rate of irrigation water demand for *u*th fruit production in *m*th month of *i*th year
$(Vs)_{m,i}$	volume of stored water in *m*th month to next month of *i*th year (m^3)
V_{dam}	maximum volume of storage (m^3)
X	cultivation area of crops and/or fruits (ha)

Greek letters

α and β	coefficients of area–volume curve

processes are: (1) the stored water is allocated to various irrigation areas based on an irrigation schedule and is released through a river. It is important to know how much of the released water is available for irrigation areas; (2) optimal multi-cropping pattern is important because it provides better opportunities for water conservation and reduces the impact of water deficits on the system.

Irrigation scheduling in the case of limited irrigation water supplies has been extensively studied for the case of single-crop irrigation. However, most irrigation areas are concerned with several crop cultivations simultaneously. There are many investigations addressing irrigation scheduling and multi-crop production and most of the irrigation areas are concerned with several crops grown at the same time.

Matanga and Mariño (1979a) developed irrigation programs, specified in terms of dates and depths of irrigation, for three crops. The information contained in the irrigation programs for each crop was then applied in an area-allocation model to determine a cropping pattern for the three crops. For a finite or infinite planning horizon, Matanga and Mariño (1979b) developed an stochastic inter-seasonal model to determine irrigation policy in terms of leaching and seasonal irrigation depths. Bender et al. (1984) proposed a generalized LP model for irrigation systems by evaluating the time-varying competition between crops for land, labor, and machinery. Chávez-Morales et al. (1987) presented an LP model for planning the management of an irrigation district, yielding the cropping pattern and the monthly schedule of reservoir storages and releases and aquifer withdrawals that maximize the profit in the district. Chávez-Morales et al. (1992) extended their previous work by developing 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. Sunantara and Ramirez (1997) developed a two-stage LP-stochastic DP model to determine the steady-state optimal operating policy and the associated optimal crop water allocations to each crop for a single-purpose irrigation reservoir. Ibañez-Castillo et al. (1997) used a combination of LP and simulation models for planning the operation of an irrigation system with two reservoirs, two irrigation districts, and water transfer capabilities between reservoirs. Malek-Mohammadi (1998) presented a mixed integer LP model for planning an irrigation system considering a reservoir, underlying aquifer, supply system capacity, and candidate cropping patterns. Carvallo et al. (1998) developed a non-linear optimization model for the determination of optimal cropping patterns in irrigated agriculture. The model furnished the optimal distribution of areas and crops, the water requirements, and the total profit. Paul et al. (2000) presented a stochastic approach for solving a multi-crop and multi-level irrigation scheduling problem using a DP decomposition scheme. Singh et al. (2001) used LP for determining cropping patterns at various water availability levels while Haouari and Azaiez (2001) proposed an LP model for determining cropping patterns under water deficits in dry regions. Teixeira and Mariño (2002) presented an optimization methodology for reservoir operation coupled with an irrigation scheduling scheme that maximized the net income to an irrigation district. Vedula et al. (2005) presented a conjunctive use modeling approach for multi-crop irrigation. Nagesh-Kumar et al. (2006) proposed 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 using a genetic algorithm.

The main purpose of this paper is to formulate a deterministic optimization model, linear programming (LP) model, for assigning multi-crop irrigation areas in a reservoir-irrigation system with corresponding reservoir operation and irrigation scheduling.

This paper presents optimal multi-cropping pattern and irrigation areas associated with proper reservoir operation and irrigation scheduling in a reservoir-irrigation system. We consider optimum monthly reservoir operation as well as optimum annual crops and allocated area to each crop, simultaneously. Reservoir operation, irrigation areas for agricultural crops and orchards, reservoir evaporation, operation policies for supplying irrigation water, and surplus water which spills from the reservoir are considered as interacting parts of the system. LP is used for optimization of the reservoir-irrigation system by providing an irrigation schedule for the optimal multi-cropping pattern for the system. The optimization process is based on historical data of stream flows. The effects of stream flows, cropping patterns, and inflow regimes are investigated by performing a sensitivity analysis.

2. Mathematical model development

The integration of reservoir operation policies and allocation of irrigation areas to optimal multi-cropping patterns are achieved through the objective of maximizing total benefits of crop and fruit production over a planning horizon. Three sets of constraints are considered in this study: the mass balance of the reservoir considering evaporation loss from the reservoir, the limitation on the available areas for crops and fruits, and the physical restrictions imposed by the reservoir capacity.

The system is characterized by two main components: the monthly reservoir releases and the seasonal irrigation areas with the associated relationships defining the interactions between them. The only input parameter of the reservoir is monthly stream flow, while the output parameters are optimal irrigation areas supplied by released water from the reservoir. A schematic diagram of the irrigation-reservoir system is presented in Fig. 1. The monthly released water consists of: (1) reservoir releases when the reservoir is not completely full and the monthly release is defined to be greater than monthly irrigation water demand by the optimization model, and (2) reservoir releases when the stored water exceeds the reservoir capacity. In the first case, after supplying the demand by the irrigation system, the excess water is conveyed through the downstream river of the irrigation intake of the system. In other words, the spill is the volume of released water that occurs because the monthly water demand for crops and fruits is less than what should be released from the reservoir. It must be noted that there is another type of release policy when the monthly inflow to the system is high enough so that the reservoir is completely full and the excess water should be spilled from the crest of the spillway. In such a case, after supplying the demand, the excess water will be spilled from the crest of the spillway to bring the reservoir storage to the normal storage value. In other words, when the total volume of monthly inflow and reservoir last-month storage is more than the total capacity of the reservoir, water release from the crest of the dam occurs.

