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LARGE-SCALE RESERVOIR OPTIMAL OPERATION UNDER UNCERTAINTY

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ABSTRACT

Reservoir operation and water resources management is always one of hottest issues around the world. In order to study large-scale reservoir optimal operation under uncertainty, operation uncertainty of multi-objective reservoir was quantified in this paper. Then, the maximum of generated energy, the squared sums of water shortage and the quantified uncertainty were selected as the objective functions, and thus an integrated model for multi-objective reservoir operation is proposed. An experimental operation conducted with the Longyangxia Reservoir is employed for the demonstration of the proposed model. The results show that the calculated operation plan has a better performance than the actual reservoir operation process because the model can make the operation uncertainty lower and obtain the equilibrium solutions of power generation and water supply.

Keywords: Reservoir Operation, Uncertainty Quantification, Optimization Constraint, Longyangxia Reservoir

1 INTRODUCTION

Scarce water resources that are the main sources of industrial, domestic, agricultural and eco-environmental water have become one of the dominating factors restricting social development (Wu, 1999; Falkenmark et al., 2013). Utilizing finite water resources to maximize comprehensive benefits and ensure its own in sustainable use are two goals we need to achieve. Reservoirs are the indispensable tools to realize sustainable utilization of water resources, operations of which are always one of the most studied subjects for solving problems induced by water quantity and quality. Nandalal et al. (2013) outlined that reservoirs have to be best operated to gain maximum benefits from them. Optimization models can remove the clearly undesirable alternatives (Nandalal et al., 2013). The optimal operations are recommended by the model benefit from perfect hydrological foresight. Depending on the model, this may or may not disturb with the use fullness of model results. The optimized time-horizon may be decreased to shorter internals, such as yearly ones, which depicts perfect annual forecasts (Haddad et al., 2014).

Reasonable reservoir operations are effective ways to copy with some issues induced by scarce water resources, like possible droughts, ecological deterioration and sudden pollution (Booker et al., 2005; Hu, 2014; Shokri et al., 2014; Zhang et al., 2015; Wanders and Wada, 2015). Water supply and flood control are designed as two of primary missions to a majority of reservoirs. Although water resources optimal operations could distribute water resources reasonably to some extent, uncertainty induced by population growth and migration, increasing water demands, limited management modes and even inflow and water demand forecasting make reservoir operation difficult to attain optimal plans in theory (Jia et al., 2006; You and Yu, 2013; Liu et al., 2014; Zhao and Zhao, 2014; Ghimire and Reddy, 2014). Inflow and water demand forecasting play the key role in reservoir operation (Cai and Hu, 2006; Jiang et al., 2011; Zhao et al., 2013; Ma et al., 2014), a serious problem should be well aware that forecast uncertainty would bring possibly great economic loss (Stone, 2011). Compared with measured data, data from inflow and water demand forecasting is still in considerable errors (Haro et al., 2014; Loon and Laaha, 2015).

However, few researchers focus on the reservoir optimal operation with quantified uncertainty. How to evaluate forecast uncertainty and obtain reasonable operation plans deserves further studies and discussions despite uncertainty is much in evidence to be inevitable. Therefore, operation uncertainty is quantified according to the targets and characteristics of reservoir in this paper. The maximum of generated energy, the squared sums of water shortage and the quantified uncertainty were selected as the objective functions, and thus an integrated model for multi-objective reservoir operation is proposed.

2 STUDY RESERVOIR

The Longyangxia Reservoir (LYXR) is selected as the study reservoir for the demonstration of optimal operation under uncertainty. The LYXR is located at the east part of Qinghai province and 1684 km away from the Yellow River source region, which controls catchment area of 131400 km^2 accounting for 18% of the Yellow River basin. The LYXR has multiple operation objectives, such as hydroelectric generation, water supply, flood control, ice prevention, and the main purpose is hydroelectric generation. As the large-scale and the tap of cascade reservoirs, the total storage, regulating storage, installed power capacity is 247×10^8 m^3, 193.6×10^8 m^3 and 128×10^4 kW, respectively. The guaranteed out-put of the LYXR is 58.98×10^4 kW and its annual electricity production is 59.42×10^8 kw·h. The normal water level is 2600 m and the dead water level is 2530 m. It can be concluded that the LYXR operation and management is the key project of the Yellow River with the immense benefits. The monthly inflow, the curve deduction mass of annual inflow quantity and the ending monthly water level in each year of the LYXR from 1987 to 2016 is shown in Figure 1, Figure 2 and Figure 3, respectively.

