

# Comparative analysis of year-end water level determining methods for cascade carryover storage reservoirs

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**Abstract.** Based on the analysis of the determining methods of year-end water level for the cascade carryover storage reservoir, two prediction methods have been used to study the year-end water level: Multi-objective decision model and statistical regression predictive function. The advantages and applicable conditions of each of them have been compared and discussed.

## 1. Introduction

The issue of determining year-end water level of carryover storage reservoir is very important in the operation of cascade reservoirs. It not only affects the operation status and economic benefit of current year, but also the following many years and the whole cascade reservoirs [1-3]. At present, research activities about year-end water level of carryover storage reservoir are still not deep going, and the solution methods are not good enough. Two methods have been widely applied: multi-objective decision model considering the max energy of cascade power [4, 5] and statistical regression predictive function based on the formerly operation experience. The two methods are used to analyze the year-end water level of two carryover storage reservoirs, which are Hongjiadu and Goupitan reservoirs in the WuJiang River basin (figure 1), the advantage and applicable condition have been compared with the two methods.

## 2. Study on year-end water level based on multi-objective decision model

The storage capacity of the carryover storage reservoir can be divided into yearly regulation and overyear regulation [6]. The yearly regulation storage is used for generating in current year, and overyear regulation storage is used for generating in years after. The energy storage in the overyear regulation reservoir contains hydropower generation in current year and power storage. Consequently, the energy storage in the yearly regulation reservoir or runoff hydropower station is just the hydropower generation in current year for the lack of regulating ability. Actually, the objective function should include hydropower generation and power storage which are relative in the cascade reservoirs. More water must be expended and year-end water storage must be reduced to increase hydropower generation of cascade stations in current year. On the contrary, less water will be expended and hydropower generation will be restricted to increase the year-end energy storage. Therefore, how to coordinate the hydropower generation of cascade stations with the year-end water storage is the key to solve the conflict [7, 8].





**Figure 1.** The map of WuJiang River cascade hydropower station.

In this paper, the year-end water level prediction model of carryover storage reservoir was established, whose objective function is energy maximization of the cascade stations [9], which is

$$\text{Max}E = \text{Max}(E_d + E_s) \quad (1)$$

Where  $E$  is the total energy storage of cascade stations;  $E_d$  is hydropower generation in current year; and  $E_s$  is year-end power storage.

In equation (1):

$$E_d = \sum_{i=1}^n \sum_{t=1}^T K_i Q_{i,t} H_{i,t} \quad (2)$$

$$E_s = \sum_{j=1}^m A_j V_{nj} \bar{H}_j \quad (3)$$

Therefore, equation (1) can be re-written as

$$\text{Max}E = \text{Max} \left[ \sum_{i=1}^n \sum_{t=1}^T K_i Q_{i,t} H_{i,t} + \sum_{j=1}^m A_j V_{nj} \bar{H}_j \right] \quad (4)$$

where  $n$  is the total number of cascade reservoirs;  $m$  is the total number of overyear regulation reservoirs;  $T$  is the total number of operating time period;  $K_i$  is the integrated output power coefficient of hydroelectric station  $i$ ;  $Q_{i,t}$  is the Power Generating Flow at a time period  $t$  at a hydroelectric station  $i$ ;  $H_{i,t}$  is the power generating net head at a time period  $t$  at a hydroelectric station  $i$ ;  $A_j = \frac{K_j}{3600}$ ;  $V_{nj}$  is the year-end water storage of overyear regulation reservoir  $j$ ;

$\bar{H}_j$  is the average power generating net head in year-end water storage of overyear regulation reservoir  $j$ ; and  $\bar{H}_j$  is the sum of average power generating water head at a downstream hydroelectric station, if there is any.

The objective function (equation (1)) is subjected to the following system constraints:

- Mass balance equation. The reservoirs system follows the mass balance principle which is given by the following equation:

$$V(i, t+1) = V(i, t) + (Q_I(i, t) - Q_O(i, t)) \times \Delta t \quad (5)$$

where  $V(i, t), V(i, t+1)$  are the starting and ending reservoir storage volume ( $\text{Mm}^3$ ) at a time period  $t$  at a hydroelectric station  $i$ ; and  $Q_I(i, t), Q_O(i, t)$  are inflow and outflow at a time period  $t$  at a hydroelectric station  $i$ .

