Ecology and Water Supply Based Multi-objective Optimal Dispatch Model and Its Case Study in Yangtze basin

Xuemin Wang, Jianzhong Zhou, and Chao Wang

Abstract—The cascade reservoir dispatching based on the ecology and water supply is a new topic in recent years. This paper present the Ecology and Water-supply Based Multi-objective Optimal Dispatch Model (EWSB-MODM) with three objectives: ecological benefit, water supply benefit and power generation benefit. Then, by using the Monthly Frequency Computation method and considering the ecological factors (includes the breeding of Chinese sturgeon and the four major Chinese carps, preventing saltwater intrusion, avoiding dissolved gas supersaturation and the water level control of the Dongting and Poyang Lake), this paper defines the suitable ecological flow for the Three Gorges Cascade (TGC), which is taken as the ecological benefit criterion. Meanwhile, with a view to the situation of water demands and the local water shortage risks appearing in the upper and middle reaches of the Yangtze River, the water requirement is determined, and it is converted into the water supply rate as the criterion of the water supply benefits. Finally, this paper imports the multi-objective differential evolution algorithm (MODE) to solving the engineering case of the Three Gorges cascade. Results show that the model and method proposed in this paper can gain non inferior solution set which is uniform distributed and meets the ecological and water supply benefits, providing a scientific basis for reservoir schedulers to make the reasonable decision.

Index Terms—Ecology, water supply, power Generation, multi-objective optimal dispatch.

I. Introduction

The Yangtze River is the world's third largest river. The Three Gorges Cascade (TGC) is a key backbone cascade in the Yangtze River, which consists of the Three Gorges power station in the upper reaches and the Gezhouba power station in the lower reaches. The Three Gorges reservoir is the leading reservoir in the cascade, with the installed power capacity of 22.4 million kW, the normal water level of 175m, flood water level of 145m and the utilizable water capacity of 24.9 billion m3. For the Gezhouba power station, it has the installed power capacity of 2.71 million kW, the normal water level of 66.5m, flood water level of 63m.

As the Three Gorges Cascade is a demarcation point of the upper and lower reaches of the Yangtze River, its operation inevitably pose a threat to the water supply security and ecosystem stability in a certain range of the river. In recent

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years, many researchers have carried out a series of studies around the issue of reservoir dispatch [1], suitable ecological flow [2], [3] and habitat research [4], [5].However, there are some problems in these researches: 1) For most ecological flow calculation methods, only the statistical law is considered, so the ecological hydrological characteristics of the river basin are ignored; 2) In the dispatch model, the evaluation criteria of water supply in the upstream is not described clearly, which makes it difficult to implement practically.

Based on the previous studies, this paper establishes the ecology and water supply-based multi-objective optimal dispatch model (EWSB-MODM). Then the criterions of the ecological benefit of the lower Yangtze Rive and the water supply in the upper Yangtze River are determined. At last, the Multi-objective difference evolution is used to solve the model.

II. Ecology and Water Supply-Based Multi-objective Optimal Dispatch Model (EWSB-MODM)

To conduct the study, we clearly set three specific goals. First, the gross power generation of the cascade directly means the economic benefit, which is taken as one dispatching objective of this model. Secondly, this paper takes the ecological over-and-short water amount in the lower reaches of the cascade as the measurable indicator of the ecological benefit. Finally, we take the water supply rate as the third objective of this model.