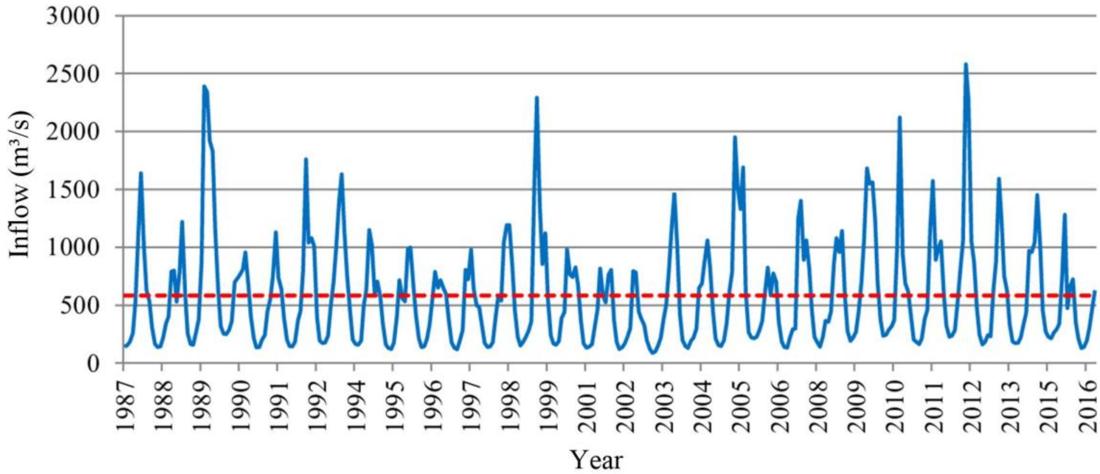

Figure 1. Monthly inflow process.

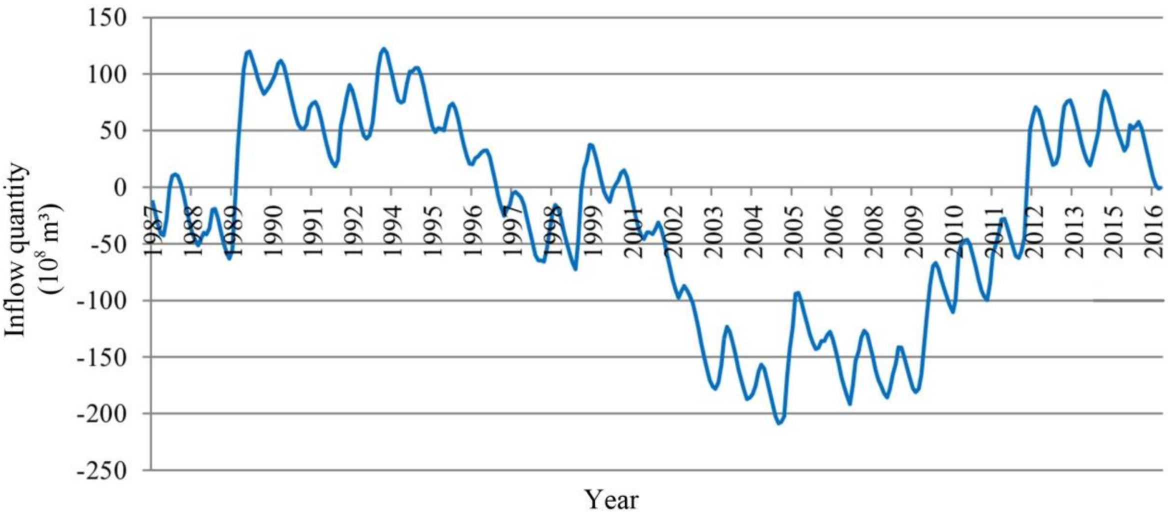

Figure 2. Curve deduction mass of annual inflow quantity.