- Flow balance equation

$$Q_I(i+1, t) = Q_O(i, t) + q(i, t) \quad (6)$$

where  $q(i, t)$  is the local inflow during time period  $t$  between hydroelectric station  $i$  and  $i+1$ .

- Water level bounds

$$Z_{\min}(i, t) \leq Z(i, t) \leq Z_{\max}(i, t) \quad (7)$$

where  $Z_{\max}(i, t), Z_{\min}(i, t)$  are the minimum and maximum limits of water level during time period  $t$  in a reservoir  $i$ ;  $Z_{\min}(i, t)$  generally is the dead water level and  $Z_{\max}(i, t)$  must be considered with the flood control.

- Release bounds

$$Q_{O\min}(i, t) \leq Q_O(i, t) \leq Q_{O\max}(i, t) \quad (8)$$

where  $Q_{O\max}(i, t), Q_{O\min}(i, t)$  are the minimum and maximum limits of water release during time period  $t$  at the reservoir  $i$ ;  $Q_{O\min}(i, t)$  is considered with water use and navigation; and  $Q_{O\max}(i, t)$  must be considered with the flood control.

- Power production constraint

$$N_{\min}(i, t) \leq N(i, t) \leq N_{\max}(i, t) \quad (9)$$

where  $N_{\min}(i, t), N_{\max}(i, t)$  are the minimum and maximum power production limits. Depending upon the power plant capacity and reliability, the minimum and maximum production has to be fixed for any power plants.

Based on the energy maximization of the cascade stations model above, the influence of inflow and year-start water level for year-end water level in the overyear regulation reservoir has been analyzed. The model was applied in the Wu-Jiang River, which has two overyear regulation reservoirs (Hongjiadu and Goupitan). Based on the inflow record (from 1951 to 2014), the scheme set of year-end water level of overyear regulation reservoirs (Hongjiadu and Goupitan) has been developed. The process of simulated calculating is as follows: first, according to the inflow frequency and the year-start water level in Hongjiadu and Goupitan, the year-end water level can be determined by the scheme set described above. Second, the hydropower generation maximization model (equation (4)) has been applied to optimal operation of the cascade stations. Third, the results of hydropower generation and firm power of the stations have been compared to the design values. This comparison indicates that the model is reliable.

**Table 1.** Comparison of conventional and optimization scheduling for key parameters.

Reservoirs		Hongjiadu	Goupitan
Average annual power generation (10 <sup>8</sup> KW·h)	Conventional Scheduling	15.59	96.67
	Optimization Scheduling	16.89	98.08
	Increasing rate (%)	1.3	1.41
Firm power (MW)	Conventional Scheduling	159.1	746.4
	Optimization Scheduling	155.1	841.3
	Increasing rate (%)	-4	95.9
Assurance rate (%)	Conventional Scheduling	95	95
	Optimization Scheduling	94	96
	Increasing rate (%)	-1	1

From table 1 we can see that the optimization operation can get the maximum average annual power generation and firm power. Therefore, prediction method of year-end water level based on Multi-objective decision model is reasonable and reliable.

### 3. Study on year-end water level based on statistical regression analysis

The conflict of hydropower generation and energy storage of carryover storage reservoir can be resolved by applying the multi-objective decision model to determine the year-end water level. This model assumes that either the hydropower generation in current year or the power storage in the subsequent years is optimal. Due to uncertainty of inflow condition, the influence of inflow in subsequent years on cascade reservoirs operation cannot be considered properly in the optimal model. So, a statistical regression function model was developed which describes by the relationship between the year-end water level and related factors.

The statistical regression function model for determining the year-end water level is widely used. As well known, the reservoir operation chart is based on the classification and summary of reservoir operation history. Like the method for obtaining operation chart, the statistical regression function for prediction of the year-end water level can be developed as follows. First, the deterministic model of cascade reservoirs operation must be established. Second, the long-series actual flow records must be used for the simulation calculation. At last, the long-term optimal operation rules and the variation range of year-end water level in the carryover storage reservoir can be obtained.