A. Objective Function

Taking the maximum power generation of the cascade, the minimum ecological over-and-short water in the lower reaches and the maximum water supply rate as the objective in this model, the objective function of EWSB-MODM is expressed as follows:

1) Maximum power generation of the cascade

$$\max f_1 = \max E = \sum_{i=1}^{Num} \sum_{t=1}^{T} K_i Q_{i,t}^f H_{i,t}^f \Delta t = \sum_{i=1}^{Num} \sum_{t=1}^{T} N_{i,t} \Delta t \quad (1)$$

2) Minimum ecological over-and-short water in the lower reaches of the cascade

$$\min f_2 = \min W^Q = \sum_{t=1}^{T} \left| Q_t^X - Q_t^S \right| \Delta t \quad (2)$$

3) Maximum water supply rate

$$\max f_3 = \max D^S = \max \frac{W^R}{W^S} \quad (3)$$

where E is the power generation of the cascade; Num is the total number of power stations in the cascade; T is the length of dispatch time; K_i is the output factor of the i-th station; $Q_{i,t}^f$ is the generation discharge of the i-th station at the t-th period; $H_{i,t}^f$ is the water head; $N_{i,t}$ is the output; Δt is the length of a single period; W^Q is the amount of the ecological over-and-short water; D^S is the water supply rate; W^R is the amount of water demands in the upper reaches; W^S is the actual supplied water; Q_t^X is the outflow of the cascade; Q_t^S is the suitable ecological flow of the downstream river.
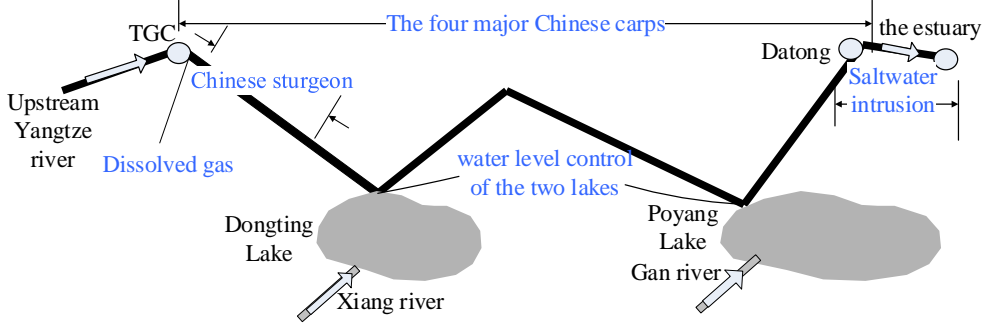

Fig. 1. Sketch map of the downstream Yangtze River.

B. Model constraint

The dispatch constraints of the cascade hydropower stations mainly includes water level constraints, water balance constraints, power output constraints and discharged flow constraints.

1) Water level constraints

$$Z_{i,t}^{\min} \leq Z_{i,t} \leq Z_{i,t}^{\max} \tag{4}$$

where $Z_{i,t}$ is the water level of the i-th power station at the t-th period; $Z_{i,t}^{\min}$ and $Z_{i,t}^{\max}$ respectively stand for the upper limit and lower limit of water level.

2) Power output constraints

$$N_{i,t}^{\min} \leq N_{i,t} \leq N_{i,t}^{\max} \tag{5}$$

where $N_{i,t}$ is the power output of the i-th power station during the t-th period; $N_{i,t}^{\min}$ and $N_{i,t}^{\max}$ respectively stand for the upper limit and lower limit of power output.

3) Flow constraint

$$Q_{i,t}^{\min} \leq Q_{i,t}^X \leq Q_{i,t}^{\max} \tag{6}$$

where $Q_{i,t}^{\min}$ is the discharge of the i-th power station during the t-th period; $Q_{i,t}^{\min}$ and $Q_{i,t}^{\max}$ respectively stand for the upper limit and lower limit of outflow.

4) Water balance constraints

$$V_{i,t+1} = V_{i,t} + (I_{i,t} - Q_{i,t}^X) \times \Delta t \tag{7}$$

$$I_{G,t} = Q_{S,t-\tau}^X + q_t \tag{8}$$

where $V_{i,t}$ is the capacity of the i-th power station of the t-th period; $I_{i,t}$ is the inflow of the i-th power station; τ is the flow time; $I_{G,t}$ is the inflow of the power station in the lower reaches; $Q_{S,t-\tau}^X$ is the discharge flow of the power station in the upper reaches of the ($t-\tau$)-th period; q_t is the inflow of the river between these two power stations.