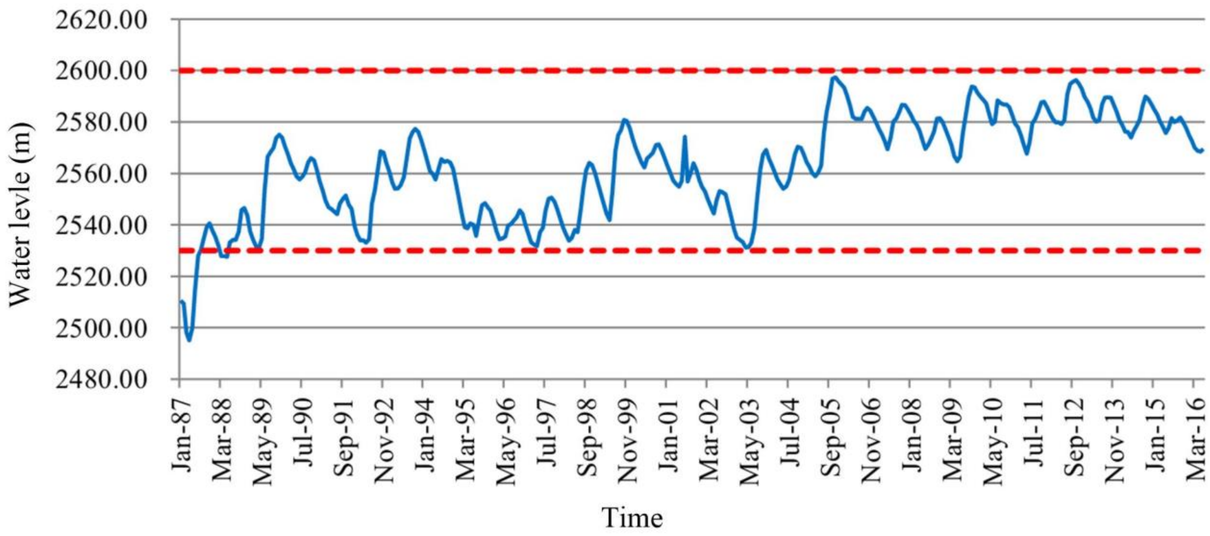

Figure 3. Ending monthly water level in each year.

3 OPERATION UNCERTAINTY QUANTIZATION

For the sake of formulation, denoting reservoir inflow, release, net evaporation loss, other losses in Stage t as $Q_{v,t}$, $R_{v,t}$, $E_{v,t}$, $L_{v,t}$, respectively, for simplify. And then, the water balance equations for a reservoir are (Zhao et al., 2012; Zhao and Zhao, 2014; Fayaed et al., 2013; de Araújo and Pruski, 2015):

$$S_1 = S_0 + Q_{v,1} - R_{v,1} - E_{v,1} - L_{v,1} \quad [1]$$

$$S_2 = S_1 + Q_{v,2} - R_{v,2} - E_{v,2} - L_{v,2} \quad [2]$$

where $t=1$ and $t=2$ represent the current Stage 1 and the future Stage 2, respectively. S_0 is the initial storage at the beginning of Stage 1; S_2 is the ending storage; S_1 is carried-over storage from Stage 1 to Stage 2.

$E_{v,t}$ and $L_{v,t}$ are combined to be $EL_{v,t}$, meanwhile, eliminating the common in both Eq. (1) and (2) can obtain:

$$S_2 = S_0 + Q_{v,1} + Q_{v,2} - R_{v,1} - R_{v,2} - (EL_{v,1} + EL_{v,2}) \quad [3]$$

Considering water supply as the primary target for reservoir and assuming that releases are entirely used to satisfy water demands (including domestic, industrial, agricultural and eco-environmental water, etc.), the equation is stated as:

$$R_{v,t} = WD_{v,t} + x_{v,t} \quad [4]$$

in which $x_{v,t}$ is the difference between water demand $WD_{v,t}$ and release $R_{v,t}$.

For simplify of the Eq. (3), this study deems that the ending storage S_2 is constant, because S_2 is fixed by empirical methods at the beginning of Stage 2 in actual reservoir operation. Thus, the following equation is obtained:

$$WD_{v,1} + \chi_{v,1} + WD_{v,2} + \chi_{v,2} = S_0 - S_{2-const} + Q_{v,1} + Q_{v,2} - (EL_{v,1} + EL_{v,2}) \quad [5]$$

In real-time operation, inflow forecasts which provide future inflow information have positive effects on operation decisions, and however, getting completely accurate inflow forecasts are arduous due to the limitation of projections technology. There are errors with the actual inflow values considering forecast uncertainty. Thus, $Q_{v,t}$ can be expressed as follows:

$$Q_{v,t} = \bar{Q}_{v,t} + \delta_{v,t} \quad [6]$$

where $\bar{Q}_{v,t}$ is inflow forecast, $\delta_{v,t}$ is inflow forecast error.