**Table 2.** Regression effect analyzing with different degrees of confidence.

Reservoirs	Hongjiadu	Hongjiadu	Goupitan	Goupitan
Degrees of confidence	0.1	0.001	0.1	0.001
Amount of forecast factor	4	3	2	2
Sum of squares	16288.69	16288.69	1723.84	1723.84
Residual sum of squares	1984.54	2203.66	1059.82	1316.03
Regression square sum	14304.16	14085.03	664.02	407.81
Multiple correlation coefficient	0.94	0.91	0.62	0.46
Residual standard deviation	6.57	6.85	4.70	5.18
Mean relative errors	0.39%	0.42%	0.53%	0.58%

The cascade hydropower generation maximization model (equation (2)) can be used for the long-series simulation operation. Based on the inflow record (from 1951 to 2014), the change law of year-end water level in overyear regulation reservoirs (Hongjiadu and Goupitan) has been established. According to the long-series results, the relationship between year-end water level and the related factors, such as year-start water level, inflow, power output and power generation can be determined. In order to analyze the accuracy of the simulation results, the statistical regression data were calculated with different degrees of confidence (0.1 and 0.001). The results are shown in table 2.

The Stepwise Regression predicting model for Hongjiadu is

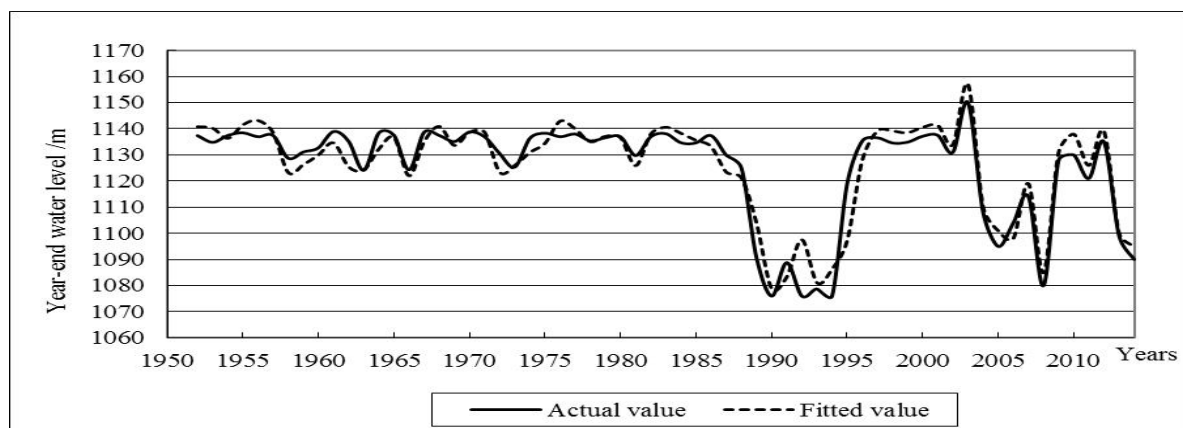
$$Z_{\text{year-end}} = 611.3808 + 3.34 \times 10^{-4} (Z_1)^2 + 0.9243 (Q_1) - 2.4119 \times 10^{-3} (Q_1)^2 + 0.0643 (Q_2) \quad (10)$$

The Stepwise Regression predicting model for Goupitan is

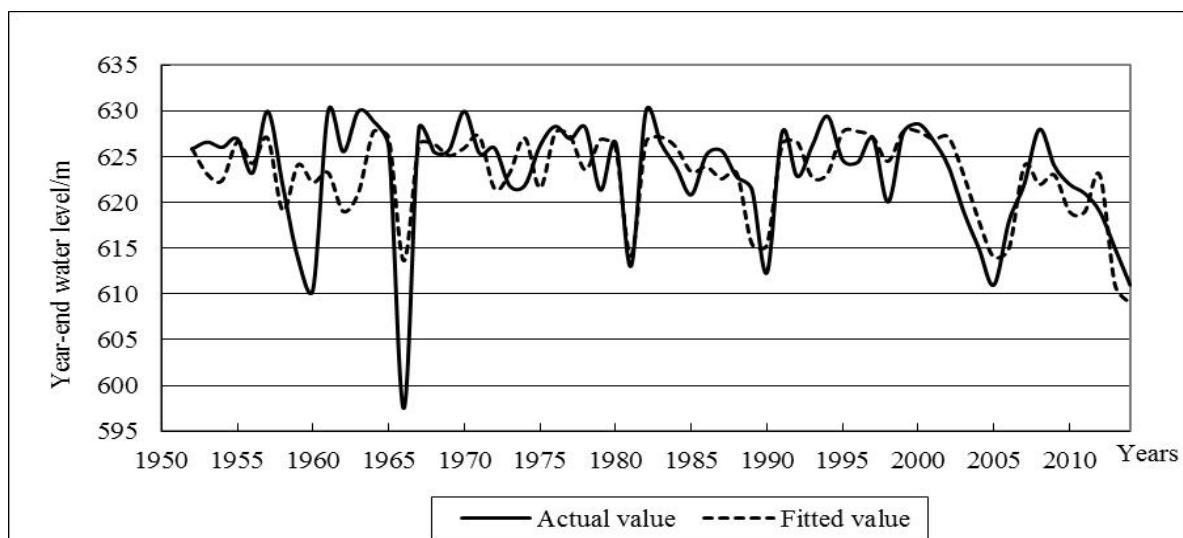
$$Z_{\text{year-end}} = 578.2711 + 0.1085 (Q_1) - 5.94 \times 10^{-5} (Q_1)^2 \quad (11)$$

