The Use of Optimization Techniques in Planning and Management of Complex Water Resources Systems

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ABSTRACT

Models developed based on optimization techniques could be used in planning and management of complex water resources systems. This paper presents an approach devised to derive and assess long-term operational strategies of multiple-reservoir systems. This approach can be used both at the planning stage of a reservoir system and at its operational stage. The methodology combines an optimization model based on Stochastic Dynamic Programming (SDP) with a simulation model. The model was applied to a subsystem of the Mahaweli Development Scheme in Sri Lanka, the system downstream of the Bowatenna reservoir including the proposed Moragahakanda reservoir. The results indicate the usefulness of optimization techniques in planning reservoirs and deriving operational policies for them. The study further shows the superiority of optimization models over simulation models, which are widely used in practice at planning and operational stages of reservoir systems.

INTRODUCTION

Shortage of freshwater in adequate quality has been predicted as one of the most pressing problems humankind must face in the foreseeable future. The main causes of this problem are growth in world population, economic development, urbanization, improved living standards, vast expansion of irrigated agriculture, and discharge of waste products into natural water bodies. The central purpose of water resources development is to match the supply of water with the demand. Water resources systems are created for this task in river basins or in their subunits.

The use of efficient techniques in planning and management of these water resources systems is undoubtedly important. Simulation models are widely used in this work. However, this technique is not very efficient, as sometimes it will lead to a solution that is a far cry from the optimal solution. Optimization techniques could be used very effectively to select the most promising solution. The most frequently used optimization techniques in water resources management can be classified into three major groups: linear programming (LP), dynamic programming (DP), and nonlinear programming (NLP). This general classification, in addition to simulation models, represents the basic methods used in planning and management of water resources systems (Yeh 1985).

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Since most of the water resources systems display considerable nonlinearities, operational assessment, especially in the case of reservoirs, is usually based on DP. SDP, which is an extension of DP, takes the stochastic nature of inflows into account. However, SDP has certain shortcomings, the most critical being the excessive computational requirement of a conventional SDP model (termed as "curse of dimensionality"). Wurbs (1993) contributed to ongoing efforts throughout the water management community in sorting out the numerous reservoir system analysis models and in better understanding of which methods might be most useful in various types of decision-support situations.

This work presents the applicability of optimization techniques (mainly SDP) in planning and management of a complex water resources system. A model called "ShellDP" (Bogardi et al. 1995), which is developed based on SDP and simulation techniques for analyzing multiunit reservoir systems, is used in this study. It is briefly described in the next section. The model is applicable at both the design and the operational stages of the system. The usage of the model is shown through its application to a subsystem of the Mahaweli Development Scheme in Sri Lanka, the system downstream of Bowatenna reservoir including the proposed Moragahakanda reservoir. Nandalal and Ampitiya (1997) used this model to derive operational policies for the reservoirs in the complex Mahaweli Development Scheme, which has a completely different configuration.

METHODOLOGY

Consider a multiple-reservoir system consisting of a number of reservoirs situated in several neighboring or distant river basins. The reservoirs interact by means of serial and parallel interconnections allowing water to be transferred from one basin to another. The optimal operation of these reservoirs is of paramount importance to obtain the maximum benefit from the system.

Because of the high dimensionality of the problem the derivation of the optimal operational strategy for such a system is confronted with prohibitive computational requirements imposed by any straightforward optimization application. The algorithm used in the paper is based on a physical decomposition of a system into a group of single-reservoir subsystems. Thus, a multidimensional decision problem is reduced to a sequence of one-dimensional optimization tasks. Consequently, a combined optimization/simulation procedure is applied to each reservoir. The sequence in which reservoirs are introduced into the analysis is mainly determined by their position in the system.

The algorithm is essentially an iterative procedure. One iteration cycle comprises optimization and simulation of operation of each reservoir within the system. These iterations are repeated until the solution converges to an acceptably stable optimal solution. The procedure starts by optimizing the performance of the uppermost reservoir of the system. The operatioal policy derived for that reservoir is then used to simulate its performance over the period, for which hydrological data are available. The sequence of free downstream releases from the reservoir is one of the results from this simulation. These releases represent the volume of water left after supplying all the demands. These nonconsumptive volumes of water (free downstream releases) are added to the incremental inflows to estimate the total inflows to the next downstream reservoir.