Moreover, the volume of evaporation from the reservoir depends on the average free surface area of the storage. The free surface area is an explicit function of current volume of storage. In order to consider the effect of evaporation on reservoir during the planning horizon, the area–volume relationship curve of the reservoir system should be applied to obtain the free surface area of the reservoir in all operating months. By considering the corresponding monthly evaporation depth value, the monthly volume of evaporation can be obtained. Note that the average free surface area can be calculated by a linear averaging of the free surface area calculated for both start and end of each month. This process can be used for evaluating the evaporation value of the model:

$$A_{i,m} = \alpha \times S_{i,m} + \beta \quad \text{for } i = 1, \ldots, n, \quad \text{and} \quad m = 1, \ldots, 12 \tag{1}$$

where $A_{i,m}$ is the free surface area of reservoir in mth month of ith year and $S_{i,m}$ is the volume of storage water in mth month of ith year. The values of α and β can be obtained from regression of the original area–volume relationship curve representing the topography.

The objective function of the reservoir-irrigation model under consideration is to maximize annual benefits of the reservoir-irrigation system. The total benefits of the system result from cultivation of agricultural crops (wheat, bean, etc.) and orchards (apple, almond, etc.). The main reason for the distinction of the two activities is that allocated areas for fruit production cannot be changed as readily as those for agricultural crops during the planning horizon. Thus, the objective function consists of maximizing the average annual benefit of the system over a planning horizon of n years, which calculates the annual benefits of the system due to crop and orchard production:

$$\text{Max} \frac{1}{n} \left[\sum_{i=1}^{n} \sum_{p=1}^{k} C_{i,p} X_{i,p} + \sum_{i=1}^{n} \sum_{u=1}^{f} C_{i,u} X_{i,u} \right] \tag{2}$$

where X is the area of crop cultivation and/or fruit productions; C the unit benefit of crop and/or fruit production; i the year of cultivation; p the type of crop; u the type of fruit; n the number of years in planning horizon; k the number of agriculture crop productions; and f is the number of fruit productions. The

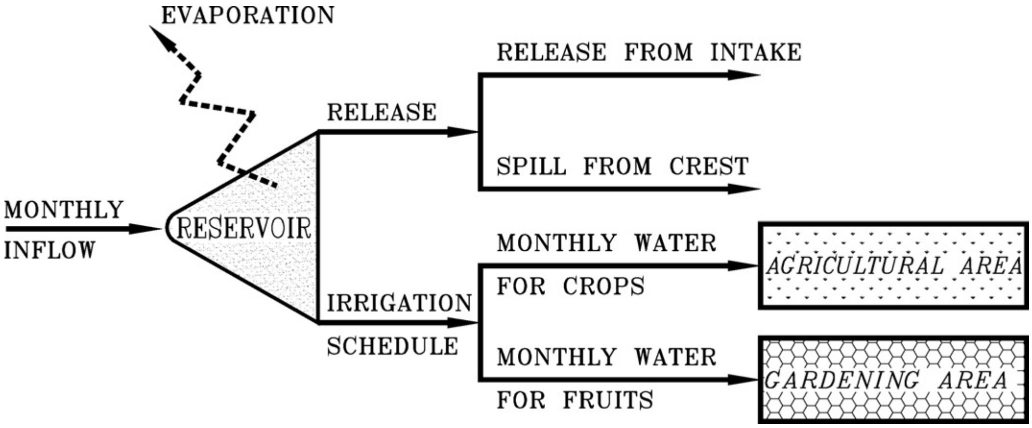

Fig. 1 – Schematic diagram of the system.

maximization of annual benefits is subject to physical and operational limitations of the reservoir-irrigation system.

The optimization model simultaneously considers areas planted with crops and orchards, while previous models have considered only crops. For instance, decision variables representing areas of irrigated crops may be changed during the planning horizon, while by considering realistic modeling of orchards and gardening activities, the allocated areas for fruit production must be constant during the planning horizon. Thus, a combination of fixed and variable irrigation areas is considered in the current optimization model while previous models have dealt only with variable irrigation areas.

The volume control equation is applied on all monthly operations of the system:

$$\sum_{p=1}^{k}(V_{m,i})_p X_{i,p}+\sum_{u=1}^{f}(V_{m,i})_u X_{i,u}+(\mathrm{EV})_{m,i}+(\mathrm{Vs})_{m,i}=(\mathrm{Vs})_{m-1,i}+Q_{m,i}$$
$$\text{for } i=1,\ldots,n, \text{ and } m=1,\ldots,12 \tag{3}$$

where $(V_{m,i})_p$ is the unit rate of irrigation water demand for pth crop production in mth month of ith year; $(V_{m,i})_u$ the unit rate of irrigation water demand for uth fruit production in mth month of ith year; m the current month of irrigation schedule; $Q_{m,i}$ the stream flow in mth month of ith year; $(\mathrm{EV})_{m,i}$ the volume of reservoir evaporation in mth month of ith year; and $(\mathrm{Vs})_{m,i}$ is the volume of storage in mth month of ith year. In fact, Eq. (3) is the monthly mass balance equation of the system, establishing a balance between volumes of irrigated water and inflow (stream flow).The allocated area of agriculture is limited over the planning horizon and area planted with crops is less than the maximum cropping area:

