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Two-Echelon Reservoir Inventory Management with Forecast Updates: Perspective from Operations of Multireservoir in Interbasin Water Diversion Projects

***Abstract**. We consider a finite-horizon, periodic-review inventory model with inflow forecasting updates following the martingale model of forecast evolution (MMFE) in multiresevoirs. This model introduces a new method of determining an operating policy in which the policy is based on the dynamic programming (DP) model with a physical equation and a recursive equation. It adequately considers the internal relationship among multireservoirs in inter-basin water diversion projects (IBWDP) and calculates the expected benefits from future operation. The stochastic nature of the inflow is taken into account by considering the correlation between the streamflows of each pair of consecutive time intervals based on MMFE. According to interdependence, the probability of transition from a given state or stage to its succeeding ones can be calculated. Finally, to assess the effectiveness of the policies, the model is compared with other model and is applied to the Chinese South-North Water Diversion project.*

***Streszczenie.** Analizowano model okresowej inwentaryzacji wraz z przewidywaniem nawodnienia w systemie wielu rezerwuarów. Wprowadzono programowanie dynamiczne uwzględniające wewnętrzne relacje między rezerwuarami w dywersyjnych projektach wodnych. Model sprawdzono na przykładzie chińskiego projektu systemu wodnego północ-południe. (**Dwu-stanowiskowe zarządzanie wielorezerwuarowym systemem wodnym z uwzględnieniem prognoz**)*

Keywords: Reservoir; Inflow forecasts; MMFE; DP
Słowa kluczowe: zbiorniki wodne, prognozowanie, zarządzanie

Introduction

Water has played a major role in human activities due to the magnitude and widespread occurrence of its positive and negative impacts. The quality of human life is directly dependent on how well water resources are managed. Water serves essential biological functions and no human can survive its complete absence. Yet the spatial distribution of water does not usually coincide with human requirements. At a certain stage of water resource development, therefore, interbasin transfers become inevitable.

Water resources problems are bound to become more complex worldwide in the future. Population growth, climate variability, regulatory requirements, project planning horizons, temporal and spatial scales, social and environmental considerations, transboundary considerations, etc., all contribute to the complexity of water resources planning and management.

Systems analysis techniques can be highly valuable tools for solving planning and operating tasks in water resources management based on the systematic and efficient organization and analysis of relevant information. A variety of methods in systems analysis or operations research have been developed for analyzing water resources systems. Optimization and simulation are used conjunctively to derive and assess alternative operating strategies for single and multiple reservoir systems (e.g., Jacoby and Loucks, 1972; Mawer and Thorn, 1974; Gal, 1979; Karamouz and Houck, 1982, 1987; Stedinger et al., 1984; Tejada-Guibert et al., 1993; Harboe et al., 1995; Liang et al., 1996). Most of the available research only considers the entire multireservoir systems optimization issue based on group rationality without sufficiently considering the internal relationship among reservoirs. In particular, it needs to consider the following questions: How to allocate scarce water resources to reservoirs considering priority and equitable allocation principles when the total supply of water resources is less than the total demand for water resources? How to transform a flood into a useful resource when a downstream reservoir is faced with a flood and an upstream reservoir is faced with a water shortage? How to "produce" and allocate the water resource to satisfy the end-demand, reduce water shortages, and achieve both economic and social benefits? These are core issues in reservoir operations management, and these will form the main focus of our study. This paper studies the optimal operation of multireservoirs considering the internal relationship among reservoirs through adjusting the release and spilling strategy.

The rest of the paper is organized as follows. Section 2 briefly reviews some of the literature on reservoirs based on different optimization methods. Section 2 introduces the Martingale Model of Forecasting Evolution (MMFE). Section 3 presents the model and formulation for two reservoirs. Section 4 develops an application of the model to the SNWD (South-North Water Diversion project). Finally, Section 6 concludes the paper and summarizes the results.

Literature review

A great deal of research has been conducted on multireservoir optimal operations in inter-basin water diversion projects. This research mainly focuses on the mathematical programming method, the aggregation-decomposition approach, the GRID computing approach, optimal control theory, the minimum norm approach, the discrete maximum principle, and the linear decision rule. Jairaj PG et al.(2000) applied fuzzy mathematical programming to multireservoir system optimization. Halliburton TS et al (1984), Sherkat VR et al. (1985), Lii CA et al. (1990), Contaxis GC et al. (1990), Turgeon A (2007), and Tilmant A et al. (2008) applied the stochastic programming method to multireservoir operations and scheduling. Nayak S et al. (1973) applied the nonlinear programming method to multireservoir system capacity decisions. Mohan S et al. (1992) developed a linear multiobjective programming model for multiobjective analysis of multireservoir systems. Wei CC et al. (2008) applied the mixed-integer linear programming method to multireservoir real-time operations for flood control. Khaliquzzaman et al. (1997) developed a network flow programming model for multireservoir sizing.

