APPLICATION OF DETERMINISTIC MATHEMATICAL METHOD IN OPTIMIZING THE SMALL IRRIGATION RESERVOIR CAPACITY

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Abstract

Restriction of surface water resources and higher cost of hydraulic structures in Iran intensify the need for an optimum capacity and operation for irrigational reservoir systems. Due to the complexity of water resource systems and some constraints, it seems necessary to employ mathematical models and optimization techniques for computing the optimum reservoir volume. In this research, to find the optimum active capacity of Keyserek reservoir active capacity, a deterministic nonlinear program (DNLP) is introduced. The model is only used for a within-year regulation. Keyserek reservoir is an off-river system used for irrigation of 325 ha farmlands via a channel from the Cheki-Chay River. The objective is to minimize reservoir volume K_a during a specific demand and reservoir deterministic inflow in requested months. The dead storage capacity must be added to K_a, which is the active storage capacity, in order to compute the total reservoir capacity. The developed model is solved by GAMS software that gives the minimum reservoir volume 2 322 912 m^3.

Keywords: Mathematical models, optimization techniques, deterministic nonlinear program, reservoir management, single-purpose reservoir system

Sulama Amaçlı Küçük Rezervuarlarda DNLP Yöntemi ile Optimum Kapasitenin Belirlenmesi

Özet

İran'daki sulama amaçlı rezervuar sistemlerinde kısıtlı su kaynakları ve hidrolik yapıların yüksek maliyetinden dolayı optimum kapasite ve işletme zorunlu bir ihtiyaçtır. Su kaynakları sistemlerinin karmaşıklığı ve bazı kısıtlardan ötürü optimum hazne kapasitesinin hesaplanmasında matematiksel modellerin uygulanması gerekli görülmektedir. Bu çalışmada Keyserek rezervuarının aktif kapasitesinin hesaplanmasında deterministik doğrusal olmayan program uygulanmıştır. Bu model sadece yıllık düzenlemeler için kullanılır. Keyserek rezervuarı akarsu yatağı dışında bir rezervuar olup Cheki-Chay nehirinden bir kanalla 325 hektar alanın sulanmasında kullanılmaktadır. Modelin amaç fonksiyonu, rezervuara giren deterministik su miktarı göz önüne alınarak ihtiyaç duyulan miktarda talebi karşılayacak şekilde rezervuar kapasitesini (K_a) minimize etmektir. Bulunan hacim aktif depolama kapasitesidir. Böylece toplam rezervuar kapasitesinin hesaplanmasında ölü hacmi depolanma kapasitesi rezervuar hacmine ilave edilmelidir. Geliştirilen model GAMS yazılım ortamında çözülmüştür. Modelin uygulanması sonucunda rezervuarın kapasitesi 2 322 912 m^3 olarak belirlenmiştir.

Anahtar kelimeler: Matematiksel Modeller, Optimizasyon Teknikleri, Deterministik Doğrusal Olmayan Program, Rezervuar İşletmesi, Tek Amaçlı Rezervuar Sistemi.

1-Introduction

A reservoir is designed for water supply, irrigation, power generation, maintaining in stream flow, and storage for recreation and fisheries. Optimal sizing of a reservoir is an important factor in reservoir implementation studies. The optimum level can decrease the building cost. Therefore the application of mathematical models plays a main role in finding the optimum capacity of a reservoir. As water resources are limited in Iran, building new hydraulic structures is costly. Thus, it is of high necessity to know the optimum volume and operation for reservoir systems. Due to the complexity of water resources systems and the presence of many constraints and limitations, the application of mathematical models and optimization techniques for computing the optimum reservoir volume is necessary. In Iran, water resources and water needs often are not compatible, thus the regulation is carried out by storage reservoirs. Although water resources are called renewable, the average usable amount is constant. It is very important to consider the optimal capacity of reservoirs and effective use of them, which have not seriously noticed in Iran yet. The reservoir planning and operation studies, which have made progresses in recent decades, are based on Rippl's graphical method. The weakness of this method, which can only consider a constant need, was overcome by Thoma's Sequent Peak algorithm. It is a multi-stage decision problem to design the capacity of water reservoir systems and operate them. Dorfman first used a Linear Programming (LP) model to solve the problems. After Yeh's (1985) state of the art study, Dynamic Programming (DP) and Linear Programming (LP) models have commonly been used for the problem. Revelle (1969) proposed a linear decision rule (LDR) to make release decisions for a single reservoir system. Louks et al. (1981) proposed a stochastic linear programming model to determine a strategy for release, giving the current state of the system and the previous inflow. By applying a monthly planning and operational model, Crawley and Dandy (1993) developed a model for the Adelaide head works system in South Australia, Australia. The model used a linear goal programming to aid the identification of optimum operating policies for the system. Afshar et al. (1991) developed a mixed integer linear optimization model for irrigation. The model was a chance-constrained optimization model that considered the interaction between design and operation parameters (reservoir capacity, delivery system capacity, etc.). Needhom and Watkins (2000) used an LP model for flood control on the Iowa and Des Moines River reservoirs. Teixeira (2002) developed a forward dynamic programming (FDP) model to solve the reservoir operation and irrigation-scheduling problem. A typical scenario in application of the model was composed of a system of two reservoirs in parallel supplying water to as many as three irrigation districts. Sattari et al. (2003) applied an LP model for optimizing single-purpose reservoir volume.