$$\sum_{p=1}^{k}X_{i,p}\le A_{\mathrm{agr}}\quad \text{for } i=1,\ldots,n \tag{4}$$

where A_{agr} is the maximum cropping area. Similarly, the limitation on orchard areas is:

$$\sum_{u=1}^{f}X_{i,u}\le A_{\mathrm{frt}}\quad \text{for } i=1,\ldots,n \tag{5}$$

where A_{frt} is the maximum area of orchards in the system. The only reason for separating orchards from the crops is that orchards are considered to be constant with a fixed pattern in the planning horizon which means that orchard's pattern cannot change in the planning horizon. Hence, in the mathematical model some constraints reflecting this issue should be added.

The system is also constrained by the total volume of water stored in the reservoir:

$$(\mathrm{Vs})_{m,i}\le V_{\mathrm{dam}}\quad \text{for } i=1,\ldots,n \quad\text{and}\quad m=1,\ldots,12 \tag{6}$$

where V_{dam} is the maximum volume of reservoir storage. That is, reservoir storage in mth month of ith year should be less than the total volume of the reservoir. In addition, there is a constraint on areas planted with fruits and gardens. Thus, the next constraint, Eq. (7), implies that the allocated area for orchards and gardens is constant during the planning horizon:

$$(X_{i,u})_m=(X_{i+1,u})_m\quad \text{for } i=1,\ldots,n,\quad m=1,\ldots,12,$$
$$\text{and}\quad u=1,\ldots,f \tag{7}$$

So as to prevent yearly carry-over reservoir storage, it is assumed that the initial reservoir storage in the first month of the planning horizon is equal to the reservoir storage at the end of the planning horizon.

$$(\mathrm{Vs})_{1,1}=(\mathrm{Vs})_{m,n} \tag{8}$$

Also, a non-negativity constraint is imposed on the model so that decision variables would not be negative values.

It is clear that the developed model is linear which means that in the optimization model the objective function and all the constraints should be in linear form. If, in some cases, even one of the constraints or the objective function follows the non-linear form the LP solvers are not capable to handle the problem. In such cases NLP solvers can be used to overcome this difficulty.

3. Application

Reservoirs play an important role in water resources management in Iran, as they have major storage utilities for regulating the excess water for later deficit water periods or sometimes for drought years. Appropriate reservoir operation and irrigation scheduling are needed for efficiently utilizing water storage in reservoir-irrigation systems. The optimization model under consideration is based on annual crop production benefit. Annual crop production benefit is obtained using reservoir operation policies, which include irrigation schedules and spilled water as well as reservoir evaporation losses.

There is a reservoir-irrigation system located in Iran where a new reservoir/dam is scheduled to be constructed. The main purpose of the system is to supply irrigation water to downstream agricultural areas. The focus is on optimal irrigation behavior of the system both in allocated areas and assigned activities with appropriate reservoir operation as well as irrigation scheduling. To find an optimal operating policy, it is necessary to specify all information and constraints of the system considering both current and future conditions.

Two different activities are assumed for downstream irrigation areas, agricultural crop production and fruit production in which total benefits of the system are achieved from those productions. There are two prominent cropping seasons in a year in Iran: a dry season and a wet season. In the dry season, all crops and fruits need irrigation water from April to October. In order to allocate irrigation water to each production, values of average monthly water demand for all productions per unit area are listed in Table 1.

The other basic parameter of the system is the monthly inflow which is based on the historical stream flows of the pertinent river. It is assumed that the inflow is a retroactive process and historical data of river inflows are reliable enough to apply as input parameter of the reservoir-irrigation system. For the proposed case study, a 35-year monthly record of river flows is available from 1965 to 2000. For this study, the planning horizon is considered as five consecutive years (April 1980–March 1985) as listed in Table 2.

To incorporate reservoir evaporation based on Eq. (1), values of $\alpha = 0.95$ and $\beta = 54425.30$ are obtained by regression of the area–volume curve, where values of monthly depth of

Table 1 – Monthly demand water for unit area of products

Number	Crops and fruits	Monthly demand water (m^3/ha)						
		Apr.	May	June	July	Aug.	Sep.	Oct.
1	Wheat	0	502	2319	2725	847	0	0
2	Barley	45	1222	2157	0	0	0	175
3	Onion	0	0	1395	2592	1746	990	0
4	Bean	0	0	1395	3177	2772	191	0
5	Potato	0	0	1741	3124	3029	1989	0
6	Cumber	0	0	539	1485	1720	488	488
7	Watermelon	0	0	991	1745	1470	879	0
8	Apple	10	142	1626	2991	3157	2389	1152
9	Apricot	0	0	1395	2858	3029	2389	957
10	Grape	10	0	933	2194	2310	1689	696
11	Walnut	5	232	1626	2592	3029	2289	827
12	Almond	0	0	1395	2327	2515	1989	827

evaporation from the free surface area are also considered based on the values listed in Table 2.

