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ORIGINAL PAPER

Optimized operation of diversion-type hydropower reservoir to alleviate ecological degradation of the de-watered river reach

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Abstract
Diversion-type hydropower stations usually cause seriously de-watered situation of the natural river reach, which has adverse effects on the downstream river ecosystem. To alleviate the negative impacts on ecosystem of natural river reach, this study quantified the ecological requirements and incorporated them into the reservoir operating schemes to provide the ecological flow, which is beneficial to the balance between ecosystem protection and hydropower generation. The method mainly includes (1) propose an optimal ecological flow calculation method based on runoff probability distribution, (2) combine minimum ecological flow with optimal ecological flow to define the ecological protection degree, and then (3) establish the multi-objective optimization model of reservoir with the goal of maximizing ecological protection degree and power generation (DPM) and solve it with NSGA-II. In the meanwhile, the optimization model with the goal of minimizing ecological water shortage and maximizing power generation (SPM) was established and solved which was regarded as a control batch. A case study performed with the Liujiaping (LJP) reservoir in Hunan Province of South China demonstrates that optimized operation can play a protective role in the ecology of the dewatered section. And DPM has better ecological benefits than SPM under the same power generation benefits, especially when the emphasis is placed on ecological benefits.

Keywords Ecological protection degree · Optimal ecological flow · de-watered river reach · LJP reservoir

Introduction

Reservoirs are one of the most effective tools for integrated water resources development and management. By changing the temporal and spatial distribution of runoff to meet the requirements of water supply, flood control, power generation, etc., they also have adverse effects on the downstream river ecosystem at the same time. Therefore, it is necessary to integrate the ecological demands into the reservoir operation plan. Over the past decades, researchers have attempted to balance human needs and environmental flow requirements to develop optimal reservoir facility operating schemes. Some of the studies proposed operating the reservoir in an ecological friendly manner by incorporating a constraint of a constant minimum ecological flow (Castelletti et al. 2008; Chen et al. 2015). This method implicitly gives lower priority to ecosystems than to human needs (Yin and Yang 2011). Ouarda and Labadie (2001) reviewed methods used for optimizing reservoir operations and pointed out that the environmental considerations included in reservoir operation are legal requirements (e.g., minimum flow releases), which could be represented as constraints. Chen et al. (2013) considered an ecological hydrograph, which was calculated with the habitat model developed by Li et al. (2011), as the constraint to adapt reservoir operation. Xu et al. (2017) added an ecological constraint to the multi-objective optimization model of reservoir operation to restore fish migration passage in the reservoir. Moreover, some scholars regard the ecological factor as an objective for research rather than as a constraint. Poff et al. (1997) argued that ecological flow should consider seasonality of the natural flow regime. Homa et al. (2005) minimized the disparity between the natural and reservoir ecological release to improve the satisfaction of ecological flow requirements. Szemis et al. (2014) included an objective function to minimize the difference in environmental flow operations between time steps accounting for updated

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environmental allocation forecast information. Wu et al. (2012) and Fang et al. (2017) established the multi-objective ecological operation model with the minimum ecological water shortage as the ecological objective.

In addition, another important issue in the study of ecological operation is the determination of ecological flow. At present, the research methods of ecological flow mainly include hydrological, hydraulics, habitat simulation, and holistic methodologies (Tharme 2003; Wang et al. 2016; Ye and Bai 2014). In particularly, the hydrological methodology is extensive while the hydraulics methodology requires specific river characteristic data (Shokoohi and Hong 2011); the habitat simulation methodology requires a lot of field work and is difficult to guarantee the accuracy of the data (Gibbins et al. 2001; Wilding et al. 2014); the holistic methodology requires multidisciplinary data such as fish ecology, limnology, botany, and so on (Mazvimavi et al. 2007).

There are many medium and small hydropower stations, especially diversion-type hydropower stations in southwestern China. They bring economic benefits along with seriously de-watered situation of natural rivers; it is necessary to incorporate ecological requirements into reservoir operation for the restoration of ecological environment. The current ecological operation model of reservoir mostly takes the ecological demand as a constraint or takes the minimum of ecological water shortage as an ecological objective. However, when the river flows below or above the ecological flow requirements under the operation of the reservoir, how to measure the effect of ecological protection needs to be further studied. In addition, because most of the rivers lack the ecological data, river cross-section and other relative data, hydraulics, habitat simulation, and holistic methodologies are difficult to implement; thus, hydrological methods are more suitable for its ecological flow calculation.

