

WATER MANAGEMENT OF IRRIGATION DAMS CONSIDERING CLIMATE VARIATION: CASE STUDY OF ZAYANDEH-RUD RESERVOIR, IRAN

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ABSTRACT

Dependency of water demands on the climate variation occurs especially in regions, where agricultural demand has a significant share of the total water demands. The variability between demands that are based on annual climate conditions may be larger than the uncertainty associated with other explanatory variables in long-term operation of an irrigation dam. This paper illustrates certain benefits of using variable demands for long-term reservoir operation to help manage water resources system in Zayandeh-rud river basin in Iran. A regional optimal allocation of water among different crops and irrigation units is developed. The optimal allocation model is coupled with a reservoir operating model, which is developed based on the certain hedgings that deals with the available water and the water demands mutually. This coupled model is able to activate restrictions on allocating water to agricultural demands considering variation of inflow to the reservoir, variation of demands and the economic value of allocating water among different crops and irrigation units. Using this model, long-term operation of Zayandeh-rud dam is evaluated considering different scenarios of inflow to the reservoir as well as agricultural demands. The results indicate that the use of operating rules which consider variable demands could significantly improve the efficiency of a water resources system in long-term operation, as it improves the benefit of Zayandeh-rud reservoir operation in comparison with conventional water supply approaches.

1 INTRODUCTION

Reservoir operation plays an important role in water resources planning and management. Operation of a reservoir for irrigation is more complicated and difficult than that for domestic water. It is due to the fact that irrigation requirements take various values depending upon climate condition, soil condition, and so on. In such a case, reservoirs should be operated to correspond with demand, inflow, and unknown future climate condition. The use of optimization techniques in determining optimal supply and demand options has been an appropriate approach to face the problems of a

coupled water resources-irrigation system. From the view point of a water resources system, the water demand of an irrigation system has specific characteristic which makes it significantly different from other water demands. Irrigation water demand may have significant variation due to the same climate variation that induces inflow as well as water loss. Dependency of water demands on the climate variation occurs especially in regions, where agricultural demand has a significant share of the total water demands. This variability is often ignored in long-term reservoir operation, where average climate conditions are used to define long-term agricultural demand with a typical seasonal variation. However, the variability between demands based on climate conditions may be larger than the uncertainty associated with other explanatory variables in operation of a reservoir (Palmer et al. 1995).

This paper uses a systematic approach to analyze the climate induced agricultural demand variation in the long-term operation of Zayandeh-rud reservoir in central part of Iran. The goals of operating water resources system of Zayandeh-rud basin are to supply domestic, industrial, and agricultural water demands with maximizing income from crops and minimizing water shortage loss. Drought is a major problem in Zayandeh-rud basin and the only solution to this problem is to use efficient agricultural water demand and to increase the productivity of limited available water resources. Maximizing the benefit of the water supply system needs both supply-side and demand-side management. To satisfy the goals, appropriate long-term and short-term decisions should be made. Researchers such as Karamouz et al (2004), and Karamouz and Araghinejad (2008) have focused on the water resources analysis in Zayandeh-rud basin. While Karamouz et al. (2004) have investigated drought characteristics in the basin; Karamouz and Araghinejad, (2008) have proposed real-time seasonal operational policies for Zayandeh-rud reservoir to mitigate drought damages. The previous works on the Zayandeh-rud basin and the reservoir have used the assumption of constant annual demand, ignoring year to year climate variation. This paper uses a systematic approach to analyze the climate induced agricultural demand variation in the long-term operation of Zayandeh-rud reservoir in central part of Iran.

2 CASE STUDY AND DATA

Zayandeh-rud basin is located in the central part of Iran as it is shown in Figure 1. The Zayandeh-rud River is the main resource of water for irrigation demands of the basin as well as domestic and industrial demands of the Isfahan metropolitan area. Zayandeh-rud reservoir with a volume of 1470 million cubic meters is the largest surface reservoir on the Zayandeh-rud River. The total annual average inflow to Zayandeh-rud reservoir is about 1600 million cubic meters of which an average annual flow of 600 million cubic meters is transferred from the adjacent Karoon River basin. More than 70 percent of water demand in Zayandeh-rud basin is related to agricultural section. There are 4 strategic crops in the basin including wheat, barely, alfalfa, sugarbeet and potato. The irrigation season of the basin starts from October and ends on October of the next year. The crops grown are supplied with irrigation water from Zayandeh-rud reservoir especially in spring and summer seasons when little or no rainfall is received. Annual hydroclimatologic data of Zayandeh-rud basin for the 29-year period of 1971 to 1999 are used in this study.