where,  $Z_{\text{year-end}}$  is the year-end water level of overyear regulation reservoirs,  $Z_1$  is the year-start water level,  $Q_1$  and  $Q_2$  is the predicting inflow in the current and subsequent years.

The year-end water level predicting model results were compared with the actual data (figures 2 and 3). According to the T-Test and F-Test results, the regression effect is significant in theory.



**Figure 2.** The actual and calculated values of the year-end water level in the Hongjiadu reservoir.



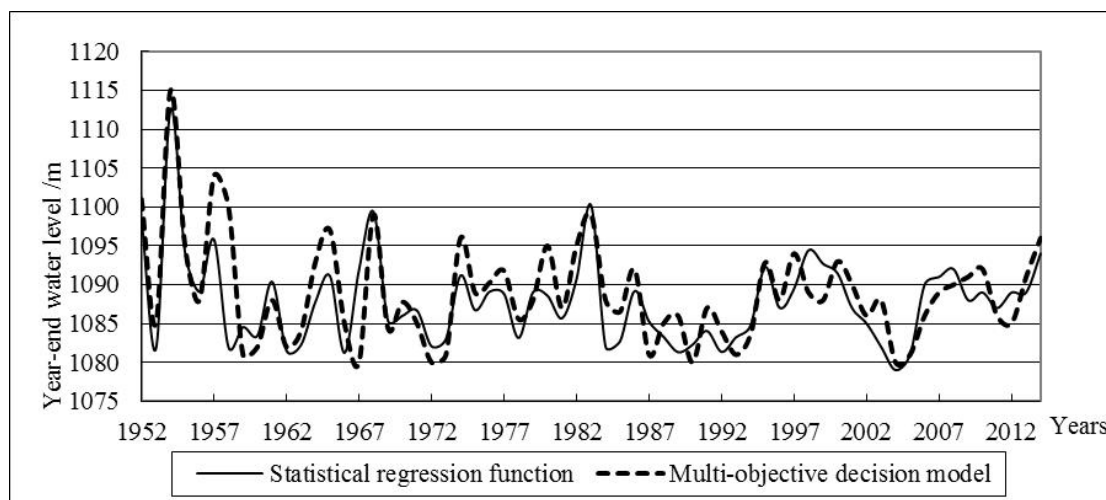
**Figure 3.** The actual and calculated values of the year-end water level in the Goupitan reservoir.

#### 4. Compared analysis of the two year-end water level prediction model

Based on the study of year-end water level of overyear regulation reservoirs, two methods for determining the optimal year-end water level were established, namely the Multi-objective decision model and the Statistical regression function model. Two methods are applied in the actual overyear regulation reservoirs which are Hongjiadu and Goupitan in Wujiang River basin. According to the long series simulation calculation results of cascade reservoirs in Wujiang River basin, the two methods for determining the optimal year-end water level are reasonable and reliable, and suitable for cascade reservoirs operation. The compared results of two different year-end water level prediction models are presented in table 3, figures 4 and 5.