Recently, more and more scholars have focused on stochastic dynamic programming and have obtained many positive results in multireservoir systems. The stochastic nature of the inflows can be handled by two approaches (Nandalal KDW and Bogardi JJ, 2007): implicit, or explicit. In the implicit approach, a time series model is used to generate a number of synthetic inflow sequences. The system is optimized for each streamflow sequence and the operating rules are found by multiple regression. During optimization, the synthetic data series are considered deterministic series. The explicit approach considers the probability distribution of the inflows rather than specific flow sequences. This approach generates an operation policy comprising storage targets or release decisions for every possible reservoir storage and inflow state in each time step rather than a single schedule of reservoir releases.

Young (1967) proposed an implicit stochastic approach to optimize the operation of a single reservoir. Opricovic and Djordjevic (1976) presented an implicit SDP-based algorithm for optimal long-term control of a single multipurpose reservoir with both direct and indirect users. Karamouz and Houck (1987) derived monthly operating rules for a set of 12 different single-reservoir test cases using their iterative DP model (Karamouz and Houck 1982) and an explicit SDP optimization model. The sampling stochastic dynamic programming approach (SSDP), first used by Araujo and Terry (1974) for the operation of a hydro system, can also be categorized as an implicit stochastic approach. SSDP was used by Dias et al. (1985) for the optimization of flood control and power generation requirements in a multipurpose reservoir. Kelman et al. (1990) included best inflow forecast as a hydrological state variable in the SSDP algorithm. Faber and Stedinger (2001) compared SSDP models employing the National Weather Service's (NWS) ensemble streamflow prediction (ESP) forecasts to SSDP models based on historical streamflows and snowmelt volume forecasts.

Butcher (1971) used explicit SDP to derive an optimal long-term operating strategy for a single multipurpose reservoir. Loucks et al. (1981) elaborated the explicit SDP approach for the optimization of single-reservoir operation. Maidment and Chow (1981) developed two SDP optimization models for a single-reservoir operation problem. Stedinger et al. (1984) compared simulation results based on different operation policies derived from the High Aswan Dam on the River Nile by five SDP based optimization models. Goulter and Tai (1985) used SDP to model a small hydroelectric system. Shrestha (1987) applied SDP to derive optimal operation policies for different configurations of a hydropower system during the planning stage. Bogardi et al. (1988) investigated the impact of varying the number of storage and inflow classes on the operational performance of SDP for both single and multiple reservoir systems. Shrestha et al. (1990) studied the effect of the number of discrete characteristic states and the impact of varying the definition of these characteristic states on SDP model performance. Huang et al. (1991) compared four explicit SDP optimization models using the operation of the Feitsui Reservoir in Taiwan as a case. Tejada-Guibert, et al. (1993, 1995) applied stochastic dynamic programming to multireservoir operating policies and hydrologic information value analysis. Vasiliadis and Karamouz (1994) adopted both the present period inflow and the next period inflow forecast as hydrological state variables. Bogardi et al. (1995) developed a model called "ShellDP" based on stochastic dynamic programming and simulation techniques for analyzing multiunit reservoir systems. The model is applicable during both design and operational stages of a reservoir system. Ampitiya (1995) applied the ShellDP package to derive optimal operation policies for reservoirs in the complex Mahaweli water resources scheme in Sri Lanka. Nandalal and Ampitiya (1997), Nandalal (1998), and Nandalal and Sakthivadivel (2002) used this modified model to derive operation policies for reservoirs in several water resources development schemes in Sri Lanka. Archibald et al. (1997, 2006) developed an aggregation and decomposition stochastic dynamic programming model for multireservoir systems operations. Tilmant et al. (2002) compared reservoir operation policies obtained from fuzzy and nonfuzzy explicit stochastic dynamic programming. Kumar et al. (2003) developed a folded dynamic programming for optimal operation of multireservoir system. A fuzzy stochastic dynamic programming model (FSDP) (Mousavi et al., 2004) was also developed for a single reservoir to model the errors associated with discretizing the variables using fuzzy set theory. Kim et al. (2007) applied sampling stochastic dynamic programming to optimizing operational policies for multireservoir system. Goor et al. (2011) applied stochastic dual dynamic programming to multipurpose-multireservoir operations.

Martingale model of forecasting evolution (MMFE)

In hydrology, there are various indices reflecting the magnitude of streamflow forecast uncertainty. However, few models illustrate the forecast uncertainty evolution process. This paper adopts MMFE from supply chain management to quantify the evolution of the uncertainty of real-time streamflow forecasts as time progresses. We consider a *T*-period periodic-review water resources inventory system with stochastic inflow and zero lead time (Iida T., Paul H. Zipkin, 2006).

In streamflow forecasts, denote T as the length of forecast lead time or forecast horizon, within which the streamflow is predictable with an available forecasting method, as showed in Fig.1. The streamflow forecasts can be represented by a vector:

(1) $$\mathbf{IF}_{i,j} = \{IF_{i,(j,j+1)}, F_{i,(j,j+2)}, \cdots, F_{i,(j,j+T)}\}$$

Let $\mathbf{IF}_{i,j} = \left(IF_{i,(j,j+1)}, \ldots, IF_{i,(j,j+T)}\right)$ be the inflow forecast vector made at the end of period j, where $\mathbf{IF}_{i,0}$ is the initial forecast vector for reservoir i. We consider additive forecast updates;

To update the inflow forecasts, we let $IF_{i,(j,j+k)}$ be the forecast inflow in reservoir i made at the end of period j for inflow in period $j+k$, $k = 0, \ldots, T-j$, because forecasts are made after the current inflow information is revealed $IF_{i,(j,j)} = IF_{i,j}$.