$EL_{v,1}$ and $EL_{v,2}$ is expressed as $EL_{v,1+2}$, the Eq. (6) is substituted into the Eq. (5):

$$WD_{v,1} + WD_{v,2} = \bar{Q}_{v,1} + \bar{Q}_{v,2} + (\delta_{v,1} - \chi_{v,1} + \delta_{v,2} - \chi_{v,2}) + (S_0 - S_{2-const}) - EL_{v,1+2} \quad [7]$$

Eq. (7) shows that Inflow forecast uncertainty has complex and perplexed effects on release decisions and consequently impact on water supply benefit. Water demand forecast, of which approximate results are merely acquired by the exiting approaches, is also indispensable before planning and managing water resources. Thus, forecast uncertainty corresponding to water demand is considered during each stage:

$$WD_{v,t} = \overline{WD}_{v,t} + \gamma_{v,t} \quad [8]$$

in which *t=1, 2*, $\overline{WD}_{v,t}$ is water demand forecast and error appearing in the process is $\gamma_{v,t}$.

Thereby Eq. (7) changes into the following expression:

$$\overline{WD}_{v,1} - \bar{Q}_{v,1} + \overline{WD}_{v,2} - \bar{Q}_{v,2} = (\underbrace{\mu_{v,1} - \gamma_{v,1} - \chi_{v,1}}_{\varepsilon_1} + \underbrace{\mu_{v,2} - \gamma_{v,2} - \chi_{v,2}}_{\varepsilon_2}) + (S_0 - S_{2-const}) - EL_{v,1+2} \quad [9]$$

In Eq. (9), $[\overline{WD}_{v,1} - \bar{Q}_{v,1} + \overline{WD}_{v,2} - \bar{Q}_{v,2} + EL_{v,1+2} - (S_0 - S_{2-const})]$ is considered as quantified uncertainty (QU).

4 RESERVOIR OPERATION MODELLING

The maximum of generated energy, the squared sums of water shortage and the quantified uncertainty were selected as the objective function; ice prevention, water balance, limited flow, limited water level etc. were selected as the constraint conditions; the long sequence operation is employed to obtain optimal operation plans in typical dry year, in this paper.

4.1 Objective function

(1) Power generation (PG)

$$\max F = \max \sum_{n=1}^{N} \sum_{t=1}^{12} K Q_{n,t} H_{n,t} \times \Delta t \quad [10]$$

In which, *N* is operation years; *K* is comprehensive output coefficient of reservoir; $Q_{n,t}$ and $H_{n,t}$ is power discharge and net head of power generation in t time of *n* th year, respectively; Δt is computing period (month).

(2) The squared sums of water shortage (WS)

The task of water supply for city and irrigation in Qinghai, Gansu, Ningxia and Inner Mongolia is undertaken by the upstream of Yellow River. Thus, the objective of water supply is:

$$\min S = \min\left(\sum_{t=1}^{T} \sum_{i=1}^{I} \left(\frac{DA_{it} - QA_{it}}{DA_{it}}\right)^2\right) \quad [11]$$

where, $DA_{i,t}$ is water demand of *i* th section in *t* time; $QA_{i,t}$ is water supply of *i* th section in *t* time. Especially, when $DA_{i,t} \le QA_{i,t}$, *S*= 100%.

(3) The quantified uncertainty (QU)

$$\min QU = \min[\overline{WD}_{v,1} - \bar{Q}_{v,1} + \overline{WD}_{v,2} - \bar{Q}_{v,2} + EL_{v,1+2} - (S_0 - S_{2-const})] \quad [12]$$

where, the expressions in Eq. (12) are same to the meanings as above.

4.2 Constraint condition

(1) Ice prevention

Ice run would arise from December of year to March of the following year in the upstream of Yellow River; reservoir operation for ice prevention is of particular importance. Thus, reservoir release is the effective operation indicator and its constraint condition can be expressed as follow:

$$IR_{t,\min} \le IR_t \le IR_{t,\max} \quad [13]$$

in which, IR_t, $IR_{t,min}$ and $IR_{t,max}$ is flow rate, minimum flow rate and maximum flow rate at *t* month, respectively, m³/s. *t* is from December of year to March of the following year. Shizuishan is selected as the control section for ice prevention and its limited flow rate can be seen in Table 1.

Table 1. Limited flow rate of Shizuishan section in each month.

Month	December	January	February	March
Maximum flow rate (m³/s)	650	550	500	450
Minimum flow rate (m³/s)	550	500	450	400

(2) Ecological flow rate

In order to maintain the habitat of aquatic organisms and ensure the stability and health of river ecosystem, Xiaheyan, Shizuishan and Toudaoguai are selected as ecological control sections.

$$EQ_{y,t} \geq Q_{ey} \quad [14]$$

in which, $EQ_{y,t}$ is flow rate of y th ecological control section at t time, m³/s; Q_{ey} is threshold value of y th ecological control section, m³/s. Threshold values of aforementioned ecological control sections are shown in Table 2 (Li et al., 2009).