**Table 3.** Compared results of different year-end water level prediction model.

Reservoirs			Hongjiadu	Goupitan
Average annual power generation (10 <sup>8</sup> KW·h)		Design value	15.59	96.67
		Multi-objective decision model	16.89	98.08
		Statistical regression function	17.12	100.55
Firm power (MW)		Design value	159.1	746.4
		Multi-objective decision model	155.1	841.3
		Statistical regression function	156.3	851.9
Assurance rate (%)		Design value	95	95
		Multi-objective decision model	94	96
		Statistical regression function	95	98

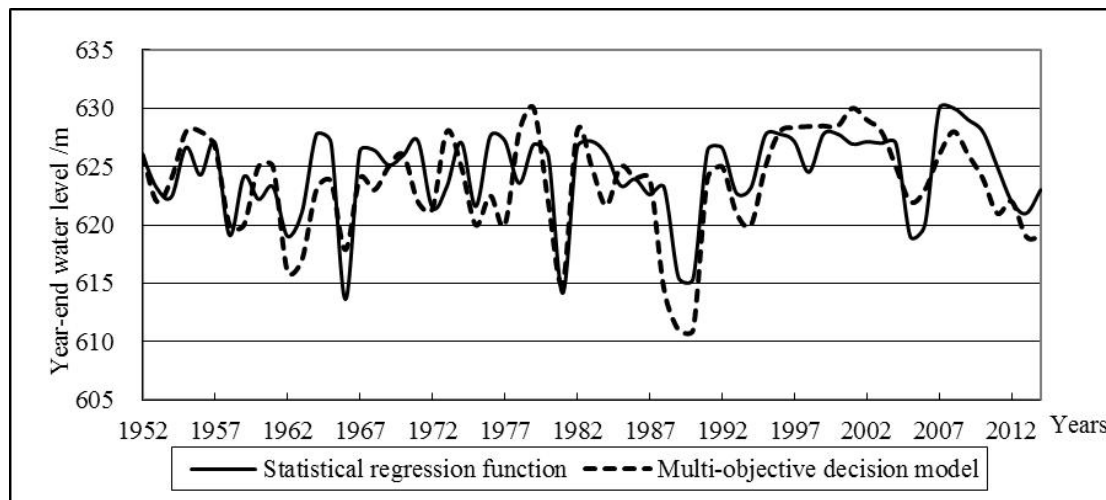


**Figure 4.** The year-end water level in the Hongjiadu reservoir derived from different models.

A comparison of two year-end water level prediction models in figures 4 and 5 shows that the two methods have the same trend, which is consistent with the long series optimal operation. However, some parts of the two curves show differences, which are caused by the following reasons: first, the year-end water level determined by statistical regression function is based on long series optimal operation results, which require long enough sample series. In the paper, there is only the 63-year inflow record, which cause the statistical regression function model only shows the prediction trend,



but the extremal problem cannot be solved. Second, due to the error accumulation of year-end water level, the simulation model has a disadvantage as uncertainty of the function type and relatively large prediction error, which impact the prediction accuracy. Third, the year-end water level has a great influence on the reservoir operational mode, while the multi-objective decision model for determining year-end water level was insensitive to that influence. In other words, the multi-objective decision model has a great effect on the different inflow frequencies, which causes the error of the extreme value at the edge zone of decision interval.



**Figure 5.** The year-end water level in the Goupitan reservoir derived from different models.

Because of the Goupitan reservoir is in the middle of the Wujiang River basin, its year-end water level is influenced by a lot of factors. Therefore, the statistical regression function model cannot be completely applicable, thus the multi-objective decision model could be used more successfully. From the figure 5, we can see that, the two methods of determining year-end water level of Hongjiadu reservoir give prediction results without big differences. However, in dry years, the prediction of year-end water levels from the statistical regression model is relatively low, which causes the increase in hydropower generation at cascade stations. Considering the good regulation performance of the Goupitan reservoir, the statistical regression method should be given priority for the Hongjiadu reservoir in dry years. Two determining methods are suitable for Hongjiadu reservoir in wet or average water years. In practical use, the year-end water level of overyear regulation reservoirs can be calculated by two methods separately, and finally the best option could be determined by the actual situation and power plant dispatcher's operation experience.

## 5. Conclusions

The issue of determining year-end water level at the carryover storage reservoir has always been one of the most complicated decisions in water resources management. Two methods for determining the optimal year-end water level are presented in this paper, which are the multi-objective decision model and the statistical regression function model. The two methods have their own advantages and disadvantages. In general, the statistical regression function is suitable for the conditions of steady inflow and the long enough series record. The multi-objective decision model is suitable for the conditions with serious contradiction in reservoir function. From the long term joint operation of cascade reservoirs, the two year-end water level determining methods are reasonable and effective.

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