2. Material and Methods

2.1. Research locations

Keyserek dam is located in Azerbaijan, a state in Iran (Anonymous 2001). The dam height is 1680 m above the sea level. This basin lies between east latitude 45˚ 16' and north latitude 38˚ 4' (Figure 1).

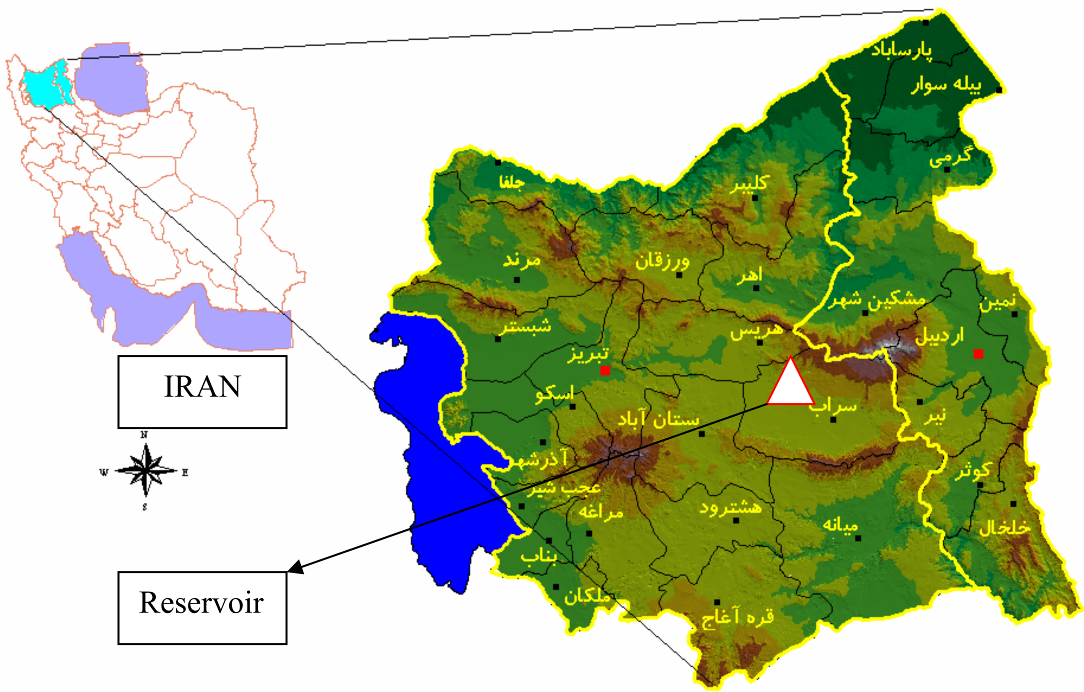

Figure 1. Location of Keyserek reservoir

The nearest climatologic station in which 27-year statistical data have been recorded is Mirkuh that has semi-dry and cold whether. Maximum temperature is 36 ˚C in August and minimum temperature is 25 ˚C in January. Annual average temperature in all statistical period is 8.4˚C and the average of monthly evaporation from free surface is shown in Table 1.

Average annual precipitation is 315 mm; its maximum that achieved in 1968 is 539 mm and its minimum that achieved in 1998 is 179.5 mm. The maximum of monthly average precipitation in the region is 63.2 mm that is 20 % of all annual precipitation in May, and the minimum of monthly average of precipitation is 6.4 mm that is 2 % of all annual precipitation in August. Therefore the spring season with 48 % of precipitation is considered as the wettest season of each year. Average precipitation on reservoir area in monthly bases is shown in Table 2.