Define $e_{i,(j,j+k)}$ as the inflow forecast update made in reservoir i at the end of period j for inflow period $j+k$, and $0 \le k \le T-j$. $i = 1,2$, $j = 1,2,\ldots,T$.

(2) $$e_{i,(j,j+k)} = IF_{i,(j,j+k)} - IF_{i,(j-1,j+k)}$$

Denote $Var\left[e_{i,(j,j)}\right] = \sigma^2_{i,j}$, and let $\mathbf{e}_{i,j}$ be the inflow forecast update vector made in reservoir i at the end of period j, $i = 1,2$, $j = 1,2,\ldots,T$.

(3) $$\mathbf{e}_{i,j} = \left(e_{i,(j,j)}, e_{i,(j,j+1)}, \ldots, e_{i,(j,j+k)}\right)$$

We assume that the forecasts are unbiased, i.e., $E\left[e_{i,(j,l)}\right] = 0, j \le l$. We also assume that forecast updates $\{\mathbf{e}_{i,j}, i=1,2, j=1,2,\ldots,T\}$ are independent over time.

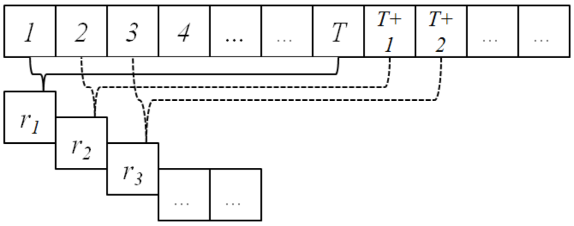

Fig.1. Schematic representation of rolling horizon decision making in a reservoir

It is worthwhile to note that forecast uncertainty and forecast horizon are two important features of streamflow forecast and can both affect reservoir operation using the forecast, as the forecast can be too uncertain if it is too long (i.e., it cannot reliably reflect inflow conditions) or too short to be applicable in supporting decision making.

Model and formulation

We consider an ideal type of two-echelon reservoir in IBWDS as the following (see Fig.2). Because the first stage of the reservoir is lower than the second stage in IBWDS, there are several pumping stations along the channel, transferring water resources from the water sources location to reservoir 1 and transferring water resources from reservoir 1 to reservoir 2. In addition, reservoir i ($i=1,2$) is faced with random inflow. Moreover, when the storage of reservoir i exceeds the flood control storage capacity, spilling operations need to be implemented in reservoir i.

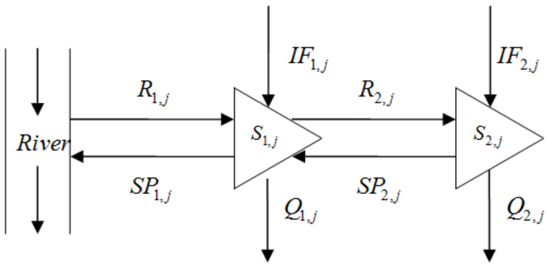

Fig.2. Two-Echelon Water Resources Inventory

(1) System Definitions and Notations Set

In order to model the problem, we set variables and parameters as follows:

$S_{i,j}$ =storage of reservoir *i* at beginning of period *j*;

$IF_{i,j}$ =incremental inflow (net precipitation or rainfall) to reservoir *i* during period *j* (Random Variable);

$D_{i,j}$ =end-user demand in reservoir *i* during period *j*;

$R_{i,j}$ =releasing amount of water from upstream reservoir to reservoir *i* during period *j*;

$Q_{i,j}$ =withdrawing amount of water from reservoir *i* to end-customer during period *j*;

$SP_{i,j}$ =spilled (abandoned) water from reservoir *i* during period *j* (overflow condition);

(4) $$SP_{i,j}=\left(S_{i,j}+R_{i,j}+IF_{i,j}-Q_{i,j}-\overline{S_{i,j}}\right)^{+}$$

$p_{i,j}$ =retailing price for unit of water from reservoir *i* during period *j*; $c_{i,j}$ =average cost of taking unit of water from reservoir *i* to customers during period *j*; $\beta_{i,j}$ =penalty factor for unit shortage water at reservoir *i* during period *j*;

$\kappa_{i,j}$ =cost of spilling (abandoning) excess water in reservoir *i* during period *j* to guarantee that the storage does not exceed the flood control storage capacity;

$Energy_{i,j}$ =energy consumed in pumping water from the upstream reservoir to reservoir *i* during *period j*:

(5) $$Energy_{i,j}=\rho\cdot R_{i,j}\cdot g\cdot LH_{i,j}$$

$LH_{i,j}$ =average lift height between upstream reservoir and reservoir *i* during period *j*;