III. ECOLOGICAL BENEFIT EVALUATION CRITERION

The study object of this paper is the Three Gorges Cascade (TGC). The suitable ecological flow is defined by the Monthly frequency computation method (MFCM) and the ecological factors in the downstream.

A. Monthly Frequency Computation Method (MFCM)

The MFCM is to calculate a suitable ecological flow [2]. Each year is divided into abundant period, normal period and dry period according to historical runoff. Then the suitable ecological flow for each month is determined by the assurance rates of each period, and the same period possesses the same water assurance rate. For Yangtze River, the dry period includes January-April, the normal period includes May and October-December, the abundant period includes June-September. Then the frequency for each month (frequency of dry period 10%, normal period 50% and abundant period 90%) is adopted. The statistic results of MFCM are shown in Table I.

B. Ecological Factors

This paper selects some key ecological factors in the downstream of Yangtze River, as shown in Fig. 1, some of the information refers to [6].

1) Chinese sturgeon is the national first-grade endangered protection animal. The breeding season includes October and November, and the outflow of the TGC is required to be 12000 m3/s.
2) The four major Chinese carps are important economic species. The breeding season is from April to July, and the outflow is required to be 11000 m^3/s.
3) Saltwater intrusion. The saltwater intrusion refers that the high salinity water of the ocean pushes upstream along the estuary with the rising tide. During the period of reducing salinity at the estuary, the outflow is required to be 5500 m3/s from December to April of the next year, but 10500 m3/s in October and 7500 m^3/s in November.
4) Saturation of the dissolved gas. When large water flow discharges through the dam's outlet, the dissolved gas in

the water downstream increases sharply so that the fish reproduction is influenced. It is required that the discharged flow should be less than 30000 m³/s.

5) Ecological water level control of the two lakes. The Dongting Lake and Poyang Lake are the habitats for precious fish and migratory birds, the lowest water level

of the lakes are limited. It requires that the outflow is larger than 5500 m³/s.

On the basis of comprehensively considering the water demands of the above typical ecological elements, we define the suitable ecological flow of the TGC as shown in Table I.

TABLE I: The Suitable Ecological Flow of the TGC (M³/S)

month	1	2	3	4	5	6	7	8	9	10	11	12
MFCM	4989	4548	5458	8613	11884	13570	22240	19845	18143	19593	10382	5970
reduce salinity	5500	5500	5500	5500						10500	7500	5500
Chinese sturgeon										12000	12000	
The Four Major Carps				11000	11000	11000	11000					
Dissolved gas						< 30000						
The Two Lakes						> 5500						
Composite results	5500	5500	5500	11000	11884	13570	22240	19845	18143	19593	12000	5970