Then the optimization and simulation of the next reservoir are carried out similarly as the previous one. These optimization/simulation cycles are continued further downstream until the operational policy of the last reservoir is assessed, which concludes one iteration. Data transfer between two consecutive iterations consists of sets of reservoir water shortages obtained by simulation in the preceding computational step. The methodology is presented as a flowchart in figure 1.

OPTIMIZATION

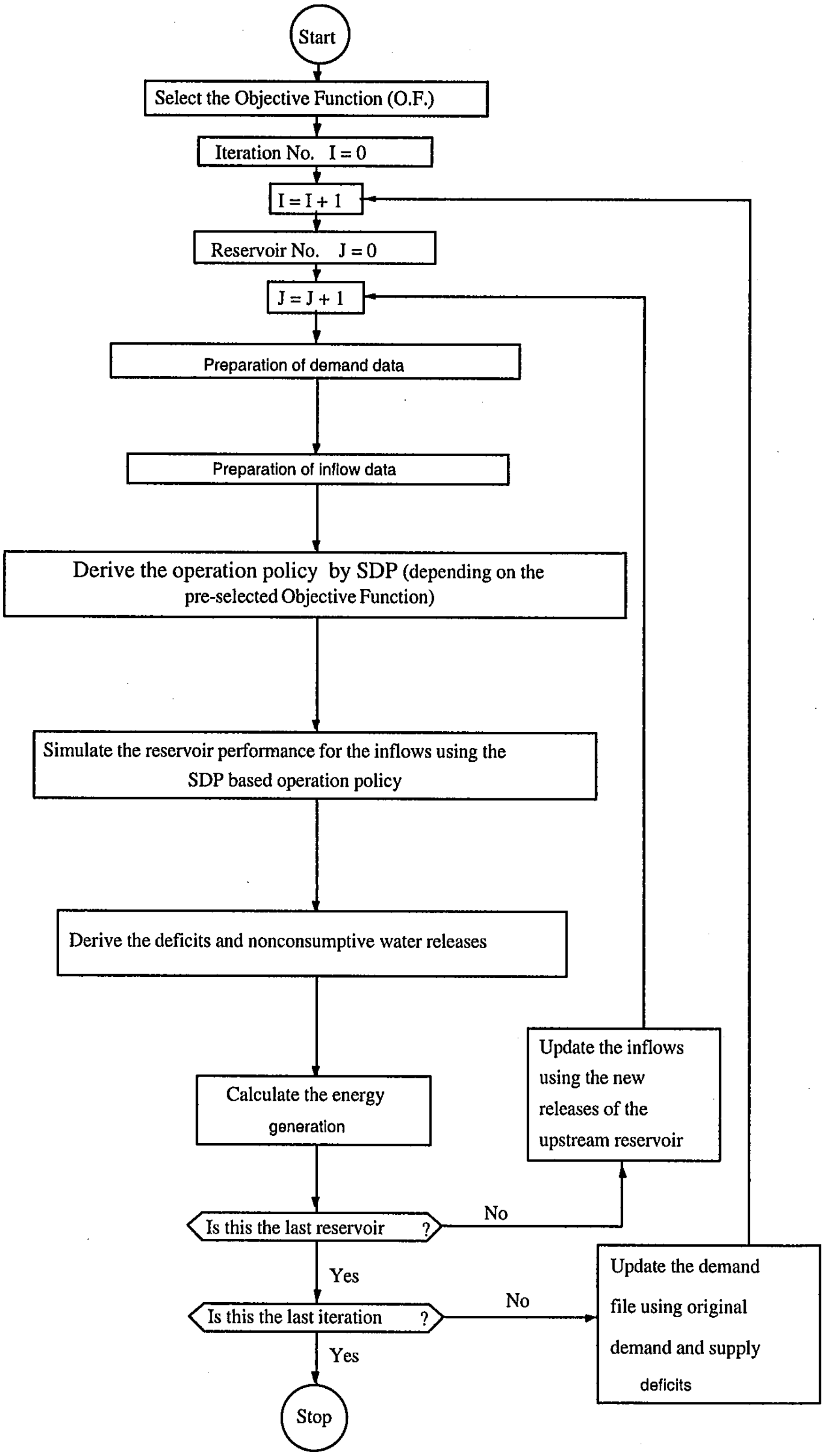
The core of the method is the SDP-based optimization algorithm. The applied SDP algorithm is a variation of the one given by Loucks, Stedinger, and Haith (1981). This SDP-based optimization procedure derives the optimal, expectation-oriented, long-term operational strategy for a single reservoir. Due to the nature of DP all state and decision variables are represented in their respective discrete domains. A month is considered as one stage in the present study. The state of the system (reservoir) is the volume of water stored at the beginning of a time stage. Uncertainty is explicitly incorporated into the optimization procedure with inflow to a reservoir being represented by different classes with their respective independent or transitional probabilities being considered as an additional state variable in the SDP-based optimization procedure. Thus, whether the inflows are considered to be random or Markovian, the system's state is described by two state variables, reservoir storage at the beginning of the month and the inflow to the reservoir during the month.