The present paper determines the optimal ecological flow according to the natural runoff distribution, defines the ecological protection degree as a quantified ecological target, and proposes a multi-objective ecological optimal operation model of reservoir which was capable of improving power generation and ecological conservation and alleviating ecological degradation as much as possible. Then, a case study is performed with Liujiaping (LJP) hydropower station in the Erdu River basin in southwestern China. Pearson type III probability distribution is initially used to develop the relationship between the flow and ecological protection degree. The optimization model with the goal of maximizing annual average ecological protection degree and power generation (DPM) is established and solved. In addition, the optimization model with the goal of minimizing ecological water shortage and maximizing power generation (SPM) is regarded as a control batch. Finally, the results obtained by different models are analyzed and discussed.

Research area and data

LJP hydropower station is located at the Erdu River basin in Hunan province, China. The distance from the hydropower station to Xupu County is 85 km. The control area and the total storage capacity of LJP reservoir are 53.63 km^2 and 33.652 million m^3, respectively. LJP Power Station is a diversion-type hydropower station with multi annual regulation ability. It is a medium-sized water conservancy project which takes power generation as its main function. The basic parameters of LJP reservoirs are shown in Table 1.

Figure 1 depicts the configuration of the LJP reservoir and the de-watered river reach. LJP reservoir has a 43.5-m-high masonry gravity dam, which can provide about 480 m energy head by shortcutting a 3.77 km long of the natural river (Liujiaping River Reach) through diversion tunnels. The diversion-type power plant of LJP reservoir is located at the end of the diversion tunnels. The discharge of LJP reservoir is diverted through diversion tunnels to the turbines of the LJP power plant. Only when the normal water level is reached and the inflow is higher than the turbine capacity, the surplus water is discharged to the natural river reach from the spillway of the LJP dam. In the absence of remediation measures, the operation of the reservoir dramatically reduces the flow in the 3.77-km-long natural river reach, and even causes dried-up sections. This seriously damages the habitat of the aquatic organisms in the dewatered river channel. The situation is the most serious during the dry period (October to next March), because inflow is lower and the reservoir manager is the most reluctant to release any water to the river channel. In order to protect the river ecosystem and the fish habitats, a certain amount of ecological flow must be dedicatedly released into the de-watered river reach through the spillway of LJP reservoir.

The inflow data were collected at the dam site of LJP reservoir on a monthly basis from April 1987 to March 2019 (Fig. 2).

Methodology

Ecological flow

Ecological flow is an amount of water required to maintain the ecological function of the river under certain water quality standards (Guo et al. 2011; Jager and Smith 2008; Suen 2011) Ecological runoff is a continuous change process of ecological flow over time (Jie et al. 2007), which emphasizes the changing characteristics of ecological flow on the temporal and spatial scales corresponding to the changes of natural runoff during the year, and reflects the ecological requirement of rivers in different periods (Wang et al. 2013).

Table 1 Basic parameters of LJP hydropower station

Properties	Value	Properties	Value
Regulation ability	Multi annual regulation	Available storage (10^6 m^3)	33.12
Normal water level (m)	1180	Turbine installation (MW)	63*3
Dead water level (m)	1146	Head loss (m)	$0.903q^2$
Output efficiency	8.43	Maximum turbine release (m^3/s)	4.74

Note: q is the turbine release of hydropower station

(1) Minimum ecological flow

The minimum ecological flow reflects the minimum demand of the river ecosystem, which means that the minimum flow in the river can meet the ecological requirements of the current situation. If the flow is lower than the minimum ecological flow, the river water body will degrade or dry up (Shang 2015). In this paper, the minimum ecological flow required by the river is calculated using the month-by-month minimum ecological runoff calculation method (Qiang et al. 2010; Yu et al. 2004). Specifically, the minimum natural monthly flow series is taken as the minimum ecological flow of the month.

(2) Optimal ecological flow

The optimal ecological flow is the most appropriate flow for the stability of the river ecosystem and the conservation of species diversity. The demand of river for ecological flow varies dynamically over time, and the ecological release of river through the reservoir operation should be as close as possible to the natural flow process.