TABLE II: Water Demand of Each Month in 2020

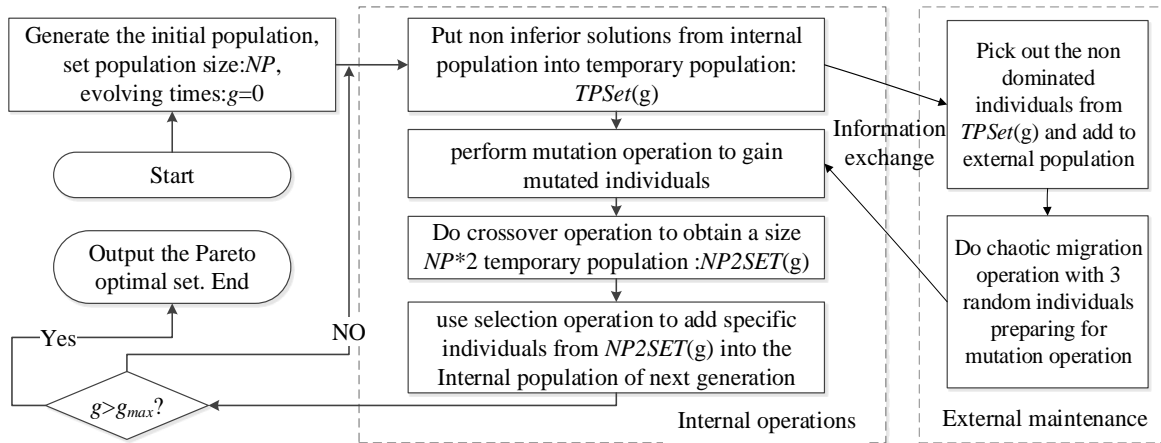| Month	1	2	3	4	5	6
Total water demand (10^6 m³)	2994.04	2990.88	3713.48	3643.27	6381.12	6833.39
Flow of the water demanded (m³/s)	1117.85	1193.68	1386.46	1405.58	2382.44	2636.34
Month	7	8	9	10	11	12
Total water demand (10^6 m³)	8814.66	8146.31	4627.24	4309.39	3033.06	2860.30
Flow of the water demanded (m³/s)	3291.02	3041.49	1785.2	1608.94	1170.16	1067.91

Fig. 2. Flow chart of multi-objective difference algorithm.

IV. Evaluation Criteria of Water Supply Benefits

As the upper Yangtze River basin is an important zone in China's economic development, the adequate water supply is required. According to the statistical result of the Yangtze Water Resources Commission (the management organization of the Yangtze River), the water demand in the upper reaches in the year 2020 will increase by 16% comparing with the year 2010. The water demands in 2020 are shown in Table 2.

In order to reflect the water supply benefits, this paper adopts the water supply rate to evaluate the water supply benefit (Eq. 3).

V. Case Study

A. Multi-Objective Difference Evolution

This paper uses a kind of modified multi-objective

differential evolution algorithm (MODE) to solve the optimal dispatch model proposed. Through the external archiving technology [7] and the chaotic sequence [8], the algorithm is designed and the flow chart is shown in Fig. 2.

B. Algorithm Encoding and Objective Fitness

The water level of the reservoir is an important parameter in the operation of the power station, which can accurately and directly reflect the connections between the power stations in the cascade and is closely related to the complicated constraints (such as water balance, water level amplitude, etc.). In view of this, this paper takes the water level sequence of the dams in the cascade as the variables of the MODE. Each individual in the population is represented as $H = (h_{0,1},...,h_{0,T},...,h_{i,t},...,h_{i,T})$, where $h_{i,t}$ represents the water level of the *i-th* station in the *t-th* period, T is the length of time period.

In the multi-objective optimal dispatch, the fitness values are normalized respectively to reduce the error caused by different dimensions [9], which is shown below:

$$f(x) = \frac{x - X_{\min}}{X_{\max} - X_{\min}} \qquad (9)$$

where $X_{\max}$ and $X_{\min}$ are respectively the minimum and maximum fitness values of solutions in the current population; x is the fitness value of the current solution; $f(x)$ is the fitness value after the normalization.
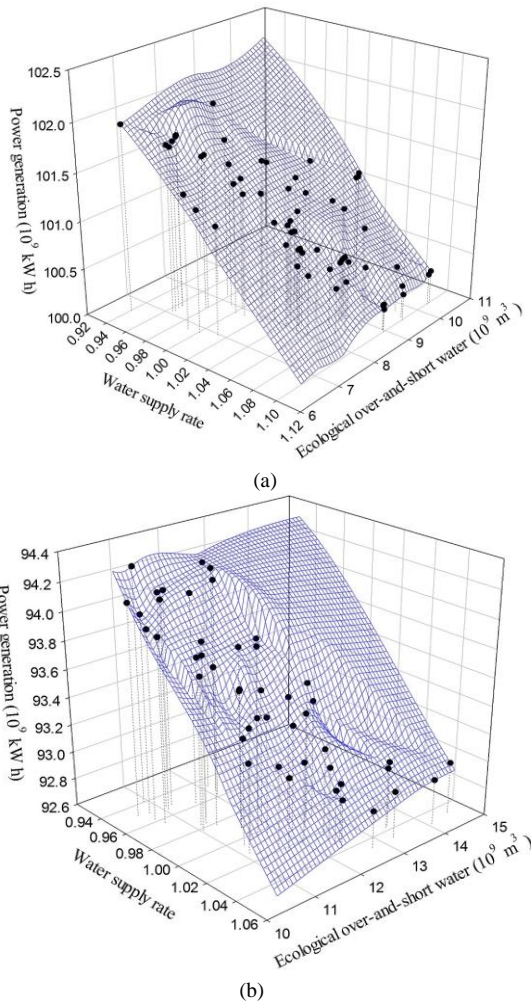