General input information of the system consists of: n, number of years in the planning horizon, 5; k, number of crops, 7 (which are wheat, barley, onion, bean, potato, cucumber, and watermelon); f, number of fruits and nuts, 5 (which are apple, apricot, grape, walnut, and almond.); A_{agr}, total area of agricultural crops, 1350 ha; A_{frt}, total area of orchards, 150 ha; and V_{dam}, reservoir capacity, 6.5×10^6 m^3. These data are inputted in the optimization model and optimal results are obtained by an LP solver. The results include the annual benefits of the system, as well as the optimal allocated areas for both crops and fruits over the planning horizon, which are listed in Table 3.

In Table 3, in the third column the unit benefit of each crop and orchard is presented. In the next five columns the yearly benefit of each crop in different operational years is presented which is the area allocated to each crop in each year. In the last column, summation of the yearly benefit from each crop in the planning horizon (in each row of the five previous columns) is presented, while in the last row in the same column, summation of the numbers in this column which is the objective function is presented. Furthermore in the last two rows of this table, the annual total area allocated to crops and orchards has been presented. These two rows demonstrate the satisfaction of constraints in the Eqs. (4) and (5), respectively.

It is observed that barley is selected as the optimum crop but its allocated area during the planning horizon is not optimal. However, consideration of monthly water demand values listed in Table 1 indicates that the highest monthly rate of water demand for barley is in May and June every year, while the other crops need more water annually 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. As it is clear in Table 2, the system experienced the greatest monthly inflows in 1983. Also, it is expected that the optimum crop would shift towards crops with greater unit benefits. This assumption is shown in Table 3, while potato and bean with greater annual benefits than barley are selected as optimum crops in 1983 while there is more opportunity for the system to supply demanded water for optimum crops.

Associated reservoir operation policies which consist of monthly volumes of spilled, stored water and inflows for optimal irrigation areas are shown simultaneously in Fig. 2. There are 5 monthly spills from the spillway crest during the planning horizon. This is due to a significant inflow to the reservoir while the water demand is low and the reservoir does not have sufficient capacity to store the inflow to the reservoir.

Table 2 – Monthly evaporation depth and river inflow over the planning horizon

Month	Evaporation depth (mm)	River inflow (10^6 m^3)				
		1980–1981	1981–1982	1982–1983	1983–1984	1984–1985
April	132	0.15	0.16	0.05	0.76	0.17
May	204	0.17	0.48	0.12	1.53	0.40
June	229	0.18	0.69	0.13	0.87	0.31
July	245	0.21	0.45	0.26	1.14	0.40
August	213	0.29	0.46	0.50	1.47	1.14
September	184	3.62	1.23	7.75	3.78	1.76
October	95	4.18	4.51	1.67	2.28	0.72
November	53	1.34	0.86	0.46	0.55	0.10
December	52	0.09	0.13	0.14	0.11	0.02
January	53	0.03	0.01	0.04	0.02	0.03
February	73	0.00	0.00	0.00	0.01	0.00
March	91	0.20	0.00	0.05	0.03	0.02
Annual	1624	10.45	8.99	11.19	12.56	5.07

Table 3 – Optimal annual allocated areas and benefits

Number	Production	Unit benefit (10^3\$/ha)	1980–1981 (ha)	1981–1982 (ha)	1982–1983 (ha)	1983–1984 (ha)	1984–1985 (ha)	Benefit (10^3\$)
1	Wheat	1.6	0	0	0	0	0	0
2	Barley	1	63	1345	0	822	362	2592
3	Onion	1.8	0	0	0	0	0	0
4	Bean	2	0	0	1115	0	0	2230
5	Potato	2.6	0	0	235	528	0	1984
6	Cumber	1.2	0	0	0	0	0	0
7	Watermelon	1.4	0	0	0	0	446	624
8	Apple	3.2	150	150	150	150	150	2400
9	Apricot	3	0	0	0	0	0	0
10	Grape	2.2	0	0	0	0	0	0
11	Walnut	2.8	0	0	0	0	0	0
12	Almond	2.4	0	0	0	0	0	0
Total agriculture areas (ha)			63	1345	1350	1350	808	9830
Total gardening areas (ha)			150	150	150	150	150	

The first two spills are in the 8th and 9th operation months of the first operating year. Also, in September and October 1982, when a total volume of 9.4×10^6 m^3 inflow enters to the system, total volume of water demand for barley and apple as the optimum crop and fruit during this period is 0.77×10^6 m^3. As the result, empty storage is filled completely while the excess water is spilled in 3 consecutive months (September–November, 1982). Monthly variations of river inflows and irrigation and spilled water during planning horizon of the system are simultaneously depicted in Fig. 3. It is observed that during the 60-month planning horizon depicted in Fig. 3, the volume of released water is greater than the water demand for crops and fruits in 10 months. There are 5 out of 10 months the reservoir is not full, but the released water is greater than required irrigation water.

4. Sensitivity analysis of alternative irrigation policies

Once the optimal irrigation areas and multi-cropping patterns associated with an appropriate reservoir operation and irrigation schedule are obtained, a sensitivity analysis is performed to test the effectiveness of the optimization model. The mathematical modeling proficiency can be verified by variation of the annual benefit in different scenarios: changes in the availability of the resources, changes in production costs, changes in the price of products, technological improvements in the irrigation system, and several others. Thus, a sensitivity analysis on the parameters can be applied for various combinations of cropping patterns and irrigation deficits, and their effects on optimal results determined.