ρ =density of water resources, g =gravity constant;

$C_{i,j}\left(R_{i,j}\right)$ =cost of transferring unit water from upstream reservoir to reservoir *i* during period *j*:

(6) $$\begin{aligned} C_{i,j}\left(R_{i,j}\right) &= k\cdot Energy_{i,j} \\ &= k\cdot\rho\cdot R_{i,j}\cdot g\cdot LH_{i,j}\triangleq\lambda_{i,j}R_{i,j} \end{aligned}$$

k =average cost coefficient of energy consumed;

$i=1,2$, $j=1,2,\ldots,T$

Decision variable:

$R_{i,j}$ =releasing amount of water from the upstream reservoir to reservoir *i* during period *j*;

$Q_{i,j}$ = withdrawing amount of water from reservoir *i* to end-customer during period *j*;

$i=1,2$, $j=1,2,\ldots,T$.

(2) Model Description and Solutions

A. Constraints

i) Water balance equations

There exists a water balance equation for the reservoir and the channel. Water storage in reservoir i at beginning of period j+1 is equal to the water storage at beginning of period j plus incremental net inflows and rainfall minus outflows, withdrawing, evaporation, and spilled (or abandoned) water in reservoir i during period j. Therefore, the water balance equation for the reservoir is as follows:

(7) $$S_{1,j+1}=S_{1,j}+IF_{1,j}+R_{1,j}-R_{2,j}-Q_{1,j}-SP_{1,j}+SP_{2,j}$$

(8) $$S_{2,j+1}=S_{2,j}+IF_{2,j}+R_{2,j}-Q_{2,j}-SP_{2,j}$$

Hereinto, $IF_{i,j}=IF_{i,(j,j)}=IF_{i,(j-1,j)}+e_{i,(j,j)}$,

$i=1,2$, $j=1,2,\ldots,T$.

ii) Reservoir storage capacity constraint

For reservoir i during period j, there exist a low bound and an upper bound for storage, the low bound being the dead storage capacity while the upper bound is the flood control storage capacity. Therefore, the reservoir storage capacity constraint is as follows:

$$\underline{S_{i,j}}\leq S_{i,j}\leq\overline{S_{i,j}}$$

iii) Release capacity constraint

For reservoir i during period j, there also exist a low bound and an upper bound for the outflow capacity, the low bound being based on the need for ecological protection, water pollution control, and shipping depth for the channel area, while the upper bound is based on the maximum pumping or effusion capacity and flood control downstream. Therefore, the outflow capacity constraint is as follows:

$$\underline{R_{i,j}} \le R_{i,j} \le \overline{R_{i,j}}$$

iv) Water withdrawing capacity constraints

For reservoir i during period j, there exist a low bound and an upper bound for the water withdrawing capacity, the low bound being based on the need for ecological protection, water pollution control, and shipping depth for the channel near the reservoir area, while the upper bound is based on the maximum pumping or effusion capacity. Therefore, the water withdrawing capacity constraints are as follows:

$$\underline{Q_{i,j}} \le Q_{i,j} \le \overline{Q_{i,j}}$$

v) Pumping output capacity constraint

In the process of pumping water from the upstream reservoir to reservoir i during period j, there exists an upper bound for the pumping output capacity, which is based on the maximum pumping ability of the pumping station. Then, the pumping output capacity is as follows:

$$Energy_{i,j}\left(R_{i,j}\right) \le \overline{Energy_{i,j}}$$

Hereinto, $Energy_{i,j} = \rho \cdot R_{i,j} \cdot g \cdot LH_{i,j}$

vi) Supply-demand constraints

The supply amount of water withdrawn from reservoir i and Channel (i,i+1) to end-users should not exceed the demand amount of water during Period j. Therefore, the supply-demand constraint is as follows:

$$Q_{i,j} \le D_{i,j}$$

Obviously, we can combine the pumping output capacity constraints with the flow capacity constraints, giving,

$$\underline{R_{i,j}} \le R_{i,j} \le \widehat{R_{i,j}} \equiv \min\left\{\overline{R_{i,j}}, \frac{\overline{Energy_{i,j}}}{\rho \cdot g \cdot LH_{i,j}}\right\},$$

We can also combine the supply-demand constraints with the water taking capacity constraints, giving,

$$\underline{Q_{i,j}} \le Q_{i,j} \le \widehat{Q_{i,j}} \equiv \min\left\{\overline{Q_{i,j}}, D_{i,j}\right\}.$$

B. Objective function

For the inter-basin water transferring project, the objective should include two aspects: one is economic profit and efficiency, and the other is social benefit. Specifically, economic profit and efficiency mainly require profit maximization while the social benefit mainly focuses on water shortage punishment, flood control, and fairness in water allocation.