The optimal ecological flow is defined as the highest frequency of natural flow for each period in this study. The calculation method is as follows: (1) using Pearson type III probability distribution which is commonly used in hydrological calculations to fit the long series of historical runoff data (Kroll and Vogel 2002), then obtaining the flow-probability curve in each period. (2) Taking the flow corresponds to the vertex of the flow-probability curve as optimal ecological flow, as shown in Fig. 3.

Ecological protection degree

As the requirements of the river on the ecological flow vary from time, the same ecological flow in different periods is with different ecological benefits. Based on the minimum

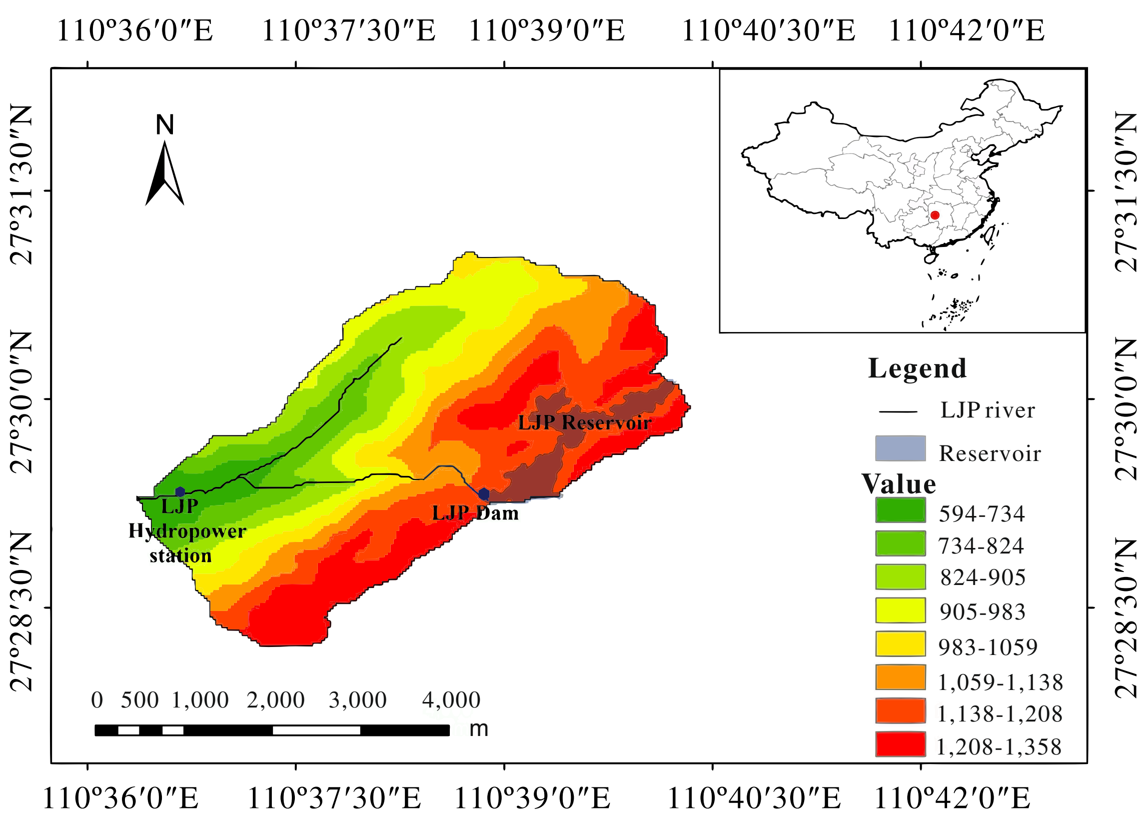
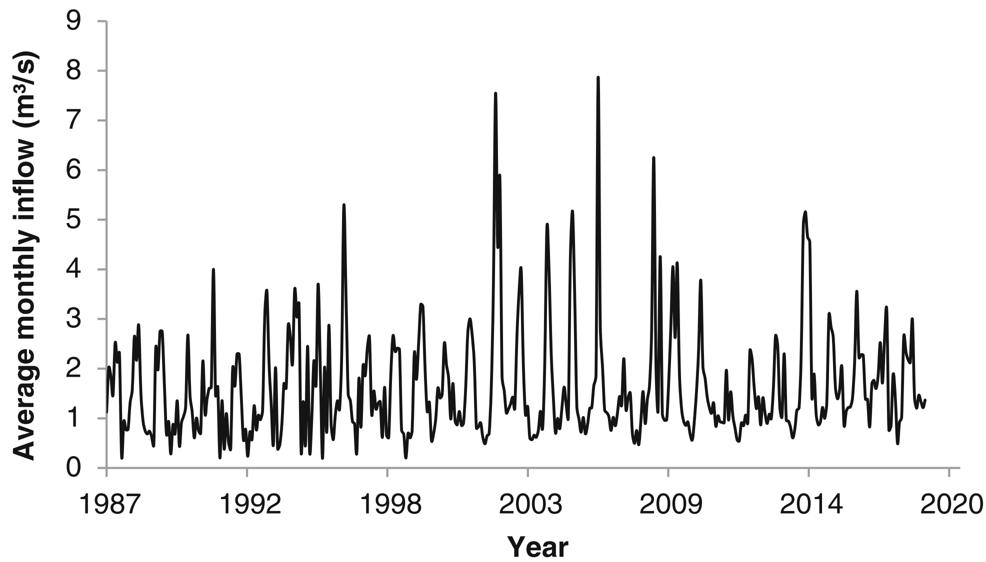


