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Research Note

USE OF DIFFERENT IRRIGATION WATER DEFICIT SCHEMES FOR ECONOMIC OPERATION OF A RESERVOIR [*]

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Abstract- Some common methods, such as 75% of full demand (75%), shortage index (SI), modified shortage index (MSI) and planned deficit at specific dry years (PD) were compared with a proposed method of constant water deficit (CWD) for a 30×10^6 m^3 reservoir of the Ardak dam located northwest of Mashhad (Khorasan province of Iran). In each case the optimum downstream area for a cropping pattern of wheat, barley, sugarbeet and corn was determined. The amount and net value (NV) of actual yield, net present value (NPV) and benefit to cost (B/C) ratio were computed for each scenario, using dated water production functions of different crops, accompanied with suitable sensitivity indices. Optimum intra-seasonal water allocation under PD was made by applying the nonlinear programming scheme. The results of this study showed that the methods of 75%, SI, and MSI are neither appropriate since they do not account for actual crop yield obtained under water deficit, and nor are they practical in real time. On the other hand, the inappropriateness of the PD method is attributed to its impossible utilization for an actual reservoir and also to its theoretical shortcomings. In contrast, the proposed method of CWD for the whole period of operation can be used in reservoir operation management, while it is coupled with optimum intra-seasonal water allocation based on a nonlinear programming scheme. This study also shows that the CWD method is more appropriate for the economical operation of the reservoir.

Keywords – Reservoir operation, deficit irrigation, non-linear programming, Ardak dam

1. INTRODUCTION

The monthly and seasonal river flow regime is variable under natural conditions. This variability in river flow may be controlled by a dam, which may be constructed at a specific site on the river.

There are two earlier methods in designing a small size reservoir under partially supplied downstream demands. In the first (75% method) [1], downstream demands must be fully supplied for 75% of time while some shortages are allowed for the remaining 25%. The amount of this shortage is not constant and can vary up to 100% for each specific time period. In the second (shortage index; SI) [2] an index is defined as the average of sums of squares of annual shortages to annual water demands and is based on a subjective criterion of $SI\leq1$. In both these methods the effects of water shortages on the downstream demands are not considered, especially during dry periods.

Rostam-Afshar [3] modified the latest method and proposed the "modified shortage index" method (MSI). He considered different values of water shortage for different periods of growing seasons downstream for crops under cultivation. He compared the methods of 75% of full demand, SI and MSI as a case study and found the MSI method to be superior.

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Although none of these three methods (75% of full supply, SI and MSI) considers the probable effects of water shortages on crop yields and all were originally designed for fixing a reservoir volume for known downstream demands, in this paper the manner is reserved, i.e., the unknown downstream demands are determined for each of these methods for a known reservoir volume, regarding the effects of dated water stress on crop yield.

In another analysis, Nairizi [4] and Nairizi and Khiabani [5] investigated the effect of deficit irrigation on crop yield and also on net present value (NPV) for two storage dams in Iran by using a dated water production function. Water allocations in a typical dry year were made simply according to the differences in the price of crops and relative sensitivities to water for different crops and for different months in their investigations.

By a given volume of water and if downstream demands are partially supplied, one can then cultivate more land, and impose deficit irrigation on all the crops. The optimum deficit in water allocation should be determined by economical analysis. Thus the objective of this study was to compare the different irrigation water deficit schemes, including reservoir characteristics, with a fixed volume using different dated water production functions.

2. INVESTIGATIVE APPROACH

a) Water production function

Dated water production function, accounting for the effect of water shortage on the amount of crop yield, was proposed by Jensen [6] as follows:

$$Ya/Ym= \prod_{i=1}^{n} (ETa_i/ETm_i)^{ai} \tag{1}$$

in which Ym is the potential crop yield under full irrigation, Ya is the actual crop yield under deficit irrigation, n is the number of growth period in a crop season, ETa_i and ETm_i are actual and potential evapotranspiration at the ith growth stage, respectively, and a_i is the water sensitivity index of crop at ith growth stage. Equation (1) is called "Jensen type water production function" (JTWPF). The following equation was proposed by Doorenbos and Kassam [7] to determine the effect of water shortage at a specific growth stage on crop yield:

$$Ya/Ym=1-Ky(1-ETa/ETm) \tag{2}$$

in which Ky is the water sensitivity index of crop and the other terms were defined previously. A similar equation for determining crop yield with water shortages at different growth stages is also presented [8]:

$$Ya/Ym= \prod_{i=1}^{n} [1-Ky_i(1-ETa_i/ETm_i)] \tag{3}$$

In the present research, this water production function is called "FAO type water production function" (FAOTWPF).