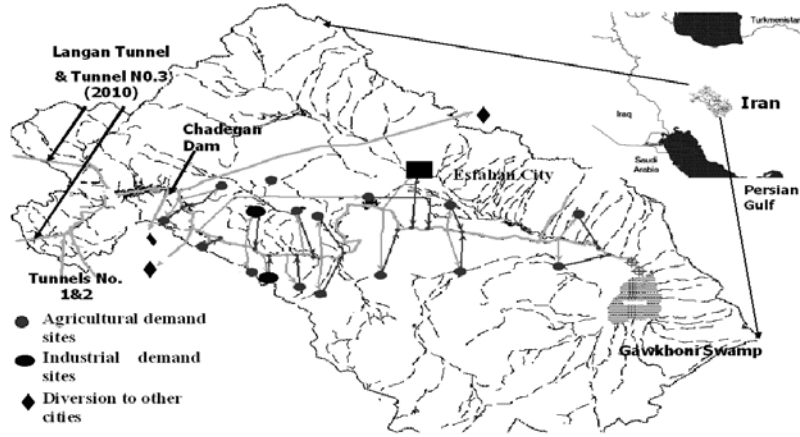


Figure 1. The Zayandeh Rud Irrigation system and related infrastructures

3 MATHEMATICAL MODELS

Two mathematical models of reservoir operating model and optimal regional allocation are coupled to derive optimal release and reservoir storage.

3.1 Model for Reservoir Operation Optimization

The continuity equation for a single reservoir is written as follows:

$$S_t + I_t - R_t - E_t = S_{t+1} \quad (1)$$

where S_t = beginning storage during time period t , S_{t+1} = ending storage during time period t , I_t = inflow during time period t , E_t = total loss during time period t , and R_t = release during time period t . During operation of reservoir, hedging rules might be activated, when shortages occur and available water ($S_t + I_t$) get to specific values of drought triggers. In general, during each time period t , the release from reservoir might be less than demands; equal to demands; and more than demands, depending on the trigger values of $S_t + I_t$. The release volume in each category is then determined as a variable function of I_t , S_t , and water demand, D_t . Draper and Lund (2004) proposed an analytical method instead of a direct search, to solve the problem of finding optimal triggers. This method is based on the equilibrium of the marginal benefit of delivered water and water storage benefit, $\partial C(S)/\partial S = \partial B(R)/\partial R$, where R =release from reservoir in a specific time period, S =reservoir storage at the end of time period, $C(S)$ =expected value of reservoir storage, and $B(R)$ =expected value of released water. Draper and Lund (2004) showed that in the case of quadratic benefit and storage value

functions where $B(R_t) = a_r + b_r R_t + c_r R_t^2$, and $C(S) = a_s + b_s S + c_s S^2$, the drought triggers are calculated as follows

$$Trigger_{1t} = (b_s - b_r) / (2c_r) \quad (2)$$

$$Trigger_{2t} = \text{Min} \left[D_t (1 + c_r / c_s) + (b_r - b_s) / 2c_s, CAP (1 + c_s / c_r) + (b_s - b_r) / 2c_r \right] \quad (3)$$

$$Trigger_{3t} = D_t + Cap \quad (4)$$

where D_t = the water demand, Cap = the maximum capacity of reservoir and a_r, b_r, c_r , and a_s, b_s, c_s = the constant values of release value function and storage value function, respectively.

The optimum release, R^* , is then obtained by an interpolation in the area between $Trigger_{1t}$ and $Trigger_{2t}$.

3.2 Model for Irrigation Scheduling Optimization

The model for irrigation scheduling optimization used in this study was originally proposed by Shangguan et al. (2002). This model is extended to consider climate factors in Zayandeh-rud basin. The model consists of three sub-models of irrigation scheduling optimization for individual crops; water allocation and planted acreage optimization across crops; and model for water allocation optimization among the irrigation units.

sub-model 1:

sub-model 1 calculates optimum crop water requirement during growing season base on a 10 days irrigation period for each crop. The objective function is to maximize crop production per hectare is

$$MAX : \frac{Y_{ac}}{Y_{\max c}} = 1 - \sum_{g=1}^n Ky_g \left(1 - \frac{ETa_{c,g}}{ET \max_{c,g}} \right) \quad (5)$$

Where $ETa_{c,g}$ = crop actual evapotranspiration at stage g (mm/10 days) of growing period; $ET \max_{c,g}$ = crop maximum evapotranspiration at stage g (mm/10 days); Ky_g = crop sensitivity coefficient in stage g, n = total number of growth stages; Y_{ac} = actual yield per unit area and $Y_{\max c}$ = maximum yield per unit area (kg/ha) (Allen et al., 1998).