Therefore, we try to combine these objectives to formulate a single-period operations objective function, as follows:

$$U_{i,j}\left(R_{i,j}, Q_{i,j}, IF_{i,(j-1,j)}\right)$$
$$= \left(p_{i,j} - c_{i,j}\right)Q_{i,j} - \lambda_{i,j}R_{i,j} - PS_{i,j}\left(Q_{i,j}\right) - CS_{i,j}\left(SP_{i,j}\right)$$

(9)

Hereinto, $PS_{i,j}\left(Q_{i,j}\right) = \beta_{i,j}\dfrac{D_{i,j} - Q_{i,j}}{D_{i,j}}$,

$$CS_{i,j}\left(SP_{i,j}\right) = \kappa_{i,j}SP_{i,j},\ i = 1,2,\ j = 1,2,\ldots,T$$

Therefore, the Dynamic Programming (DP) for the water resources inventory is as follows:

$$\underset{R_{i,j},Q_{i,j}}{\text{maximize}}\, E\left[\sum_{j=1}^{T}\sum_{i=1}^{2} U_{i,j}\left(R_{i,j}, Q_{i,j}, IF_{i,(j-1,j)}\right)\right]$$

$$s.t.\begin{cases} S_{1,j+1} = S_{1,j} + IF_{1,(j-1,j)} + e_{1,(j,j)} + R_{1,j} - R_{2,j} - Q_{1,j} - SP_{1,j} + SP_{2,j} \\ S_{2,j+1} = S_{2,j} + IF_{2,(j-1,j)} + e_{2,(j,j)} + R_{2,j} - Q_{2,j} - SP_{2,j} \\ \underline{S_{i,j}} \le S_{i,j} \le \overline{S_{i,j}} \\ \underline{R_{i,j}} \le R_{i,j} \le \widehat{R_{i,j}} \\ \underline{Q_{i,j}} \le Q_{i,j} \le \widehat{Q_{i,j}} \end{cases}$$

(10) $\qquad i = 1,2 \quad j = 1,2,\ldots,T$

C. Recursive equation

The recursive equation for SDP optimization is the following (Nandalal & Bogardi, 2007):

(11) $F_j^n(k,p) = \max\limits_{l}\left\{B_{k,p,l,j} + \sum\limits_{q}\Pr_{p,q}^{j} \times F_{j+1}^{n-1}(l,q)\right\}$

where: $k=$ storage state space consisting of representative values of joint storage states of reservoirs at beginning of period j, $l=$ decision space consisting of representative values of joint storage states of reservoirs at beginning of period $j+1$, $p=$ inflow state space consisting of representative values of joint inflow states during period j, $q=$ inflow state space consisting of representative values of joint inflow states during period $j+1$, $F_j^n(k,p)=$ accumulated expected cost generation by optimal operation of system over the last n stages (when storage class at beginning of period j is k and inflow class during period j is p), $B_{k,p,l,j}=$ cost generation when the system changes from state k (reservoir 1 and reservoir 2 at states k_1 and k_2 to state l (reservoir 1 and reservoir 2 at states l_1 and l_2) when inflow class is p (p_1 to reservoir 1 and p_2 to reservoir 2) in period j, and $\Pr_{p,q}^{j}=$ joint transition probabilities of inflows as defined by Eq. (12). The joint transition probability $\Pr_{p,q}^{j}$ that the probability that the inflows to reservoir 1 and reservoir 2 at period $j+1$ will fall in states q_1 and q_2 (represented by state vector q) given that at period j, the streamflows to reservoirs 1 and 2 were in states p_1 and p_2 (represented by state vector p), respectively. This can be expressed as:

$$\Pr_{p,q}^{j} = prob(I_{1,j+1} = q_1, I_{2,j+1} = q_2 \mid I_{1,j} = p_1, I_{2,j} = p_2) \quad (12)$$

also

$0 \le JP_{p,q}^{j} \le 1.0$; for all p and q; $j = 1,2,\cdots,12;$

$\sum\limits_{q} JP_{p,q}^{j} = 1.0$; for all p; $j = 1,2,\cdots,12;$

where,

$I_{i,j}=$ inflow to reservoir i during period j ($10^6 m^3$), $i = 1,2;\ j = 1,2,\cdots,T.$

The flow chart of the SDP procedure of two reservoirs is displayed in Fig.3.