The decision to be taken at each stage within one annual cycle is the storage volume of the reservoir at the end of the time interval. Thus, the operating policy is defined for each month and is expressed in terms of the optimal decision to be taken as a function of system states.

The operational policies were derived and the performance of the system was based on the following objective function.

Objective Function. To minimize the expected value of the annual sum of squared shortages of supply water (single-sided deviation of the releases from the respective monthly irrigation demands).

Figure 1. Flow chart of the sequential approach.



$$Minimize\ \xi\,[\sum_{j=1}^{N} DEF_j\,]$$

$$(DEF_j = 0;\ \ if\ \ R_j > Q_{D,j}\ )$$

where,

DEF_j = $(Q_{D,j} - R_j)^2$,

x = expectation operator,

N = number of stages (months) in 1 year, i.e., $N = 12$,

$Q_{D,j}$ = water demand (target release) from the reservoir during period j, and

R_j = the total release from the reservoir during period j.

The optimization is subjected to constraints in reservoir storage volume and release. The state transformation equation is based on the principle of continuity of the reservoir.

SIMULATION

Once an operational strategy is defined, simulation is carried out to assess and incorporate the effects of the reservoir's performance into the operation of the system as a whole. The simulation is carried out over the total historical record of inflow. The role of simulation in the presented approach is twofold:

1. It is used to evaluate the effectiveness of a reservoir's operating policy.
2. In conjunction with the release allocation algorithm, simulation provides necessary information on the interaction among reservoirs (i.e., expected levels of each individual demand fulfillment and deficit, additional flows available to reservoirs situated downstream of the river course, and shortages in supply that a reservoir is going to encounter by following the derived operating policy).

APPLICATION

The Moragahakanda Reservoir Project is one of the major projects proposed for the development of Sri Lanka's hydroelectric energy and irrigation potential under the Mahaweli Development Scheme. However, due to various reasons, the project was abandoned for a period of nearly 20 years. The Government of Sri Lanka intends to take up this project in the near future to develop the areas in Systems D1, D2, and G. The main objective of the project is to construct a reservoir at Moragahakanda and to further extend the land used for cultivation in the northeastern dry zone of the country, presently supplied with water from five tanks namely, Minneriya, Girithale, Kantale, Kaudulla, and Parakrama Samudra. The project area considered in this study within the Mahaweli Development Scheme is shown in figure 2.

Figure 2. Schematic diagram of the Mahaweli Development Scheme.