b) Maximization algorithm

A cropping pattern may be used downstream of a dam. If the available water is less than the required amount downstream in a specific year, optimum allocation of water among different crops and at different growth periods must be made such that the benefit is maximized according to the following equation:

$$MAX{:}M= \sum_{i=1}^{m} a_i . Pi.Fi.Ym \tag{4}$$

in which m is the number of crops in the cropping pattern, a_i, Pi, Fi, and Ym are areas under cultivation, net benefits for crop per unit area, water production functions of the ith crop Eqs.(1) or (3), and maximum crop production per unit area, respectively. Equation (4) must be maximized under the following constraints:

$$\Sigma_i \Sigma_j Wa_{i,j}=x \cdot IR \tag{5}$$

$$0<Wa_{i,j}<=Wo_{i,j} \tag{6}$$

in which x is the portion of full irrigation water demand per unit area (IR) that can be delivered safely to the unit area downstream, and $Wa_{i,j}$ and $Wo_{i,j}$ are partial and full irrigation water demands for each growth stage and for each crop, respectively:

$$IR=\Sigma_i \Sigma_j ETm_{i,j} \tag{7}$$

Equation (4) was maximized under the constraints of Eqs. (5) and (6), by compiling Kuhn-Tucker conditions based on a nonlinear programming scheme [9]. This maximization algorithm has been used recently by Ghahraman and Sepaskhah [10].

c) Cropping pattern

The proposed Ardak dam site is located 45 km northwest of Mashhad, in Khorasan province of Iran. Four crops were considered in the cropping pattern downstream of the dam. These crops and their relative cultivated areas are wheat (40.7%), barley (28.9%), sugarbeet (17.8%) and corn (12.6%) [11]. Water requirements (i.e., ET) of these crops are reported elsewhere [11].

d) Water sensitivity indices

Agricultural crops show different responses to water shortage during their growth stages. The sensitivity indices for water shortage (a_i) in JTWPF [6], Eq. (1), can be obtained from Aryan [12] and Honar [13]. These authors derived the water sensitivity indices of wheat and barley and corn for the semi-arid region of Bajgah, Fars province of Iran, respectively. Thus far, we have not been able to find the sensitivity indices for sugarbeet, and therefore a substitution was made for the water sensitivity indices of potato [14] for sugarbeet, as both are root crops. As river flow was recorded monthly, the computed indices were changed to monthly values according to the growth stages of different crops (Table 1).

Table 1. Monthly water sensitivity indices for crops in the cropping pattern for different water production functions

Month		Wheat		Barley		Sugarbeet		Corn	
		JTWPF[1]	FAOTWPF	JTWPF[1]	FAOTWPF	JTWPF[2]	FAOTWPF	JTWPF[3]	FAOTWPF
Meh.	Oct.	.08	.133	.8	.133	.1	.205		
Aba.	Nov.	.15	.2	.15	.2				
Aza.	Dec.								
Dey.	Jan.								
Bah.	Feb.								
Esf.	Mar.	2.1	.6	.7	0.56				
Far.	Apr.	.3	.424	.18	.165	.1	.205		
Ord.	May.	.2	.11	.14	.08	.1	.205	.76	.235
Kho.	Jun.	.2	.11			2.62	.38	.98	1.387
Tir.	Jul.					.18	.369	.87	1.5
Mor.	Aug.					.1	.205	.90	.726
Sha.	Sep.					.1	.205	.41	.239

1- Aryan [12], 2- Hill, et al. [14], 3- Honar [13]

Water sensitivity indices (Ky) of different crops for FAOWPF [7], Eq. (3), are present in the literature [7]. The indices are not reported for all growth stages of the crops for the present study. Some relevant values were considered for the missing growth stages by comparing the reported values with those of relevant indices of Jensen type. Then, the sensitivity indices for different growth stages were changed to monthly periods. The results are shown in Table (1).