sub-model 2:

The objective function for this sub-model to maximize the summed benefit of all crops within an irrigation unit is:

$$MAX : \left\{ \sum_{k=1}^K F_K(Q_K) A_K Y_{\max k} P_K \right\} \quad (6)$$

where K = total number of crops; $F_K(Q_K)$ = functional relation between maximum relative yield and allocated irrigation water for crop k ; A_K = the acreage for crop k (ha); $Y_{\max k}$ is the maximum yield for crop k (kg/ha); and P_K = income of crop k (US Dollar). In order to calculate $F_K(Q_K)$ for crop k , the first sub-model needs to be run with various values

sub-model 3:

The Last sub-model distributes optimally the total release of the reservoir between the irrigation units. The objective function is to maximize the summed benefit of all the units, as follow:

$$MAX : \left\{ \sum_{n=1}^N F_n(Q_n) \right\} \quad (7)$$

where N = total number of units; $F_K(Q_K)$ = functional relation between maximum benefit and allocated water for each unit.

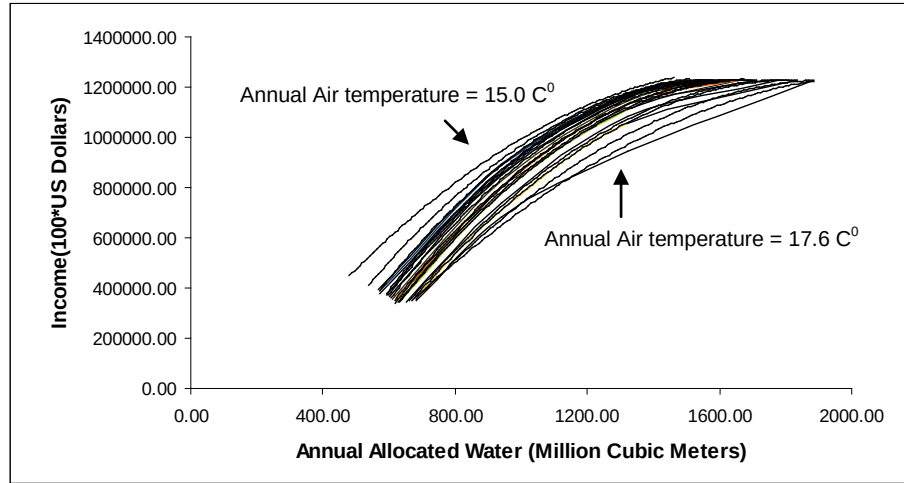
The recorded 29 years historical climate data from 1971 to 2001 are considered as the climate scenarios that the basin might experience in the long-term operation. Consequently, 29 functions of $F_K(Q_K)$ is derived presenting the annual allocation benefit corresponding to different climate scenarios.

3.3 Experiments of Reservoir Operation

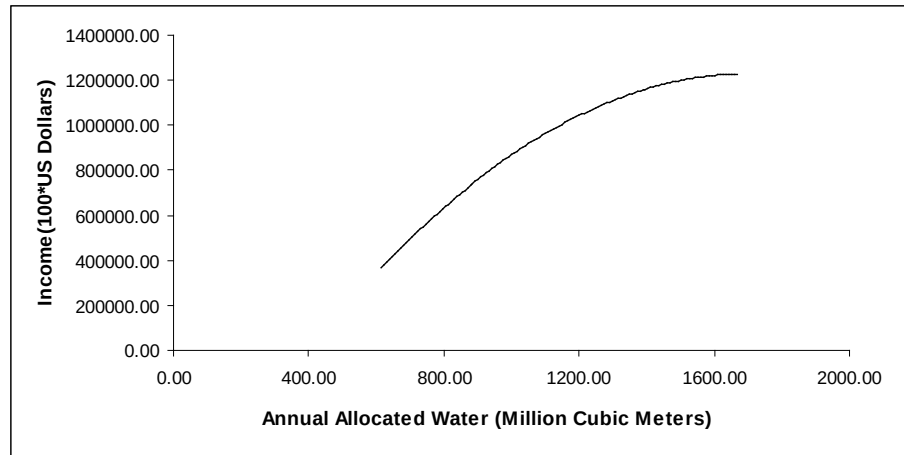
Zayandeh-rud reservoir operation is simulated and optimized in 3 different experiments. In the first experiment the annual reservoir operation is simulated by simple Standard Operating Policy (SOP) which considers variable annual demand during the operating time horizon. In the second experiment, considering constant annual demand, the reservoir operation is optimized using optimal hedging rules described in the previous section. Finally, in the 3ed experiment, the reservoir operation is simulated by optimal hedging rules considering variable demands. The results are compared by the length and severity of droughts at each experiment, income in US Dollars as well as water shortage loss. The drought loss considered in the analysis is a summation of tangible and non-tangible losses caused by droughts, which is reported by the water company of Isfahan province. The simulation results in 3 experiments are presented in the next section.