The most important and major parameter in irrigation-reservoir systems which exerts significant influence on system productivity is the monthly inflow to the system. Thus, 10 different scenarios are considered by applying monthly reduction factors to inflows (0.1–1.0) and three additional scenarios of monthly increased factors to inflows (2, 5, and 10) to normal monthly inflows of the system. The total irrigation area in these cases is compared with the variation of river inflows. Fig. 4 depicts total irrigation area for agricultural crops with variation of river inflow while monthly inflow factors are varied. Non-zero crop/fruit cultivation areas

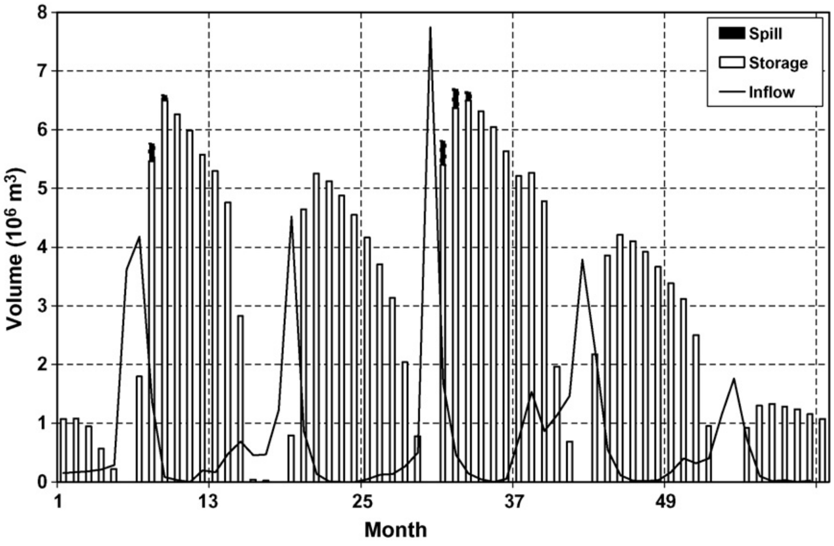

Fig. 2 – Monthly spill, storage, and inflow over planning horizon.

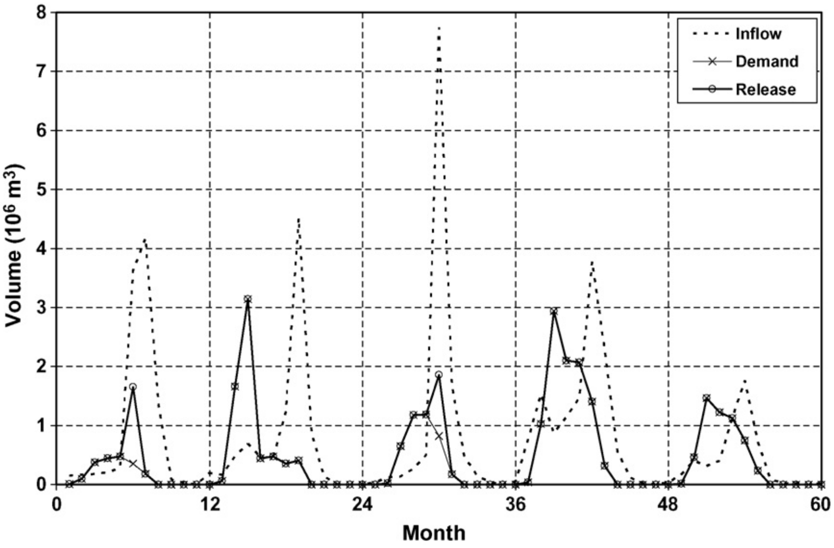

Fig. 3 – Monthly release, demand, and inflow over planning horizon.

in operational years with changes in inflow are shown in Table 4. Finally, changes in annual benefits and the maximum, minimum, and average values of the reservoir operation volumes which include volume of release, irrigation water, reservoir storage, reservoir evaporation, and spilled water for all inflows are listed in Table 5.

Table 5 shows that while the monthly volume of inflow as the unique resource of the system varies linearly, the overall benefit has not followed the same variation. As the total input water is reduced to 10% of normal inflow, the total annual benefit declined to 34% of its original benefit ($1,966,000 for normal inflow to $675,000 for 0.1 reduction factor of monthly inflow). This procedure is also repeated for other monthly inflows greater than the normal inflow as annual benefit is nearly doubled by applying 10 times of normal inflow as input water to the system ($1,966,000 for normal inflow to $3,953,000 for 10-factor increase in monthly input inflow). Variation of annual benefit versus changes in inflows over the planning horizon is also shown in Fig. 5. This implies that a $1-\log$ increase in flow, doubles the economic benefit and a $1-\log$ decrease, halves the benefit.