e) Storage dam specifications

Construction of a dam with a 30×10^6 m^3 reservoir size has been reported as a solution to control the Ardak river flow, which needs 37,733,067 Rials (1$=3000 Rls.) in investments [11]. One percent of the total cost of construction was considered for annual maintenance and repair costs.

f. Economic analysis with planned irrigation water deficit (PIWD):

The simulation analysis [15] was used to optimize the cultivated area downstream of a dam with a fixed reservoir volume. This method has appropriate flexibility for modification of the parameter values (e.g., evaporation from reservoir surface and overflow from spillway). In the methods of the 75%, SI, and MSI, the effect of water shortage on crop yield reduction has not been considered, which is not a real case. In determining the effects of water shortages on crop yields, the specific periods of temporary water shortages and their amounts should be known. This was done for 50 years of reservoir operation by using Eqs. (1) and (3). The actual yield and net benefit for each year of operation were calculated, and then all net benefits converted to present values (NPV) with an 8% discount rate.

In a planned deficit of specific dry years (PD) [4,5], water allocation among different crops and different months in a specific dry year has been made qualitatively, based on "prices of crops, amount of water needed and relative water sensitivity indices". In contrast to their qualitative allocation of water, we propose an exact nonlinear programming procedure. According to the method of Nairizi and Khiabani [4,5], the driest year in 50 years of reservoir operation was determined. Ten percent of water requirements for the cropping pattern was reduced and the remainder allocated such that the maximum net benefit was obtained. This procedure was repeated for 2nd, 3rd, ... and 25th of the dry years and also repeated for 20, 30, ... and 80 percent of water reductions. For each water production function the optimum downstream area for cultivation was determined by a similar procedure, as explained previously.

Constant water deficit method (CWD), a new proposal, is based on the premise that a constant shortage of water may be imposed on all growth stages of crop during the operation periods. The water allocations among different crops and at different growth stages were calculated by incorporating a nonlinear programming system theory [9]. Two different WPF's, i.e., JTWPF and FAOTWPF were used and NPV and B/C ratio were also computed.

3. RESULTS AND DISCUSSION

a) Seventy five percent, SI, and MSI methods

Results of the economical investigations for these methods are presented in Table 2. The optimal downstream area cultivation for these methods are 4400, 3992, and 4217 hectares, respectively. The SI method shows more benefit than other methods, although it is not significantly different from MSI method. Rostam-Afshar [3] has compared these three methods for the Goosikhard dam in India and found that the MSI method works better, but his investigation was only related to the minimization of dam reservoir size and was not to study the effect of water shortages on crop yields, especially in dry seasons. Originally, in all of these three methods the effects of water shortages on crop yields have not been taken into consideration. However, in the present study it was considered in the analysis. Meanwhile, Table 2 shows that utilization of JTWPF and FAOTWPF present completely different results. Independent research has not been carried out to show the suitability of FAOTWPF. Nevertheless, the results of the present study show that these indices *may not* be appropriate for some regions of the world (at least the dry and semi-arid regions of northeast Iran). Of course, the authors concede that a firm conclusion on this matter cannot be made until more field supports are available.

Table 2. Economic analysis for 75%, SI, and MSI methods (8% discount rate)

	NPV(*1E9)		B/C ratio	
	JTWPF	FAOTWPF	JTWPF	FAOTWPF
75%	-3.886	3.711	0.908	1.088
SI	3.476	8.248	1.082	1.195
MSI	0.124	7.130	1.003	1.168

b) Planned deficit at specific dry years (PD)

Figure 1 presents NPV for two different water-production functions (JTWPF and FAOTWPF) and for an 8% discount rate. The response of B/C ratio is identical to this figure and therefore is not presented. Figure 1 shows that for mild stresses (up to 30% of water shortage) in JTWPF, increasing the number of dry years, i.e., imposing more planned irrigation water deficit, also increases the NPV of the project. However, some irregularities exist with more water shortages in Fig. 1. This trend may be explained by the fact that the applicability of FAOTWPF is restricted to less than 50% water reduction [7]. The same reason may exist for JTWPF [8]. The results for FAOTWPF are not in complete agreement with the JTWPF, and more research is needed in this regard.