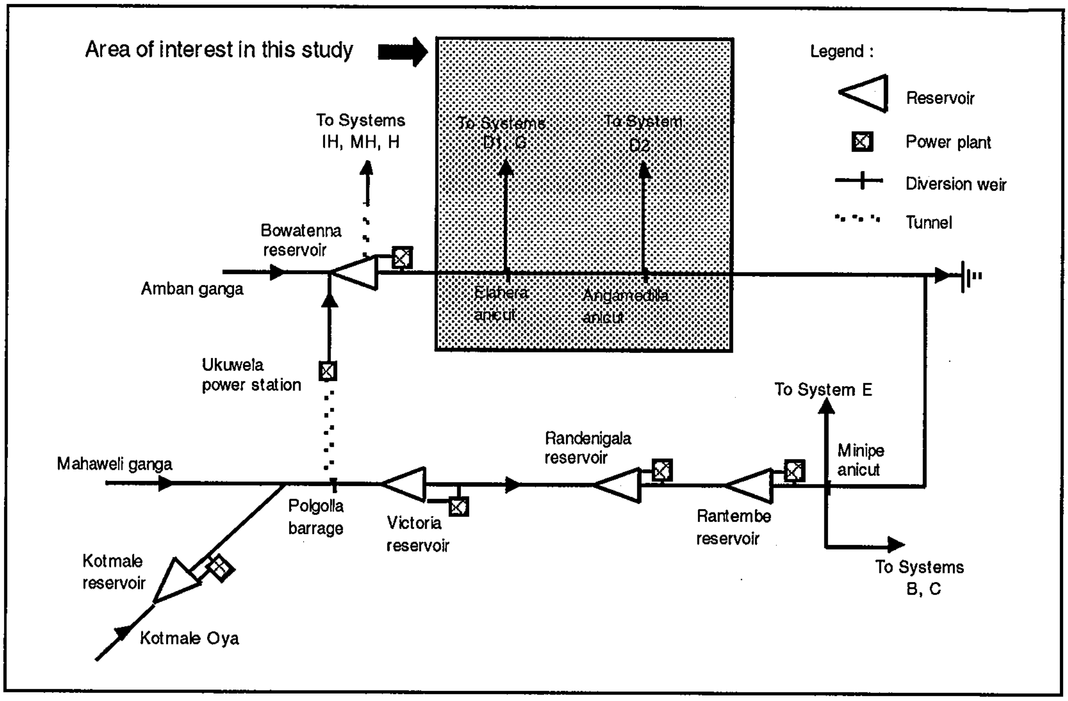
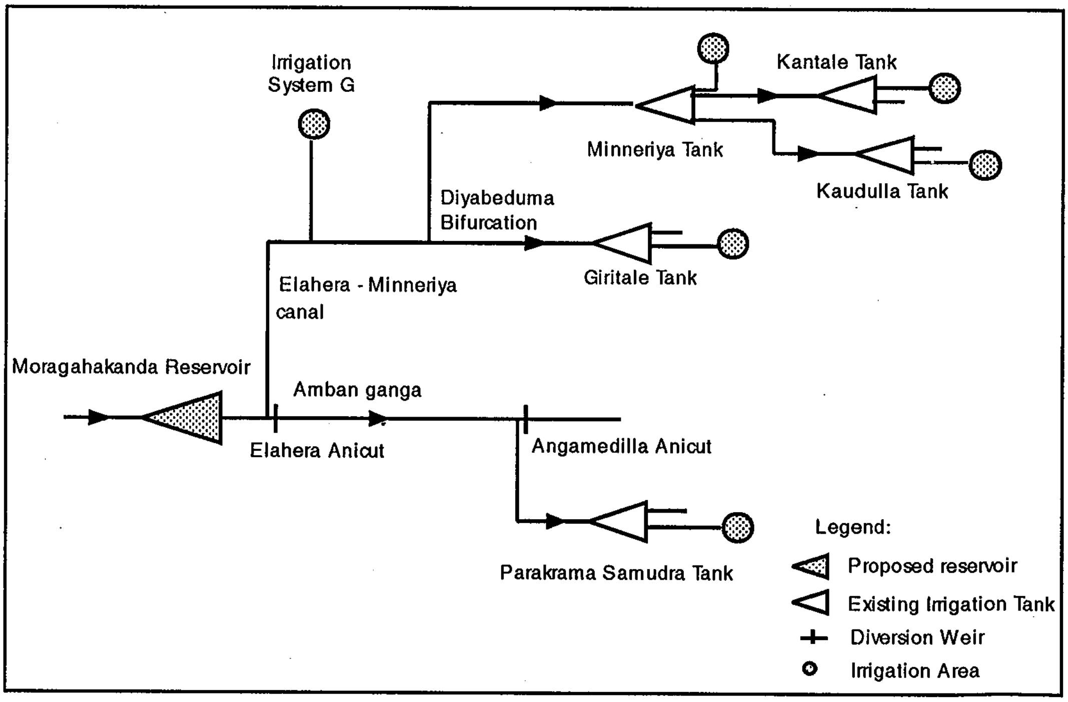


Figure 3. Schematic diagram of the system downstream of the Moragahakanda reservoir.