To propose a more reliable approach to account for the stochastic behavior of the inflow to the system, supplementary scenarios are examined for evaluation of the deterministic LP model. As in previous steps, the optimal multi-cropping pattern and corresponding reservoir operation have been obtained, four different scenarios are assumed to apply in the proposed LP model by considering constant inflow to the system and constant multi-cropping pattern as Cases 1–4. The average monthly inflows over the planning horizon are

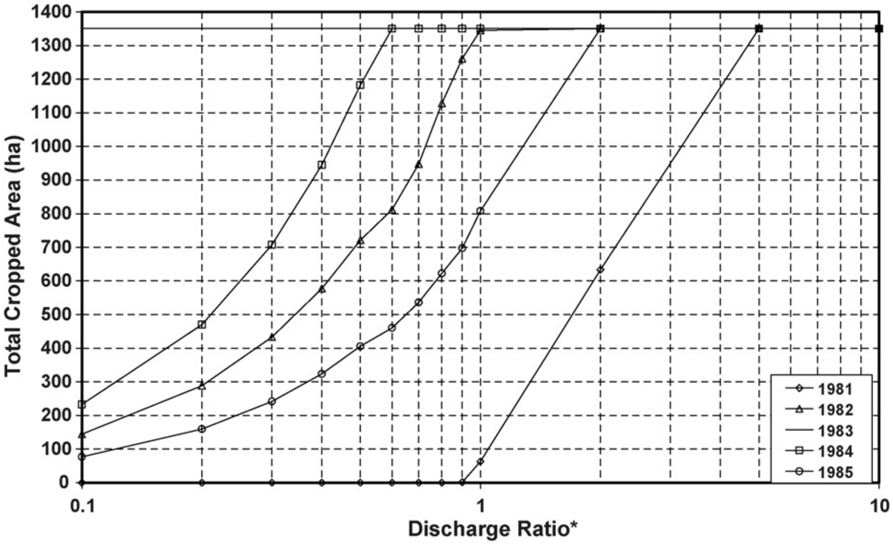

Fig. 4 – Sensitivity of total crop area to stream flow variation (*ratio of assumed discharge (considered in sensitivity analysis) to the natural inflow of river (considered in the main case)).

Table 4 – Non-zero crop/fruit cultivation areas in operational years with changes in inflow (ha)

Year	Crop/fruit	Q/Q_{normal}												
		0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	2	5	10
1980–1981	Barley	0	0	0	0	0	0	0	0	1.57	62.9	575	911	116
	Potato	0	0	0	0	0	0	0	0	0	0	0	439	1234
	Watermelon	0	0	0	0	0	0	0	0	0	0	58.1	0	0
	Apple	0	0	0	0	0	0	0	0	150	150	150	150	150
	Apricot	11.6	30.3	49.1	67.8	86.5	120	142	150	0	0	0	0	0
1981–1982	Barley	145	289	433	577	721	812	948	1128	1261	1345	983	0	0
	Potato	0	0	0	0	0	0	0	0	0	0	367	1350	1350
	Watermelon	0	0	0	0	0	0	0	0	0	0	58.1	0	0
	Apple	0	0	0	0	0	0	0	0	150	150	150	150	150
	Apricot	11.6	30.3	49.1	67.8	86.5	120	142	150	0	0	0	0	0
1982–1983	Bean	1350	1350	1350	1350	1350	1350	1236	1187	1157	1115	916	514	0
	Potato	0	0	0	0	0	0	114	163	193	235	434	836	1350
	Watermelon	0	0	0	0	0	0	0	0	0	0	58.1	0	0
	Apple	0	0	0	0	0	0	0	0	150	150	150	150	150
	Apricot	11.6	30.3	49.1	67.8	86.5	120	142	150	0	0	0	0	0
1983–1984	Barley	165	341	517	693	869	1045	1156	1033	912	822	79.5	0	0
	Potato	0	0	0	0	0	35.6	194	317	438	528	1270	1350	1350
	Watermelon	68.1	129	191	252	313	270	0	0	0	0	0	0	0
	Apple	0	0	0	0	0	0	0	0	150	150	150	150	150
	Apricot	11.6	30.3	49.1	67.8	86.5	120	142	150	0	0	0	0	0
1984–1985	Barley	31.5	74.7	118	161	204	460	536	418	329	362	457	0	0
	Potato	0	0	0	0	0	0	0	0	0	0	310	1350	1350
	Watermelon	45.8	84.8	124	163	202	0	0	204	368	446	583	0	0
	Apple	0	0	0	0	0	0	0	0	150	150	150	150	150
	Apricot	11.6	30.3	49.1	67.8	86.5	120	142	150	0	0	0	0	0

Q/Q_{normal}: discharge ratio, ratio of assumed discharge (considered in sensitivity analysis) to the natural inflow of river (considered in the main case).

considered to be constant while the constant multi-cropping pattern is defined as fixed irrigation areas and activities for both agricultural crops and fruits over the planning horizon. The four different scenarios by combinations of constant and/or variable inflow versus constant and/or variable multi-cropping pattern and irrigation areas are considered as additional scenarios. The model is applied based on these new scenarios and the new results are listed in Table 6. It is clear that by applying a constant multi-cropping pattern and irrigation areas, the annual benefit of the system is decreased from $1,966,000 (variable inflow with a variable cropping pattern in Case 3) to $860,000 (Case 1 with a fixed cropping

Table 5 – Sensitivity analysis of benefit and basic operation schedule parameters