Table 2. Threshold values of selected ecological control section.

Section	Xiaheyan	Shizuishan	Toudaoguai
Threshold value (m³/s)	203	166	250

(3) Water balance

$$S_t - S_{t-1} = (Q_t - R_t - E_t - L_t)\Delta t \quad [15]$$

in which, S_t is ending storage at t time, m³; S_{t-1} is ending storage at $(t-1)$ time, m³; Q_t, R_t, E_t, L_t is inflow, release, net evaporation loss, other losses, respectively, m³/s.

(4) Reservoir release

$$R_{t,\min} \leq R_t \leq R_{t,\max} \quad [16]$$

$$ER_{t,\min} \leq ER_t \leq ER_{t,\max} \quad [17]$$

$$SR_t = R_t - ER_t \quad [18]$$

In which, R_t, $R_{t,min}$ and $R_{t,max}$ is flow rate, minimum flow rate and maximum flow rate at t month, respectively, m³/s; ER_t is release of hydropower generating sets at t time, $ER_{t,max}$ is maximum release capacity of hydropower generating sets at t time, m³/s; SR_t is surplus water flow at t time, m³/s.

(5) Water level

$$Z_{t,\min} \leq Z_t \leq Z_{t,\max} \quad [19]$$

In which, Z_t, $Z_{t,min}$ and $Z_{t,max}$ is water level, minimum water level and maximum water level at t month, respectively, m. Especially, initial water level of LYXR is 2565.9 m and ending water level of LYXR is 1715.5 m.

(6) Nonnegative constraint

The parameters in the proposed reservoir optimal operation model must be nonnegative.

$$x_i \geq 0 \quad [20]$$

5 RESULTS AND DISCUSSION

NSGA-Ⅱ is employed to optimally compute the reservoir operation model (Malekmohammadi et al., 2011; Yin and Yang, 2011; Wang et al., 2016). Further, the Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS) is used to optimize non-inferior operation plans by approach degree calculation (Srdjevic, 2004; Huang et al., 2009; Aghdam and Pradhan, 2016; Zhu et al., 2018). The results can be seen in Table 3 and Figure 4. In Table 3, Power Generation, the Squared Sums of Water Shortage, the Quantified Uncertainty and Approach Degree is simplified to be PG, WS, QU and AD, respectively. It can be seen that No. 21 plan is the optimal operation plan.

Table 3. Calculated approach degrees of non-inferior operation plans.

Plan	PG (10^8 kwh)	WS	QU (10^8 m³)	AD	Plan	PG (10^8 kwh)	WS	QU (108 m³)	AD
1	1481.23	10.68	0.05	0.4500	16	1474.57	4.94	0.04	0.6452
2	1481.15	10.24	0.03	0.4611	17	1473.48	4.56	0.04	0.6535
3	1480.93	9.80	0.05	0.4721	18	1471.86	4.17	0.05	0.6501
4	1480.88	9.24	0.05	0.4909	19	1470.67	3.69	0.03	0.6563
5	1480.61	8.56	0.01	0.5150	20	1470.33	3.50	0.03	0.6601
6	1480.47	8.25	0.03	0.5266	21	1469.56	3.20	0.02	0.6607
7	1480.24	8.01	0.03	0.5347	22	1467.78	2.79	0.03	0.6462

8	1479.55	7.59	0.02	0.5480	23	1466.89	2.57	0.04	0.6387
9	1479.01	7.30	0.06	0.5570	24	1465.85	2.37	0.05	0.6282
10	1478.72	7.05	0.06	0.5672	25	1465.07	2.19	0.05	0.6216
11	1478.58	6.80	0.04	0.5802	26	1464.49	2.08	0.03	0.6160
12	1477.71	6.42	0.04	0.5924	27	1462.07	1.78	0.05	0.5891
13	1477.18	6.05	0.02	0.6083	28	1460.82	1.49	0.05	0.5806
14	1476.40	5.70	0.02	0.6217	29	1458.52	1.21	0.04	0.5606
15	1475.95	5.33	0.04	0.6394	30	1457.23	1.08	0.02	0.5500