The available water resources of the project consist of the natural runoff from the basin of the *Amban ganga* (river) and part of the diverted water from the Mahaweli Ganga through the Polgolla diversion tunnel. The Amban ganga flow augmented by the Polgolla diversion is impounded at the Bowatenna reservoir. Part of the regulated water is diverted from the Bowatenna reservoir to Kalawewa region Systems H, IH, and MH areas. Water available for the project is estimated as the balance of the above diversions and the natural runoff in the basin.

Downstream of the Bowatenna reservoir, there are two existing intake weirs at Elahera and Angamedilla. Intake water at the Elahera anicut is led to the existing fields in Systems G and D1 through the Elahera-Minneriya canal, which links four existing tanks, Minneriya, Giritale, Kaudulla, and Kantale. Water diverted at the Angamedilla anicut is impounded at the Parakrama Samudra and the regulated water is supplied to the existing fields in System D2. The analyzed water resources system is shown in figure 3. Table 1 shows the salient features of the existing tanks in the system.

Table 1. Salient features of the existing tanks.

Reservoir	Storage Capacity (MCM)			HWL	LWL	Area at
	Total	Dead	Active	m	m	FSL (km²)
Minneriya	136.9	0.0	136.9	93.7	82.1	25.5
Kantale	160.6	0.0	160.6	59.3	42.8	28.7
Kaudulla	128.3	4.9	123.4	73.2	64.0	25.9
Giritale	25.3	0.0	25.3	92.2	79.0	3.2
Parakrama Samudra	135.1	18.5	116.6	59.1	51.8	25.7

FSL=Full supply level; HWL=High water level; and LWL=Low water level.

ANALYSIS AND RESULTS

A simulation model was used to obtain the inflows to the Moragahakanda reservoir. It simulates the operation of the system from the Polgolla barrage to the Moragahakanda reservoir. The inflows to the five existing tanks, Minneriya, Kaudulla, Kantale, Giritale, and Parakrama Samudra for the period 1950–1977, available in the feasibility report (JICA 1988), were used in the study. The irrigation water requirements of all the irrigation areas were also obtained from the same report. The incremental inflows for the study period at the Polgolla barrage in the Mahaweli ganga and at Bowatenna, Elahera, and Angamedilla in the Amban ganga were obtained from the Water Management Secretariat of the Mahaweli Authority of Sri Lanka.

The irrigation water requirements of the different irrigation areas used in this study, obtained from JICA 1988, are presented in table 2. The total irrigation area is 62,200 hectares, which is the total area after the planned developments. The total annual water requirement of this system is 1,821 MCM.

Table 2. Irrigation water requirements of the system (in MCM).

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
System G	12	11	18	19	27	23	18	26	25	16	8	13
Giritale	8	11	5	1	9	15	15	12	1	3	4	5
Minneriya	26	33	16	4	28	46	46	38	4	10	12	14
Kaudulla	40	51	25	9	43	71	66	57	8	13	18	22
Kantale	36	49	39	19	50	72	70	58	27	20	17	20
Parakrama Samudra	32	40	19	6	38	59	55	47	9	10	13	17
Total (1,821)	154	195	122	58	195	286	270	238	74	72	72	85

The methodology presented was employed to develop long-term optimal operational policies for the reservoirs in the system considered (Moragahakanda, Minneriya, Giritale, Kantale, Kaudulla, and Parakrama Samudra) and to assess the performance of the system based on the derived operational policies. Since the design of the Moragahakanda reservoir was a primary requirement in the system, several alternative sizes were considered for it. The alternatives are the three alternative sizes studied by JICA (alternatives I, II, and III) and an additional one (alternative IV) as presented in table 3.

Table 3. Alternatives studied for the proposed Moragahakanda reservoir (in MCM).

Alternative	I	II	III	IV
Total storage	1,110	900	658	540
Dead storage	308	214	40	40
Active storage	802	686	618	500

The model develops long-term operational policies for the reservoirs in the system. The operational policy designated for a reservoir by the model is a set of rules specifying the storage level at the beginning of the next month for each combination of storage levels at the beginning of the current month and the inflow during the current month. The simulation process is used to assess the derived operational policies and to evaluate the system operation.