(a)

(b)

Fig. 3. Pareto optimal set of 40% (a) and 60% (b) typical inflow.

C. Results and Discussion

Taking 40% and 60% of the inflow of the TGC as the input and dispersing the water supply rate from 0.9 to 1.1, this paper uses the EWSB-MODM and the MODE to simulate the dispatch operation in year 2020 which is divided into 12 periods (one month for each). The obtained Pareto optimal set about the total generated energy, ecological over-and-short water and water supply rate, as is shown in Fig. 3. The projections of Pareto optimal set in Fig. 3(a) is shown in Fig. 4. Table III shows detailed data of Fig. 3. This paper determines the following parameters in solving this case: the crossover probability factor Cr=0.4, mutation factor F=0.2, maximum iteration for the chaotic migration $kmax$=16, population size Np=120, external population size Na=60, evolution generations GN=1500.
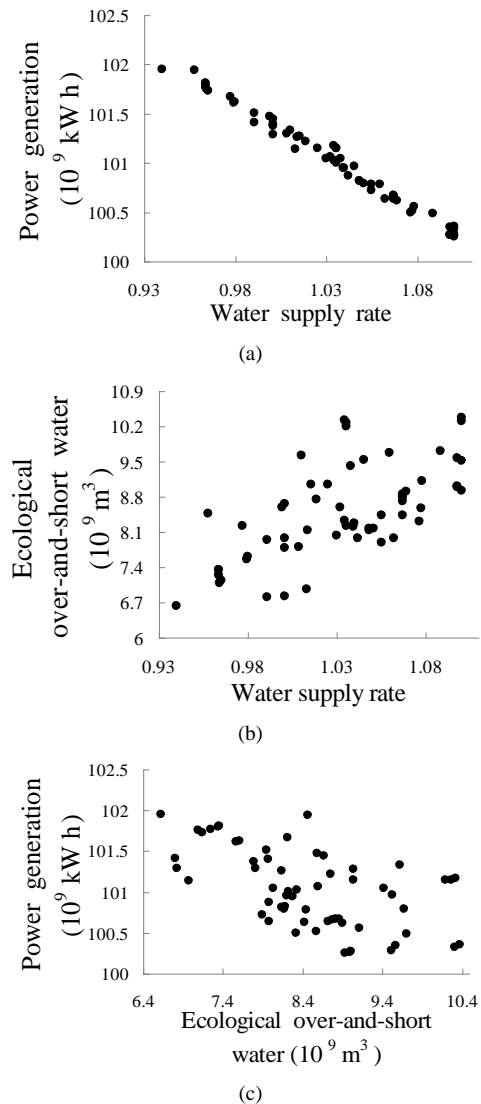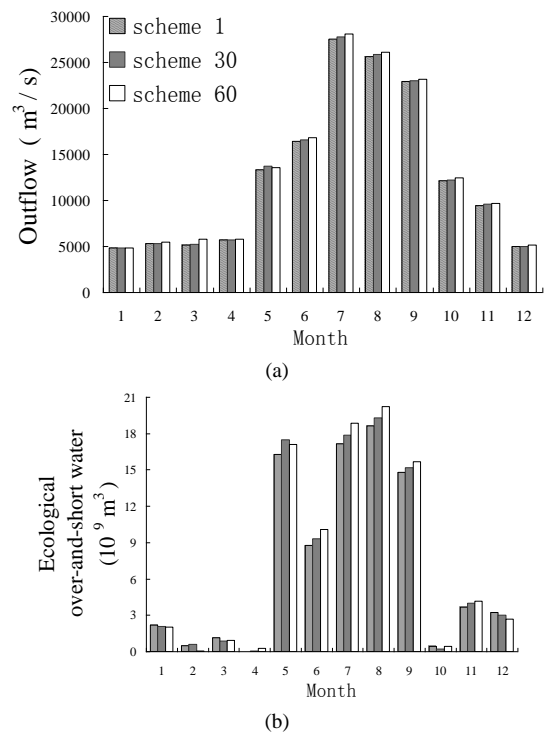