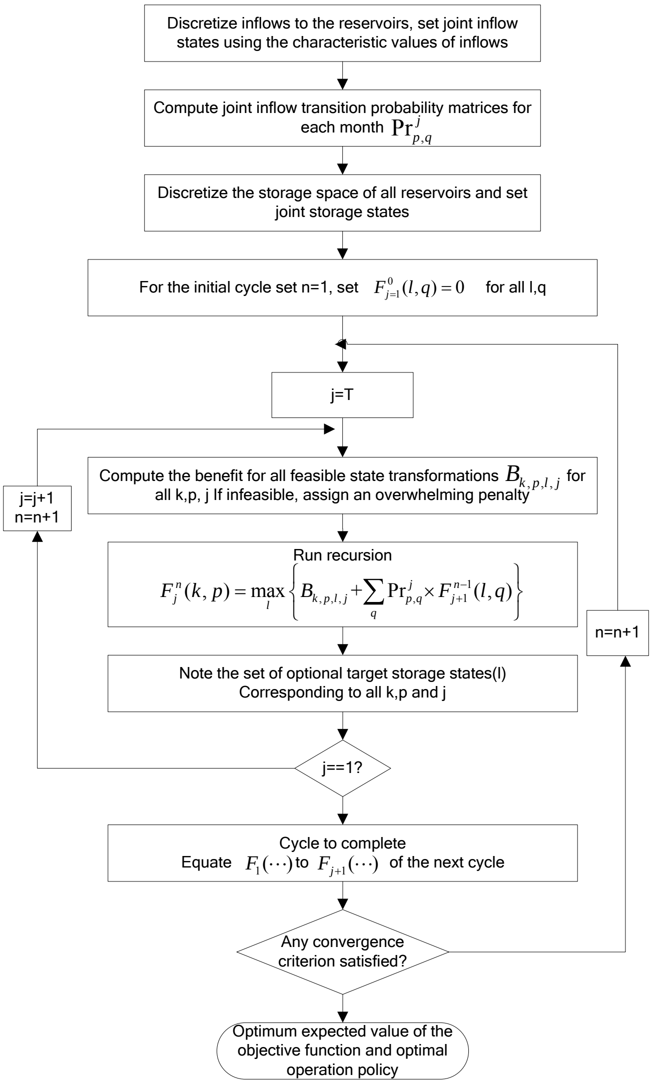

Fig.3. SDP Flow diagram for two-reservoir

Table 1. Comparison of results of SDP and SDP_MMFE

Policy No	Average annual energy (GWh)		Annual firm energy (GWh)		Average annual shortage (106m³)	
	SDP	SDP_MMFE	SDP	SDP_MMFE	SDP	SDP_MMFE
1	1265.9	1286.8	150.8	154.7	93.1	91.6
2	1274.3	1287.5	153.1	157.5	85.5	84.2
3	1284	1301.9	123.1	126.8	84.1	82.7
4	1283	1305.6	164.3	168.4	85.1	83.7
Average	1276.8	1295.45	147.825	151.85	86.95	85.55

Comparison analyses

To verify the efficiency of our model, we consider applying our model based on MMFE to the Victoria–Randenigala–Rantembe reservoir subsystem of the Mahaweli, Sri Lanka. The objective function is to maximize the expected energy generation. The analysis is based on historical (37-year-long) monthly streamflow data at each reservoir and at the Minipe diversion (Nandalal 1986, Bogardi 1988).

The comparison results are shown as Table 1 and Fig.4. The average annual energy and the firm energy show improvements at different levels using the model based on MMFE. The average annual shortage decreases moderately. The increase ratio of average annual energy (AAE) and annual firm energy (AFE) are 1.46% and 2.74%, respectively. The decrease ratio of the average annual shortage (AAS) is 1.61% based on MMFE. This indicates that our model based on MMFE can solve the water resource operation problem effectively and lead to an optimal operation policy.