4 RESULTS AND DISCUSSIONS

The range of annual production functions of the entire system for the 29 different climate scenarios are presented in Figure 2. The production functions of the system have considerable differences due to the climate variation especially air temperature in different years. Maximum water requirement is 1800 Mm³, associated with the average annual temperature of 17.8 C⁰. The associated income for this scenario is 120000000 US Dollars, which it could be reached by less than 1500 Mm³ water allocation during the years with better climate conditions as it is demonstrated in Figure 2.



(a)



(b)

Figure 2. Variation of productivity function in the basin due to the climate variation (1971-1999) (a), and Average productivity function of the basin due to the long-term climate (b)

The results of long-term operation of Zayandeh-rud reservoir using SOP rules are shown in Table 1. Water shortage spells, severity, and duration as well as water shortage loss are shown in this Table. As demonstrated in Table 1, 4 water shortage events are experienced in the first experiment in which 25 of 29 years of the simulation period are faced with drought circumstances. The most severe water shortage in the first experiment has the severity of 8100 Mm³ and lasts 10 years.

The results of optimal long-term operation of reservoir by hedging rules are also shown in Table 2 for two cases of constant and variable agricultural demands in the 2ed and the 3ed experiments, respectively. In the 2ed experiment, the average production function shown in Figure 2b is used as the expected production function of the entire

system. As shown in Table 2, in the 2ed experiment, 5 water shortage events are observed and 20 out of the 29 water years are affected by water restriction. In the 2ed experiment, the system has experienced a total 11520 Mm3 severity during 29 years operation. The most severe drought in this scenario lasts 10 years with 6000 Mm3 severity. In the 2ed experiment, total water shortage damage is estimated as 1700 million Dollars. In the 3ed experiment, using variable demands in annual operation, water shortage events have reduced to total 11000 Mm3 severity. The results demonstrate that annual operation of the reservoir using optimal hedging rules and variable demands could reduce the drought damage by 10 percent in comparison with the 2ed experiment. The water shortage loss is reduced from 1700 million Dollars in the 2ed experiment to 1500 million Dollars in the 3rd experiment.

Comparison between results presented in Table 1 with what is presented in Table 2 demonstrates significant help of hedging rules in reducing water shortage impacts in the basin. The water shortage damage in the 3rd experiment is significantly less than the 1st experiment. This is because of the hedging rules which prefer the system to meet droughts with fewer severities in comparison with the application of SOP.

Table I. Performance indices using SOP

performance indices				
Water Shortage Periods	Water Shortage Duration (years)	Water Shortage Severity (Mm3)	Water Shortage Loss (million US Dollar)	Total Income (US Dollars)
1972-74	3	2500	407	
1976-85	10	8100	1360	
1988-91	4	2400	380	
1994-99	6	4300	790	
Summation	23	17300	2937	2400000000

5 SUMMARY AND CONCLUSION

An approach was proposed to provide guidance to the water managers in long-lead operation of the Zayandeh-rud reservoir in Iran. The approach used long-term hydroclimatologic variables to calculate production functions of the crops for different climate conditions as well as hedging rules to activate specific restrictions on the agricultural demand allocation. This approach is suitable for considering demand management tools into the reservoir operation. Results indicated that operating schedules from the proposed approach, which consider the aspect of variable demand is different from those obtained from a model that does not consider this issue. In the simulation scenarios, comparing the proposed approach with the standard operation policy of Zayandeh-rud reservoir, the effectiveness of the proposed approach was demonstrated by decreased risk of water shortage damages. The paper was focused on the water resources management of the Zayandeh-rud basin, however, the proposed approach could be used for different water resources systems with significant variation in demands.

Table II. Performance indices using SOP

Experiments	approach	performance indices				
		Water Shortage Periods	Water Shortage Duration (years)	Water Shortage Severity (Mm3)	Water Shortage Loss (million US Dollar)	Total Income (US Dollars)
2	constant demand	1971	1	240	12	
		1973-74	2	1530	230	
		1976-85	10	6000	780	
		1989-90	2	1050	172	
		1995-99	5	2700	500	
		Summation	20	11520	1694	2800000000
3	variable demands	1971	1	385	29	
		1973-74	2	1400	210	
		1976-85	10	5700	690	
		1989-90	2	1100	178	
		1995-99	5	2500	420	
		Summation	20	11000	1527	2940000000

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