Fig. 1 Sketch map of LJP hydro junction

Fig. 2 Average monthly inflow of LJP reservoir



ecological flow and optimal ecological flow in different periods, this paper defines ecological protection degree to measure the ecological protection effect of ecological flow on the river, as shown in Eqs. (1), (2), and (3)

$$R_t = \begin{cases} 0, & Q_t < Q_{t,\min} \\ f(Q_t)/f_{t,\max}, & Q_t \geq Q_{t,\min} \end{cases} \tag{1}$$

$$f(Q_t) = \frac{\beta^\alpha}{\Gamma(\alpha)}(x-a_0)^{(\alpha-1)}e^{-\beta(x-a_0)} \tag{2}$$

$$f_{t,\max} = \frac{\beta^\alpha}{\Gamma(\alpha)}\left(Q_{t,d}-a_0\right)^{(\alpha-1)}e^{-\beta\left(Q_{t,d}-a_0\right)} \tag{3}$$

where R_t is the ecological protection degree corresponding to the discharge of hydropower station during the period t; $Q_t$is the reservoir release to the de-watered river during the period t (m^3/s); $Q_{t,\ \min}$and$Q_{t,\ d}$are the minimum ecological flow and the optimal ecological flow of de-watered river during the period t (m^3/s), respectively; $f(Q_t)$ is the probability when the flow of the river is Q_t in the natural state;$f_{t,\ \max}$ is the probability when the flow of the river is$Q_{t,\ d}$ in the natural state; α,$\beta$and$a_0$are the shape, scale, and position parameters of the Pearson type III probability density curve, respectively.

Figure 4 shows the relationship between ecological flow and ecological protection degree. The ecological protection degree is set to 0 when the ecological flow is lower than the minimum ecological flow. And the ecological protection degree is set to 1 when the ecological flow is the optimal ecological flow. In addition, the ecological protection degree decreases with the increase of the ecological flow when the ecological flow exceeds the optimal ecological flow; this is because that excessive flow could also have adverse effects on the river ecosystem (Li et al. 2015; Orth and Leonard 1990).

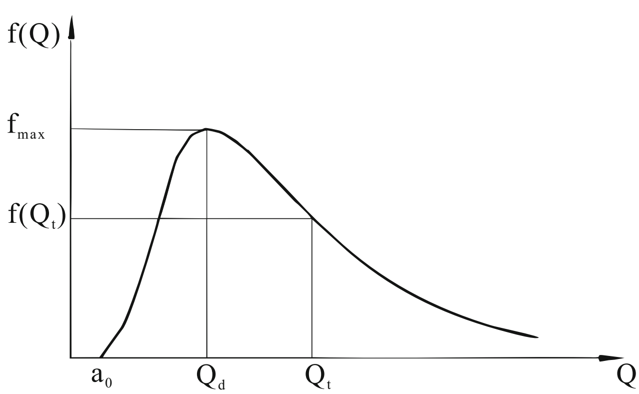


Fig. 3 A schematic for flow-probability curve

Multi-objective ecological reservoir operation model

The reservoir optimization model is proposed to determine the release to meet the ecological requirements as far as possible and to provide reliable amounts of hydropower as well. Generally, the optimal operation model of reservoirs consists of objective function, constraints, and optimization algorithm.