Table 4 presents the average annual irrigation supply deficits for the alternatives. The system without a reservoir at Moragahakanda is termed as "no reservoir." Irrigation water supplies for System G are fully satisfied for all the alternatives while the requirements from the Minneriya tank are supplied for all the alternatives except for the "no reservoir" case. Deficits of the Kantale tank remain unchanged for the first three alternatives, but have increased slightly for the fourth alternative. Irrigation supply deficits of the Kaudulla, Giritale, and Parakrama Samudra tanks increase with the decrease in the active storage capacity of the Moragahakanda reservoir.

Table 4. Average annual deficits of the irrigation water supplies (in MCM).

Alternative	System G tank	Minneriya tank	Kantale tank	Kaudulla tank	Giritale Samudra	Parakrama
Alternative I	0.0	0.0	1.84	33.09	4.22	8.90
Alternative II	0.0	0.0	1.84	34.02	5.62	9.66
Alternative III	0.0	0.0	1.84	34.86	6.37	8.89
Alternative IV	0.0	0.0	1.92	41.59	7.44	12.25
No reservoir	0.0	0.95	22.35	248.72	45.29	28.15

Table 5 presents the total irrigation water supply deficits as a percentage of the total annual requirement for the whole system. As it reveals, the irrigation supply deficit has increased with the decrease in the active storage capacity of the proposed Moragahakanda reservoir. However, this increase is not very significant. Due to the decrease in the active storage capacity of the reservoir from 802 MCM to 500 MCM (about 40%) the total system deficit has changed from 2.64 percent to 3.47 percent only. The total system deficit for an irrigable area of 62,000 hectares, that is the total area after the planned developments, is high (18.97%) if the Moragahakanda reservoir is not constructed. The JICA (1988) report, based on a simulation study, reveals that the average annual deficit without a reservoir at Moragahakanda is about 8.5 percent if the irrigable area under this subsystem is 42,000 hectares.

Table 5. Deficit as a percentage of irrigation requirement.

Alternative	Total system deficit (%)
Alternative I	2.64
Alternative II	2.81
Alternative III	2.85
Alternative IV	3.47
No reservoir	18.97

The irrigation supply deficit of the system obtained by the simulation model used in the report by JICA (1988) is available only for alternative II and its value is 3.7 percent. The irrigation supply deficit for the same alternative obtained by the methodology presented in this paper is only 2.81 percent. The reduction in the deficit is due to the better operational policies of the reservoirs obtained from the presented methodology. Besides, the results suggest that a smaller reservoir at Moragahakanda would still satisfy the irrigation requirements, if they were operated using a good policy.

CONCLUSIONS

The paper presents a relatively simple approach based on an optimization technique to derive and assess long-term operation of the complex reservoir systems. The application of the model to the water resources system downstream of the Bowatenna reservoir including the proposed Moragahakanda reservoir indicates its suitability in the analysis of complex systems. The model develops optimal operational policies for all the reservoirs in the system based on the SDP technique.

Due to the sequential "element-by-element" analysis of the algorithm, it easily accommodates changes in a system's structure. That is, the inclusion of new reservoirs or demand centers, or exclusion of some system elements can be incorporated into the model without having to perform major programming tasks.

Simulation is used to analyze the effects of the proposed management plans. System performance achievement is evaluated on the basis of the selected sets of decisions. By definition, simulation methods do not claim that the particular combination of decisions represents the optimal one. The difficulty inherent in this approach is the large number of feasible operational plans to be checked. If simulation alone were used, the search for the "best" solution might not only be very tedious, but could lead to alternatives far from the optimal one. Optimization models narrow down the search for promising combinations of decision variables. Optimization eliminates all the undesirable operational plans and proposes policies that are close to the global optimal solution. Therefore, the use of optimization models at the design stage of water resources systems is undoubtedly advantageous. The results of the analysis indicate this fact. The use of long-term expectation-oriented operational policies at the operational stage of the system gives better performance of the system.

The application of reliability criteria such as time-based reliability, resilience, vulnerability, average inter-arrival time, etc., could be used to compare the results besides the monthly mean deficits used in the present study.

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