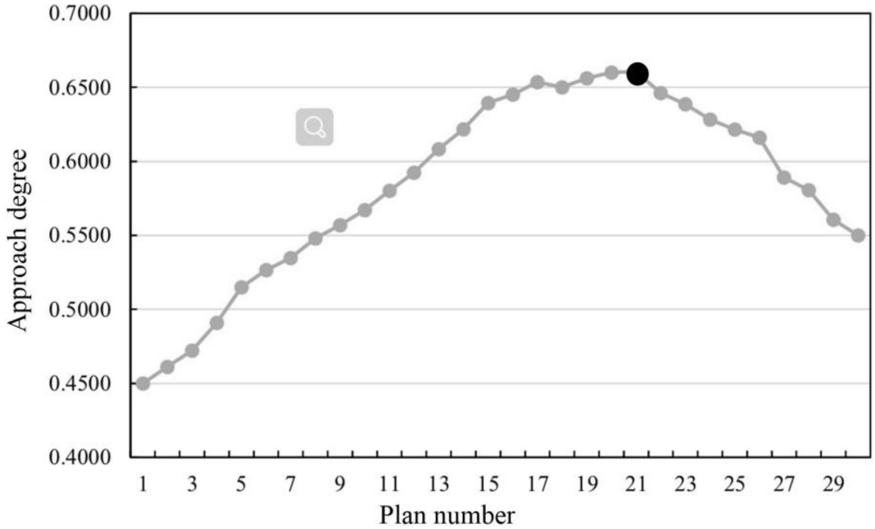

Figure 4. Approach degrees distribution.

Actual power generation in dry year is compared with the optimal operation plans to verify the rationality of calculated optimization results. Table 4 shows that the actual power generation of the LYXR from 2000 to 2005 is 173.65×10^8 kwh and the optimal result is 192.51×10^8 kwh, the corresponding increment is 14.56×10^8 kwh.

Table 4. Compared power generation of the LYXR.

Year		2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	Total
Power generation (10^8 kwh)	Actual state	40.79	32.98	36.92	35.50	46.33	192.51
	Optimal result	42.68	35.41	27.48	31.34	36.65	173.65

Table 5 shows that the stability of water supply in actual reservoir operation (2000-2005) needs to be enhanced, and the optimal result is partial to balanced benefit within 5 years making water supply process more reasonable.

Table 5. Compared water supply of the LYXR.

Year		2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	Total	Standard deviation
Squared sums of water shortage	Actual state	0.95	0.81	0.95	0.37	0.11	3.20	0.34
	Optimal result	0.51	0.53	2.29	0.59	0.26	4.17	0.73

Table 6 shows the compared result with regard to the satisfaction degree of ice prevention, which implies the flow rate at Shizuishan section meets the requirement of control flow rate in ice flood season. In addition, Table 7 demonstrates that the flow rates of the selected ecological control sections all meet the requirements of ecological water demand. Especially, the flow rate of Toudaoguai section is above 250 m³/s and water supply under this section can also be satisfied.

Table 6. Compared ice prevention flow of Shizuishan section.

Year		Month			
		12	1	2	3
Flow rate (m^3/s)	2000-2001	566	504	454	401
	2001-2002	567	503	481	410
	2002-2003	565	504	456	403
	2003-2004	640	544	500	445
	2004-2005	650	550	500	450
	Target value	650-550	550-500	500-450	450-400

Table 7. Compared flow rates of ecological control sections.

Ecological control section		Year					Target value
		2000-2001	2001-2002	2002-2003	2003-2004	2004-2005	
Flow rate (m^3/s)	Xiaheyan	382	387	384	426	431	203
	Shizuishan	401	400	401	334	326	166
	Toudaoguai	274	275	277	286	283	250

6 CONCLUSIONS

The worldwide is suffering from the situation where scarce water resources restrict economic and social development. Multi-objective reservoir operation is of importance to alleviate the contradiction between water supplies and demands induced by fewer inflows. The generation of future operation decisions needs the supports from all kinds of forecasts with regard to water resources, which, inevitably, involve in many uncertainties. In order to study large-scale reservoir optimal operation under uncertainty, operation uncertainty of multi-objective reservoir was quantified in this paper. Then, the maximum of generated energy, the squared sums of water shortage and the quantified uncertainty were selected as the objective functions, and thus an integrated model for multi-objective reservoir operation is proposed. Through the demonstration of the experimental operation conducted with the Longyangxia Reservoir, the results show that the calculated operation plan has a better performance than the actual reservoir operation process because the model can make the operation uncertainty lower and obtain the equilibrium solutions of power generation and water supply.

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