2.2. Chaky-Chay River

The Chaky-Chay River is a sub-river of the Aji-Chay River and streams from Mount Yaghli. This river, near the Alan village, flows from Alan diversion dam in East-North into the Aji-Chay River in West-South. The area of basin in the Alan dam point is 189.8 km^2. According to 46-year statistical data, the rate of inflow was calculated with some probability as shown in Table 3.

The water of the river after stored behind the Alan Dam has been divided into two parts, one of which has a fixed amount of water that flows into the concrete channel as an input of Keyserek reservoir. Therefore the inflow to reservoir is a deterministic value from artificial channels (Table 4).

Keyserek reservoir is an off-river system. In off-river systems, a reservoir is out off river path in the optimum topography and demand necessary state. In this time, other channels inflow some water, which is totally 800000 m^3, from sub-basins in wet seasons added to the reservoir as an inflow (Table 5).

Meanwhile, some water as a result of leakage loss could not be controlled. After an empirical assessment, the amount of this water was computed (Table 6).

In this plan, the total irrigated area is 325 ha. Many kinds of products are cultivated in this land. Whole irrigation water demand was computed using Cropwat4 software (Table 7).

Table 1. Rate of evaporation from free surface, (mm)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
e_t	109.4	55.2	9.5	1.3	1.0	2.0	55.4	93.5	146.4	189.0	226.7	211.5

Table 2. Rate of precipitation on reservoir area, (mm)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
p_t	23	31	23	19	20	30	51	63	33	9	6	8

Table 3. Discharge of river inflow, (m^3/s)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
75%	0.19	0.26	0.23	0.32	0.30	0.58	2.53	4.35	2.25	0.58	0.17	0.07
90%	0.09	0.14	0.13	0.20	0.24	0.45	1.83	3.32	1.23	0.35	0.08	0.04

Table 4. Volume of inflow to the reservoir, (1000 m^3)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
QF	0	50	200	200	200	400	1330	400	50	0	0	0

Table 5. Volume of inflow from sub basin to the reservoir, (1000 m^3)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
IN	11.55	39.60	55.55	44.55	33.55	39.60	51.15	84.15	150.05	57.75	18.70	8.80

Table 6. Volume of outflow as a loss from the reservoir, (1000 m^3)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
Q	15.48	15.48	15.48	24.90	24.90	24.90	39.84	39.84	39.84	19.80	19.80	19.80

Table 7. Volume of irrigation water demand, (1000 m^3)

Month	OCT	NOV	DEC	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP
D	113.10	0.00	0.00	0.00	0.00	0.00	79.95	230.10	568.75	768.60	671.78	290.88

2.3. DNLP model developing

Nonlinear programming models have been applied extensively to optimal resource allocation problems (Larry and Tung 1992). As the name implies, NLP models have a basic characteristics, that is, the objective function and/or constraints are nonlinear functions of decision variables. For computational result, we use GAMS (General Algebraic Modeling System). GAMS is specifically designed for modeling linear, nonlinear and mixed integer optimization problems. The system is especially useful for large and complex problems. GAMS is available for using on personal computers, workstations, mainframes and supercomputers. GAMS allows the user to concentrate on the modeling problem by making the setup simple. The system takes care of the time-consuming details of the specific machine and system software implementation. GAMS is especially useful for handling large, complex, and one-of-a-kind problems, which may require many revisions to establish an accurate model. The system models problems in a highly compact and natural way. The user can change the formulation quickly and easily from one solver to another, and can even convert from linear to nonlinear with a little effort (Anonymous 2005).

As the reservoir storage-area relationship is nonlinear, an alternatively nonlinear function is possible with fitting of the storage-area relationship as shown in Eq.1.

$$A = A_0 + \alpha \times ST + \beta ST^2 \qquad (1)$$

$$A = 41752 + 0.253 \times ST + (-2 \times 10^{-8})\,ST^2$$

$$R^2 = 0.9882$$

Where A is reservoir area and ST is the storage volume. A_0, α and β are parameters of nonlinear equation.