Q/Q_{normal}	Total benefit (10^3\$)	Annual benefit (10^3\$)	Release		Demand		Storage		Evaporation		Spill	
			Ave (10^6 m^3)	Max (10^6 m^3)	Ave (10^6 m^3)	Max (10^6 m^3)	Ave (10^6 m^3)	Max (10^6 m^3)	Ave (10^6 m^3)	Max (10^6 m^3)	Ave (10^6 m^3)	Max (10^6 m^3)
0.1	3,375	675	0.04	0.44	0.06	1.15	0.33	0.86	0.04	0.12	0.00	0.00
0.2	4,159	832	0.09	0.91	0.10	1.15	0.67	1.72	0.07	0.23	0.00	0.00
0.3	4,944	989	0.13	1.37	0.15	1.37	1.01	2.58	0.11	0.35	0.00	0.00
0.4	5,728	1,146	0.18	1.84	0.20	1.84	1.35	3.44	0.14	0.46	0.00	0.00
0.5	6,513	1,303	0.23	2.30	0.24	2.30	1.69	4.29	0.17	0.57	0.00	0.00
0.6	7,294	1,459	0.27	2.75	0.29	2.75	2.04	5.04	0.21	0.67	0.00	0.00
0.7	8,037	1,607	0.33	3.03	0.35	3.03	2.27	5.20	0.23	0.71	0.00	0.00
0.8	8,737	1,747	0.38	2.99	0.40	2.99	2.57	5.97	0.26	0.83	0.00	0.00
0.9	9,374	1,875	0.44	2.97	0.44	2.97	2.84	6.50	0.29	0.95	0.02	0.46
1	9,829	1,966	0.50	3.14	0.47	3.14	2.98	6.50	0.30	0.99	0.02	0.40
2	13,416	2,683	1.21	11.35	0.72	4.42	3.76	6.50	0.39	1.24	0.08	1.24
5	18,185	3,637	3.50	38.72	1.08	4.67	4.56	6.50	0.52	1.48	0.21	1.43
10	19,765	3,953	7.50	77.46	1.24	4.67	4.30	6.50	0.54	1.43	0.25	1.43

Q/Q_{normal}: discharge ratio, ratio of assumed discharge (considered in sensitivity analysis) to the natural inflow of river (considered in the main case), Ave: average, Max: maximum.

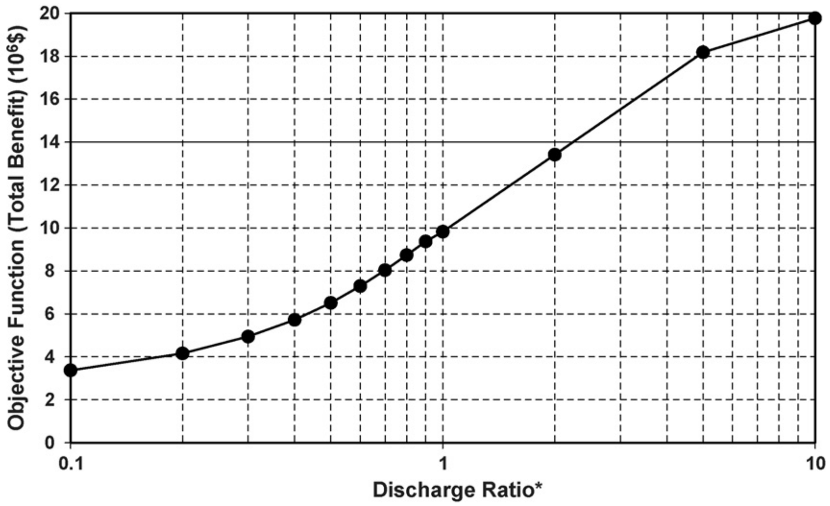

Fig. 5 – Sensitivity of project's total benefit to stream flow variation (*ratio of assumed discharge (considered in sensitivity analysis) to the natural inflow of river (considered in the main case)).

pattern and variable inflow), which resulted in more than 55% reduction in annual total benefits. As seen in Case 2 of Table 6, by considering both a constant cropping pattern and fixed inflow for the reservoir-irrigation system, annual benefits decreased only about 15%, i.e., down to \$1,665,000. An interesting result is obtained in Case 4, where the inflow is fixed as the average monthly inflow to the system during planning horizon but the cropping pattern is variable. Optimal results show about a 3% increase in total benefits of the system, implying that if the system has a constant inflow, the optimal multi-cropping pattern will be adjusted based on the constant supplied resource and may have a better efficiency over the consecutive years of the planning horizon and the overall benefit will reduce significantly during drought periods. In contrast, by considering a monthly average (fixed) inflow during all operating periods, the system has more benefits than considering the variable monthly inflow from one year to the next (Table 6).

Table 6 – Optimal results of cases 1–4 ($10^3\$$, 10^6 m^3)

Case number	1	2	3	4
Inflow	Variable	Fixed	Variable	Fixed
Crop pattern	Fixed	Fixed	Variable	Variable
Total benefit ($10^3\$$)	4,301	8,324	9,829	10,093
Annual benefit ($10^3\$$)	860	1,665	1,966	2,019
Initial storage ($10^6\$$)	2.60	4.21	1.08	4.20
Release				
Ave	0.37	0.50	0.50	0.46
Max	1.92	2.41	3.14	2.83
Demand				
Ave	0.26	0.5	0.46	0.46
Max	1.40	2.41	3.14	2.83
Storage				
Ave	4.03	3.23	2.98	3.49
Max	6.50	5.25	6.50	6.50
Evaporation				
Ave	0.44	0.31	0.30	0.35
Max	1.02	0.65	0.99	0.78
Spill				
Ave	0.06	0.00	0.02	0.01
Max	0.92	0.00	0.40	0.32
Deficit				
Ave	0.00	0.00	0.00	0.00
Max	0.00	0.00	0.00	0.00