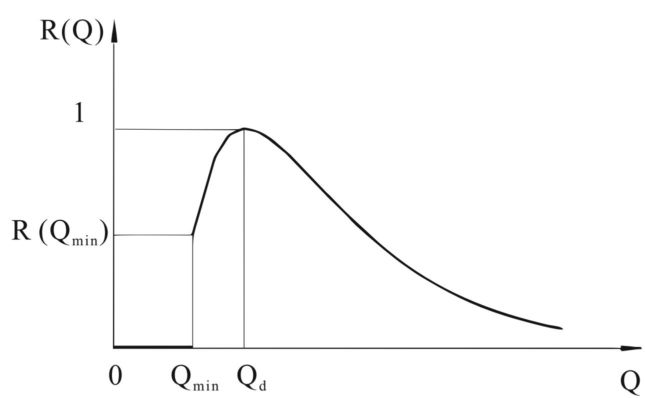


Fig. 4 The relationship between ecological flow and ecological protection degree

Objective functions

Hydropower generation and ecological conservation are the main objectives of LJP reservoir. Thus, the following two objective functions are considered in the proposed optimization model.

Ecological objective The ecological objective of DPM model proposed in this study is to maximize the degree of ecological protection, which is a relative index. And SPM aims at minimizing ecological water shortage, which is an absolute index and has been used by many scholars in reservoir ecological dispatching. They are shown in Eqs. (4) and (5)

a. Ecological objective of DPM: maximizing ecological protection degree

$$\max F = \max \frac{1}{T} \sum_{t=1}^{T} R_t, \quad t = 1, 2, \cdots, T \tag{4}$$

where F is the average ecological protection degree, T is the total time steps, and R_t is the ecological protection degree corresponding to the discharge of hydropower station during the period t.

b. Ecological objective of SPM: minimizing ecological water shortage

$$\min W = \min \sum_{t=1}^{T} \left| Q_t - Q_{t,d} \right| \times \Delta t, , \quad t = 1, 2, \cdots, T \tag{5}$$

Power generation objective

$$\max E = \max \sum_{t=1}^{T} A q_t H_t \Delta t, \quad t = 1, 2, \cdots, T \tag{6}$$

where$E$(kW·h) is the power generation, T is the total time steps, q_t(m^3/s) is the turbine release of hydropower station during the period t, A is the output efficiency of hydropower station, H_t(m) is the average water head of hydropower station during the period t, and Δt(s) is the time step.

Constraints

The following constraints are considered in this study:

(1) Water balance constraints

$$S_{t+1} = S_t + (W_t - U_t) \times \Delta t \tag{7}$$

where S_t, S_{t+1}(m^3) are the storage at the beginning and end of the period t, W_t(m^3/s) is the inflow during the period t, and U_t(m^3/s) is the outflow during the period t .

(2) Reservoir storage limits

$$S_{\min} \le S_t \le S_{\max} \tag{8}$$

where $S_{\min}$(m^3) and $S_{\max}$(m^3) are the minimum and maximum storage limits, respectively.

(3) Output constraints

$$N_{\min} \le N_t \le N_{\max} \tag{9}$$

where N_t(W) is the power output of hydropower station during the period t, and $N_{\min}$(W) and $N_{\max}$(W) are the minimum and maximum power output of hydropower station, respectively.

(4) Outflow constraints

$$q_{\min} \le q_t \le q_{\max} \tag{10}$$

where q_t(m^3/s) is the generating flow during the period t, $q_{\min}$(m^3/s) and $q_{\max}$(m^3/s) are the minimum and maximum flow allowed by the turbine, respectively.

The NSGA-II

The non-dominated sorting genetic algorithm II (NSGA-II) is one of the widely used multi-objective optimization algorithm methods in many engineering fields (Ghodsi et al. 2016; Li et al. 2017). The initial version, non-dominated sorting genetic algorithm (NSGA) proposed by Srinivas and Deb (1995) could find multiple pareto-optimal solutions in one simulation run for multi-objective optimization problems. The NSGA-II proposed by Deb in 2002 is an improved version of NSGA, which uses the crowding distance to estimate the density of solution points and replaces the fitness sharing and retains the outstanding individuals to prevent the loss of good solutions. The NSGA-II consists of five operators: initialization, fast non-dominated sorting, crowding distance calculation, elite strategy, and genetic operators.