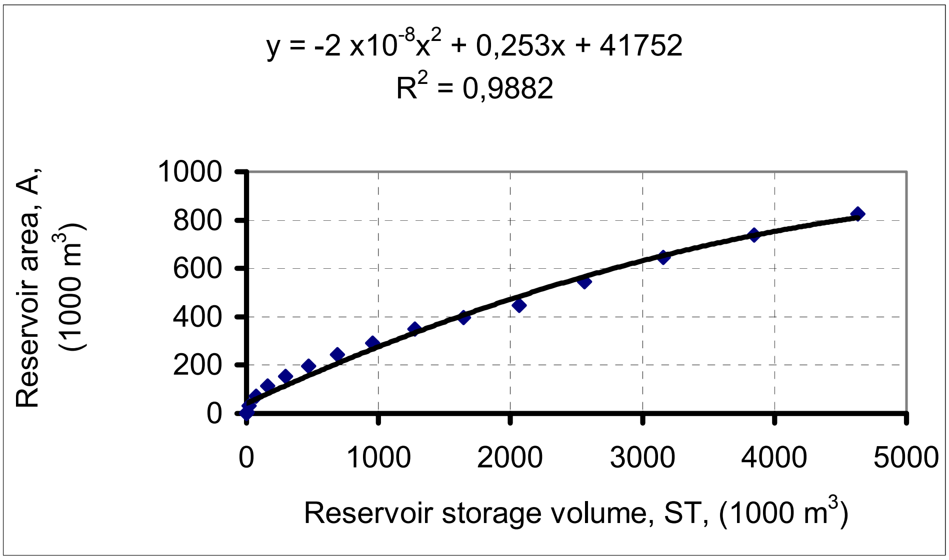

Figure 2. Reservoir storage-area relationship

The essential feature of an optimization model for reservoir capacity determination is the mass balance equation (Eq. 2),

$$ST_{t+1} = ST_t + QF_t + PP_t - R_t - EV_t + IN_t - SP_t \quad (2)$$

$t = 1,2,\ldots,12$

Where ST_t is the reservoir storage at the beginning of time period t, QF_t is the reservoir inflow in period t, PP_t is the precipitation amount on the reservoir surface in period t, R_t is the reservoir release in period t, EV_t is the evaporation and SP_t is the seepage loss during period t. IN_t is the amount of water that flows from sub basin to the reservoir.

A model to determine the minimum active storage capacity (K_a) for a specified release as a demand formulated as

Objective Function Minimize K_a (3)

Reservoir capacity cannot be exceeded during any time period, thus:

$$ST_t \leq (K_a + K_d) \quad (4)$$

$ST_1 = ST_{13}$ (Reservoir is within-year)

Where K_d is the dead storage (100 000 m^3).

In case that evaporation and precipitation volumes are functions of the surface area of the reservoir that, in turn, depend on the reservoir storage, one could incorporate the storage-area relationship in the optimization model. The storage-area relationship can be derived from conducting a topographical survey that determines the storage volume and surface area for a given elevation. For almost all reservoir sites, the relationship between storage volume and surface area is nonlinear. Therefore, the model represented by Eq. (2) is a nonlinear optimization model. The nonlinear storage-area relation can be approximated by a nonlinear function (Eq. 1). Thus EV (Eq. 5) and PP (Eq. 6) can be simplified using the nonlinear approximation:

$$EV_t = e_t \left[A_0 + \alpha \left(\frac{ST_t + ST_{t+1}}{2} \right) + \beta \left(\frac{ST_t + ST_{t+1}}{2} \right)^2 \right] \quad (5)$$

$$PP_t = p_t \left[A_0 + \alpha \left(\frac{ST_t + ST_{t+1}}{2} \right) + \beta \left(\frac{ST_t + ST_{t+1}}{2} \right)^2 \right] \quad (6)$$

Where p_t and e_t are the deterministic depths of precipitation and evaporation per unit area during period t, respectively. In this model QF_t, IN_t, SP_t and R_t (as a demand) are known parameters.

3. Results and Conclusion

In this section, the optimal value of the objective function and other decision variables are reported. The result of the model shows that K_a is 2 322 912 m^3. The volumes of the decision variables are given in Table 8. Figure 3 shows the reservoir operation rule curve for all month in a year.

Table 8. Results of the model

Month	ST (m^3)	PP (m^3)	EV (m^3)
OCT	226 505	2 534	12 010
NOV	100 000	2 732	4 847
DEC	172 005	3 099	1 347
JAN	413 826	4 111	216
FEB	637 371	5 762	288
MAR	851 495	11 229	749
APR	1 276 675	27 153	29 283
MAY	2 229 643	42 558	63 500
JUN	2 422 912	22 028	97 456
JUL	1 898 944	4 852	101 900
AUG	1 071 221	1 942	73 464
SEP	326 824	978	25 928