The aforementioned scenarios, Cases 1–4, are also analyzed for further variable conditions to investigate how the optimal results will be changed with any variation in the conditions of Cases 1–4. For example, Case 5 has the same multi-cropping pattern as Case 1 but with constant inflows that are equal to the average of inflows during the planning horizon. This criterion is applied to generate new Cases 6–8 based on the same multi-cropping patterns and different inflow regimes from Cases 2–4, respectively. In the Cases 6–8, the crop patterns are considered to be fixed and equal to Cases 2–4, respectively. Thus, the flexibility of the reservoir operation in the optimization model decreases due to fixed combination and allocated area for different crops. So, the system's capability in satisfying the required water for crops decreases and subsequently the demand constraints cannot be satisfied and the LP cannot find a feasible solution.

By applying the optimization model to these new scenarios, only Case 5 converged to feasible results and all other scenarios, Cases 6–8, yielded infeasible results. The optimal results of the new scenarios are shown listed in Table 7.

So as to search for feasible results for Cases 6–8, a new coefficient of input flow, C_{in}, is defined to multiply the monthly stream flows. The minimum values of this coefficient with optimal feasible results are listed in Table 8, where Cases 9–12 are respectively formed based on Cases 1–4 considering new coefficients of input inflows. It is found that by reducing inflows for Cases 2–4 to 13.4, 63.4, and 49.7% of their initial inflows, feasible and maximum annual benefits are obtained.

Table 7 – Optimal results of Cases 5–8 (10^3\$, 10^6 m^3)

Case number	5	6	7	8
Inflow at planning	Fixed	Variable	Fixed	Variable
Crop pattern same as	Case 1	Case 2	Case 3	Case 4
Total benefit (10^3\$)	4,302	**Infeasible**	**Infeasible**	**Infeasible**
Annual benefit (10^3\$)	860	**Infeasible**	**Infeasible**	**Infeasible**
Initial storage (10^6\$)	5.18	1.41	4.14	1.38
Release				
Ave	0.26	0.48	0.42	0.46
Max	1.40	2.41	3.14	2.83
Demand				
Ave	0.26	0.50	0.46	0.46
Max	1.40	2.41	3.14	2.83
Storage				
Ave	4.69	3.61	3.79	3.64
Max	6.50	6.50	6.50	6.50
Evaporation				
Ave	0.51	0.38	0.41	0.39
Max	1.05	0.98	1.11	0.96
Spill				
Ave	0.06	0.03	0.02	0.04
Max	0.65	0.80	0.99	0.90
Deficit				
Ave	0.00	0.02	0.04	0.00
Max	0.00	0.53	1.38	0.12

Table 8 – Optimal results of Cases 9–12 (10^3\$, 10^6 m^3)

Case number	9	10	11	12
Inflow at planning	Fixed	Variable	Fixed	Variable
Crop pattern same as	Case 1	Case 2	Case 3	Case 4
C_{in} (coefficient of monthly input inflow)	1.66	0.13	0.64	0.50
Total benefit (10^3\$)	7,140	1,111	6,262	5,017
Annual benefit (10^3\$)	1,428	222	1,252	1,003
Initial storage (10^6\$)	4.75	1.35	5.06	2.60
Release				
Ave	0.43	0.49	0.33	0.34
Max	2.32	2.41	2.00	2.39
Demand				
Ave	0.43	0.07	0.29	0.23
Max	2.32	0.32	2.00	1.41
Storage				
Ave	3.82	3.17	4.38	4.18
Max	5.94	6.50	6.50	6.50
Evaporation				
Ave	0.38	0.32	0.48	0.46
Max	0.73	0.80	0.91	1.02
Spill				
Ave	0.00	0.02	0.04	0.08
Max	0.00	0.58	0.55	0.86
Deficit				
Ave	0.00	0.00	0.00	0.00
Max	0.00	0.00	0.00	0.00

5. Concluding remarks

Linear programming models can be used as an effective tool for determining the optimal multi-cropping patterns and allocating of irrigation areas, corresponding to reservoir operation and irrigation scheduling, in a coupled reservoir-irrigation system. By having simple tools such as linear optimization models, decision makers and water authorities can better evaluate their preliminary cost-benefit analysis of reservoir-irrigation systems.

This paper described an optimization model for optimal multi-cropped irrigated areas associated with proper reservoir operation and irrigation scheduling to maximize annual benefits derived from crops and fruits over a planning horizon. The constraints sets are linked together appropriately by additional reservoir capacity constraints.

Sensitivity analysis of inflows as the main input parameter associated with various supplementary scenarios such as constant/variable inflow regime and cropping pattern were investigated. Changing the monthly inflow to the reservoir in a wide range of variation caused little change in the optimum benefits obtained for the system, which shows the reliability of the reservoir in flood and drought years in supplying the demand water. The model shows that a reliable 10-fold increase in firm water, doubles the economic benefits.

Other cases evaluated in this paper showed the effect of considering constant and variable inflows as well as the cropping patterns in the planning horizon. Results indicate that considering variable cropping patterns can lead to more benefit of the system, which is due to the flexibility of the system for adapting to different inflow regimes. The optimal policy generated by the model in different cases suggested a diversified multi-cropping pattern.

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