In addition to the theoretical shortcomings and qualitative nature of water allocation among different crops and in different months, the PD method [4,5] reveals three other shortcomings: a) the exact time of the dry year is easily known in a historical event (or simulated series), but in real time it is not known. So this method may be used for a historical series but it is not applicable for reservoir operation in real time. This means that the years for which future water allocation must be decided are not known; b) consequently in a dry year, only one specific amount of water shortage (i.e., 10% or 20% or...) was used [4,5], but imposing infinite combinations of water shortages (e.g., 20% in driest year and 50% in the next driest year and so on) is not possible; c) irrigation scheduling is nearly impossible with such a variable amount of irrigation water deficit and unknown application time.

c) Constant water deficit method (CWD)

This method was proposed in this study to overcome the shortcomings encountered with the PD method [4,5]. The B/C ratio in this method is presented in Fig. 2. The trend for NPV criterion is similar (not shown). Figure 2 shows that applying FAOTWPF [7] yields an ever-increasing benefit as a function of water reduction for the project under study, which does not seem realistic. This abnormal rise may be attributed to the inappropriateness of the sensitivity indices [7]. If this is the case, more field support is needed to reach a firm conclusion.

Figure 2 also shows that for JTWPF there are three consecutive maxima. Among these, the first maximum is accepted. Such a trend has also been reported by Ghahraman and Sepaskhah [16]. Although the exact reason of this abnormal trend is not obvious, it may be due to the fact that the water sensitivity indices at ETa/ETm>0.5 are not applicable, as explained earlier. Thus, only the first maximum for water deficit (30%) may be accepted.