The purpose of operating rules (policies) for water resource systems is to specify how water is managed throughout the system (Larry and Tung 1992). These rules are specified to achieve system stream flow requirements and system demands in a manner that maximizes the study objectives that may be expressed in the form of benefits. System demands may be expressed as minimum desired and minimum required flows to be met at selected locations in the system. Operation rules may be designed to vary seasonally in response to the seasonal demands for water and the stochastic nature of supplies. Operation rules, often established on a monthly basis, prescribe how water is to be regulated during the subsequent months based on the current stay of the system. Figure 3 shows that in June, due to less demand, ST have the highest amount. The volume of EV is the most important factor in reservoir loss. It depends on the local temperature and reservoir surface area. The results of PP and EV show a high amount of evaporation in the hot months and a high amount of precipitation in wet months (Figure 4). The variation of these parameters in large scales might have a considerable effect on the reservoir storage and capacity.

Anonymous (2001) applied a graphical based classic method for the same reservoir capacity computing. In this classical method, precipitation and evaporation from reservoir area have been ignored. Therefore, the result shows that K_a is 2 600 000 m^3. The volume increases the height of the dam as nearly as 0.4 m, which raises the economical cost of reservoir construction as the high dam head increases. In small reservoir the difference between the height and capacity may be inconsiderable but in big dams the difference has a very important effect on the building cost. Therefore, using mathematical models is very important for decreasing the capacity of reservoirs and construction costs.

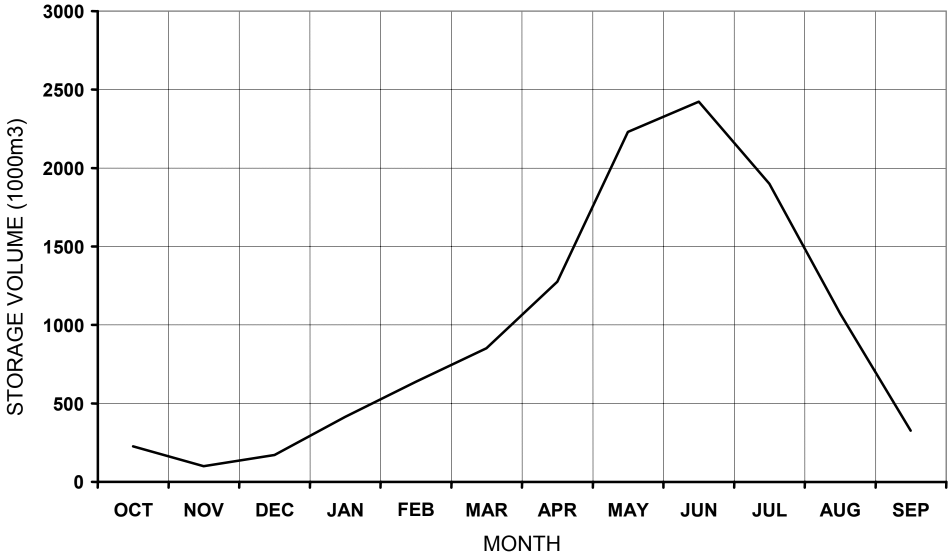

Figure 3. Operation rule curve

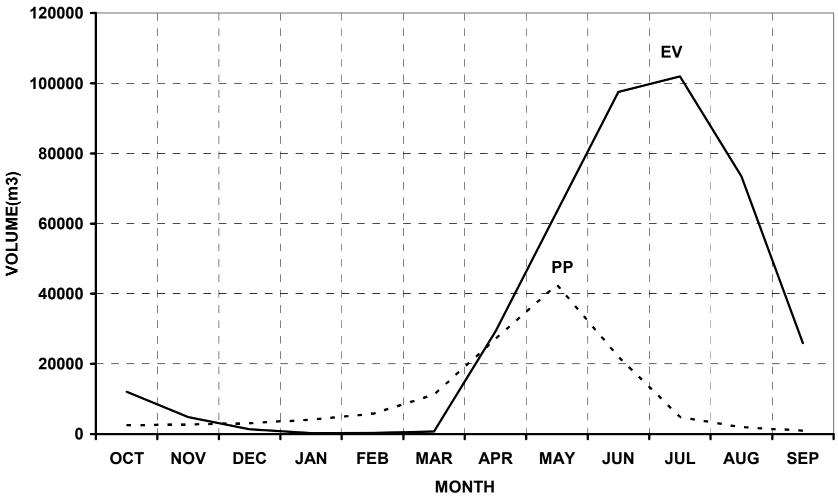

Figure 4. Amount of PP and EV

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