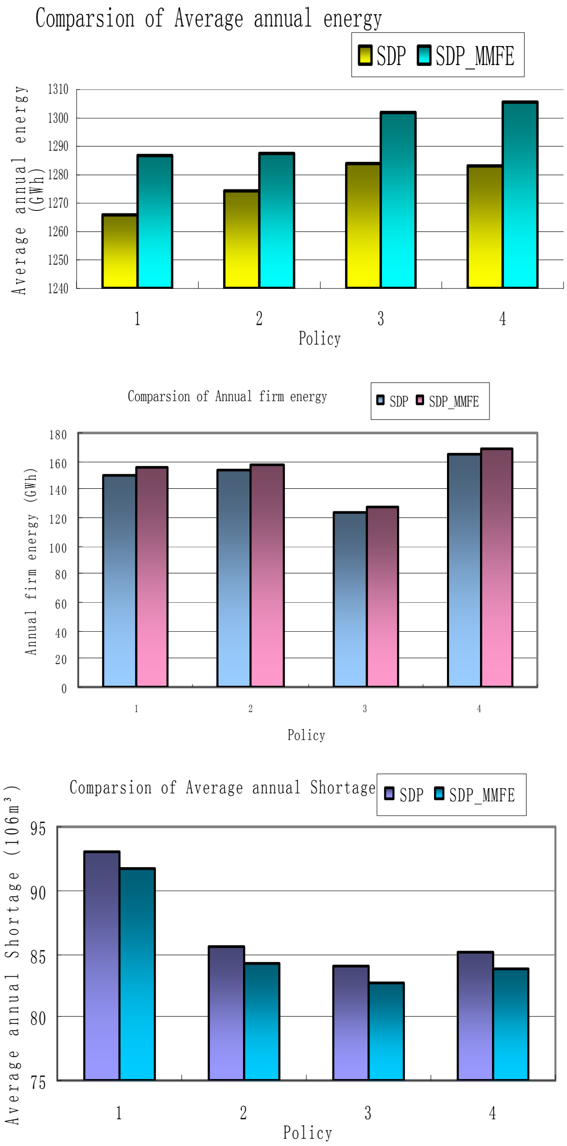

Fig.4. Comparison the differences between SDP and SDP_MMFE

Application of the model to the snwd project

The South to North water diversion project is the largest water resources engineering project involving the largest water resources allocation aiming to resolve the serious water shortage problem in Northern China. The Eastern route of the SNWD project is a highly complex interbasin system with multi-source, multi-object, and multi-project which pumps, stores, and supplies water to achieve rational water distribution in Northern China. The project was constructed and extended with a total investment of US$10 billion based on the Northern water transfer project in Jiangsu Province. The Eastern route project transfers water resources from the Yangzi River in Jiangdu through the Beijing-Hangzhou Grand Canal and its parallel river, linking Lake Hongze, Lake Luoma, Lake Nansi, and Lake Dongping, with 13 pumping stations and a total lift of 65m. To verify the model, we consider as an example the Yangzi River and the plan to transfer water to Lake Hongze and Lake Luoma, as showed in Fig.5. Lake Hongze has a total storage capacity of 4.25 billion m³ and a non-flood season adjustment capacity of 3.15 billion m³, while Luomahu Lake has a total storage capacity of 0.91 billion m³ and a non-flood season adjustment capacity of 0.59 billion m³).

The operation policy designated for a reservoir by the model is a set of rules specifying the storage level at the beginning of the following month for each combination of storage levels at the beginning of the current month and the inflow during the current month. As an example, the operation policy is designed for a month using 4 inflow classes and 3 storage classes for each reservoir. The numerical values used to identify the different inflow and storage levels are presented in Tables 2 and 3, respectively.

Table 4 reports the mean, standard deviation, and historical maximum and minimum of the monthly flows for the Lakes Hongze and Luoma for the past fifty years (1958-2007). Some parameters are initiated , as shown in Table 5.

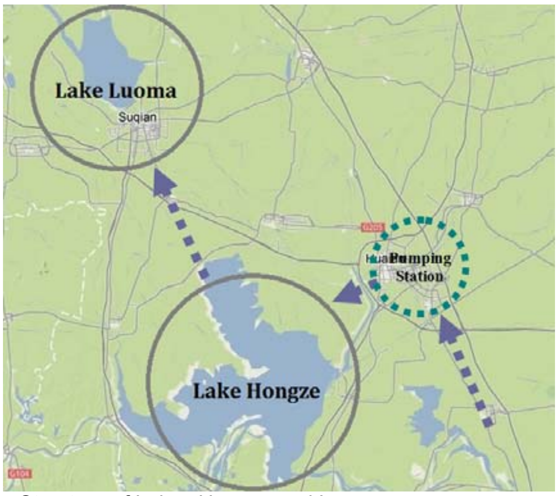

Fig.5. Structure of Lakes Hongze and Luoma

Table 2. Inflow class discretization of the operation policy (Unit 10^6m³)

Inflow Class		Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
1	Hongze	89.5	53.4	52.3	70.6	78.7	117.7	108.5	128.2	127.8	123.6	173	165.1
	Luoma	82.3	43.4	40.2	42.1	45.7	40.8	37.5	36.2	37.1	49.2	49.9	98.7
2	Hongze	88.5	53.4	52.3	71.6	78.7	121.7	108.5	121.2	124.8	107.8	172	178.5
	Luoma	127.4	108.6	63	56.2	65.6	54.4	51	48	52.2	67.4	86.1	183.8
3	Hongze	89.5	53.4	52.3	76.6	78.7	123.6	108.5	125.2	131.4	118.7	181	171.7
	Luoma	198.9	176.2	97.8	72.4	97.8	70	67.2	60	71.6	89.6	116.1	299.5
4	Hongze	88.5	53.4	52.3	75.9	78.7	117.7	108.5	129.8	134.8	121.6	181.7	175.1
	Luoma	275	266.7	132.8	89.1	128	97.8	84.1	83.7	85.6	114	159.1	457.4
5	Hongze	220.8	128.9	75.1	114.3	199.4	311	252.6	234.1	286.7	201.5	293.6	405.7
	Luoma	82.3	43.4	40.2	42.1	45.7	40.8	37.5	36.2	37.1	49.2	49.9	98.7
6	Hongze	225.8	125.9	75.1	112.6	177.8	308	252.6	256.1	289.7	204.3	289.6	413.4
	Luoma	139.3	108.6	63	57.2	65.6	54.4	51	48	52.2	67.4	86.1	183.8
7	Hongze	221.8	123.9	75.1	99.7	201.5	317	252.6	267.4	293.5	211.5	275.7	418.9
	Luoma	198.9	176.2	97.8	72.4	97.8	70	67.2	60	71.6	89.6	116.1	317.1
8	Hongze	208.8	129.9	75.1	110.3	198.4	318.5	252.6	268.8	293.7	210.5	297.1	432.7
	Luoma	277	266.7	132.8	89.1	128	97.8	84.1	83.7	85.6	114	159.1	468.9
9	Hongze	336.3	188.6	106.3	158.4	297.2	456.3	341.3	393.2	453.9	318.8	453.8	737.2
	Luoma	82.3	43.4	40.2	42.1	45.7	40.8	37.5	36.2	37.1	49.2	49.9	98.7
10	Hongze	338.3	190.6	112.3	160.4	294.7	475.3	341.3	396.4	461.1	317.6	431.9	742.3
	Luoma	139.3	108.6	63	56.2	65.6	54.4	51	48	52.2	67.4	86.1	183.8
11	Hongze	340.3	185.6	106.3	148.7	288.2	488.7	341.3	396.2	465.9	331.4	459.3	753.8
	Luoma	198.9	176.2	97.8	78.4	97.8	70	67.2	60	71.6	89.6	116.1	317.1
12	Hongze	334.3	183.6	111.3	160.4	266.2	489.1	341.3	400.2	468.4	329.1	432.7	762.7
	Luoma	277	266.7	132.8	89.1	128	97.8	84.1	83.7	85.6	114	159.1	468.9
13	Hongze	489.7	305.9	137.6	232.1	409.9	756.1	529.5	563.6	719.8	421.5	598.4	875.8
	Luoma	82.3	43.4	40.2	42.1	45.7	40.8	37.5	36.2	37.1	49.2	49.9	98.7
14	Hongze	512.4	305.9	139.6	225.6	410.6	753.6	529.5	569.1	730.7	432.1	585.6	911.6
	Luoma	139.3	108.6	63	56.2	65.6	54.4	51	48	52.2	67.4	86.1	183.8
15	Hongze	508.5	305.9	153.6	225.1	407	765.5	529.5	581.3	732.1	429.7	653.6	932.5
	Luoma	198.9	176.2	97.8	72.4	97.8	70	67.2	60	71.6	89.6	116.1	317.1
16	Hongze	506.4	305.9	137.6	230.1	399.7	777.1	529.5	584.5	728.8	435.8	685.3	967.5
	Luoma	277	266.7	132.8	89.1	128	97.8	84.1	83.7	85.6	114	159.1	468.9