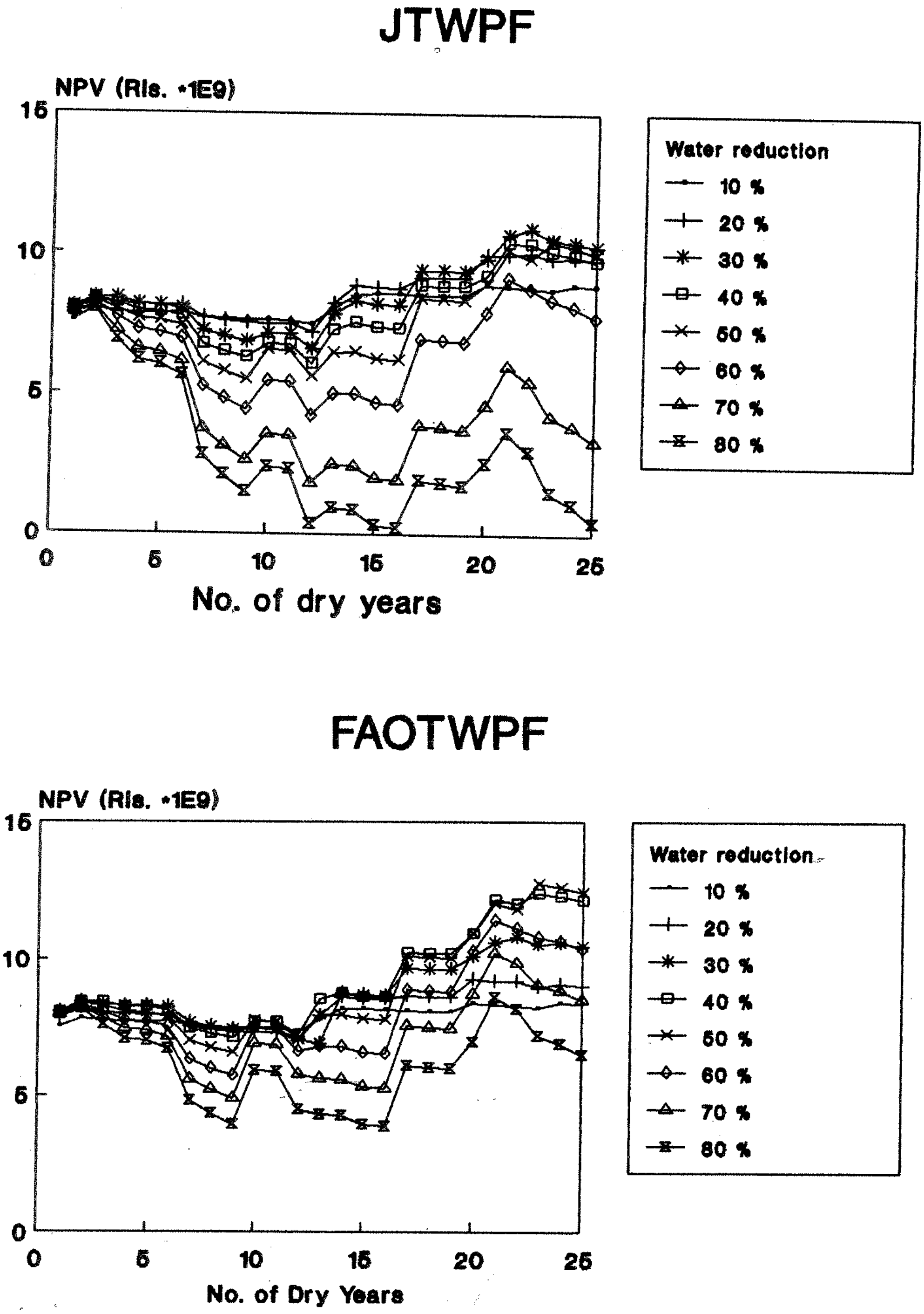

Fig. 1: Net present value (NPV) for planned deficit at specific dry years (PD) method with 8% discount rate

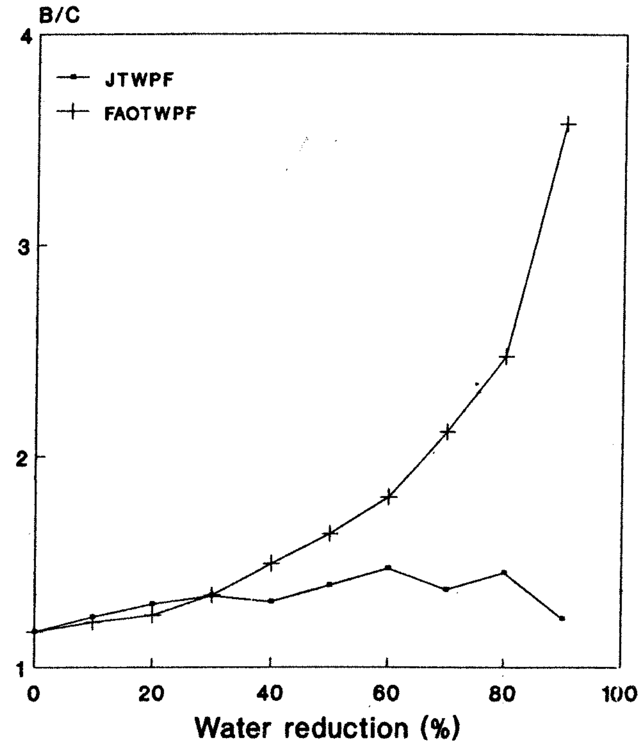

Fig. 2. Benefit to cost (B/C) ratio for constant water deficit (CWD) method with 8% discount rate

4. CONCLUSION

a) The methods of 75%, SI and MSI were originated to determine a reservoir volume with a known amount of downstream demands. A method was presented in this study to consider the above-mentioned methods in a reverse procedure, and also to include the effect of dated water stresses on the amount of crop yield. Although the economical considerations are included in these, propositions, the practical usages of these methods are not applicable for a real time operation.

b) Although the PD method [4,5] is not recommended, due to its theoretical shortcomings and impracticality in the real world, the results of the present investigation show that a 30% water shortage is allowed to utilize JTWPF. The results for FAOTWPF [7] do not agree completely with JTWPF.

c) The proposed method of CWD was based on a sound theoretical basis and can be utilized in future investigations. Such a method overcomes the particular difficulty of the unknown occurrence of a specific dry year. Also, simpler irrigation scheduling is a consequence of this method.

d) The results revealed that more field research is needed to reach a firm conclusion about the applicability of Ky indices the Doorenbos and Kassam's.

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