(a)

(b)

(c)

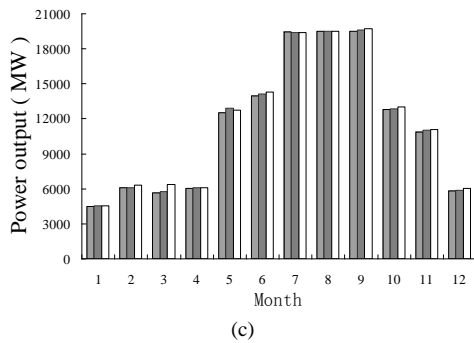Fig. 4. The projections of Fig. 3(a).

(a)

(b)

Fig. 5. The sequences of outflow (a), ecological over-and-short water (b) and power output (c) of NO.1, 30 and 60 schemes.

It can be seen through Fig. 4 that there is clear inverse relation between the cascade generation and the water supply, as they are conflicting and restrict each other. With the increase of power generation, the ecological over-and-short water mainly increases, that is, the ecological benefit reduces, which means that the cascade power generation and the ecological benefit are opposite. With the increase of water supply rate, the ecological over-and-short water mainly increases, which indicates that the water supply benefit and ecological benefit are opposite as well.

The result sequences of the NO.1, 30 and 60 schemes are shown above, the water supply rates are respectively 1.1, 1.03 and 0.94. First, in the dry season, the scheme with higher water supply rate has smaller outflow which increases the ecological water shortage, on the contrary, the ecological overflow decreases in the flood season. Secondly, it can be seen from Fig.5 (b) that the high water supply rate makes the power output reduce obviously. Finally, sharp contradiction between ecological and economic benefit is indicated from Fig.5 (a) and (c). This paper uses 40% and 60% typical inflows for calculation. It can be seen through Fig.3 that the value range of 40% inflow is wider than the 60% inflow in the power generation, ecological benefit and water supply. So in the case of larger inflow, the cascade can have more space of coordinating and optimizing the dispatch.

VI. CONCLUSIONS

Taking the generation benefit, ecological over-and-short water and water supply rate as the objective, this paper builds the EWSB-MODM. In addition, this paper formulates the criteria of the ecological benefit for the above model with the monthly frequency method and some key ecological factors in the lower reaches of the Yangtze River. According to the water demands in the upper reaches, this paper also obtains the criteria of the water supply benefit. Finally, this paper introduces the multi-objective differential evolution algorithm to solve the optimal dispatch model, providing a new idea for the reasonable dispatching of water resources.

VII. CONCLUSION

A conclusion section is usually required. Although a conclusion may review the main points of the paper, do not replicate the abstract as the conclusion. A conclusion might elaborate on the importance of the work or suggest applications and extensions.

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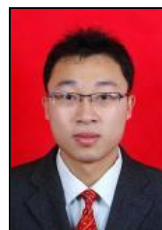
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