Table 3. Storage classes of the operation policy (Unit 10^6m³)

Class	Hongze	Luoma	Class	Hongze	Luoma	Class	Hongze	Luoma
1	38	286	4	158	465	7	490	682
2	68	478	5	266	585	8	605	778
3	148	390	6	328	620	9	724	896

Table 4. Serial correlation coefficients of Lakes Hongze and Luoma

Month	Jan.	Feb.	Mar.	Apr.	May.	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
Hongze	0.22	0.29	0.5	0.39	0.51	0.68	0.31	0.55	0.19	0.07	0.01	0.54
Luoma	0.22	0.07	0.36	0.21	0.53	0.55	0.44	0.49	0.36	0.11	0.05	0.33

Table 5. Value of some parameters in the simulation

Parameters	c_1j	c_2j	p_1j	p_2j	□_1j	□_2j	□_1j	□_2j	LH_1j	LH_2j	□_1j	□_2j	□	g	k
Value	0.2	0.3	1.99	3.01	0.5	0.5	0.01	0.01	10	10	98	98	1000	9.8	0.001

Table 6. Simulation results for Lakes Hongze and Luoma

Policy No	Number of state discretizations		Total annual cost ($)	Average monthly cost ($)	Average annual storage ($10^6 m^3$)	Average annual release ($10^6 m^3$)	Average annual withdrawing ($10^6 m^3$)	Ratio of average annual shortage
	Inflow	Storage						
1	2	2	894,000	74,500	1.78	891	564	0.06
2	3	3	885,000	73,750	-1.132	912	765	0.03
3	4	3	930,000	77,500	0.6	976	975	0.01
4	5	4	921,000	76,750	0.64	864	875	0.03
5	6	5	918,000	76,500	-1.45	895	910	0.07

The simulation results are summarized in Table 6. Policy No. 3 is observed to be the best policy for this water resources system when considering the total annual cost and average annual storage, release, and withdrawing. The ratio of average annual shortage is a very important index in an operation policy for water resources management. In terms of average water shortage, this policy is negligibly inferior when compared to Policy No.1 and Policy No.5. As shown in Table 6, as the number of state discretization for inflow and storage in Lake Hongze and Luoma increases, the computing complexity and computing time vary greatly. Therefore, it is very important to decide the number of states in the multireservoir to choose an optimal release and withdrawing policy based on SDP.

Conclusions

Although streamflow forecast uncertainty plays an important role in reservoir operation, the effects of forecast uncertainty on reservoir operation have yet to be thoroughly addressed in a unifying framework. The Martingale Model of Forecast Evolution (MMFE) was introduced to synthetically generate deterministic and probabilistic streamflow forecasts through explicit representations of forecast uncertainty under various scenarios. A stochastic dynamic programming model with a physical recursive equation was developed to determine the optimum operation of the multireservoir operation systems. The experience reported in this paper and the resulting conclusions provide additional guidance in the use of this type of dynamic programming model in real-world reservoir operations. As a result of economic and social development, shortages in water resources are becoming more severe. However, the shortage experienced in many cities and regions can be solved using this general model.

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