The non-dominated sorting divides the population into several layers according to the dominance relation. The first layer is the non-dominant individual set, the second layer is the non-dominant individual set with the first layer removed from the population, and so on. Crowding distance calculation refers to the algorithm that uses the crowding distance comparison operator to calibrate the fitness of individuals in each level after hierarchical sorting. Elite strategy refers to the algorithm that retains the outstanding individuals in the parent generation, while adding outstanding individuals in the offspring to ensure the diversity of the population. Genetic manipulation methods include selection, crossover, and mutation operators. The flowchart of NSGA-II is shown in Fig. 5, and more

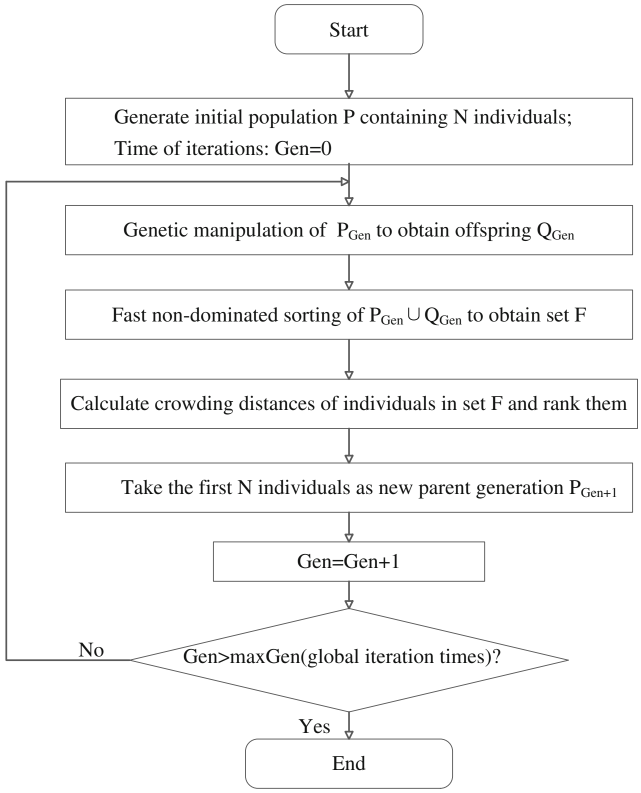


Fig. 5 The flowchart of NSGA-II

detailed process about NSGA-II can be found in previous study (Deb et al. 2002).

Results and discussion

Determination of ecological discharge

The minimum ecological flow in the de-watered river reach downstream of LJP reservoir is calculated by month-by-month minimum ecological runoff calculation method; the optimal ecological flow is obtained by fitting the historical flow using Pearson type III probability distribution. The results are shown in Table 2.

The wet period of the basin, where LJP power station is located, is from April to September, and the dry period is from October to March of the following year. As can be seen from Table 2, the minimum ecological flow of the river is generally below 0.5 m^3/s in the dry period due to its less runoff. During the wet period, the minimum ecological flow is increased to 1 m^3/s or more. The optimal ecological flow of the area is larger than the minimum ecological flow in each month, and the increase rate in the wet period is higher than that in the dry period. Therefore, it is necessary to optimize the allocation of water in the wet and dry periods, to meet requirements of ecological flow of the river downstream LJP reservoir and power generation benefit.

Optimization performance of LJP reservoir

The operation of LJP reservoirs from April 2004 to March 2019 is simulated using DPM and SPM. Thus, the total number of time steps is 180 months. The algorithm parameters of NSGA-II are as follows: the population size *N* is 600, the number of global iterations *maxGen* is 1000, the crossover probability is 0.9, and the mutation probability is 0.1. Specifically, crossover is to select two individuals from the population and exchange some coding bits of the two individuals according to a greater probability. It is the main method to generate new individuals, which reflects the global search ability of the algorithm. Variation generates new individuals by changing some coding bits of individuals according to a smaller probability, which determines the local search ability of the algorithm. The results are shown in Table 3. And the average annual power generation, average ecological protection degree, and average ecological discharge are multi-year averages from April 2004 to March 2019.

From Table 3, it can be seen that different operation schemes have different focus extent between ecological benefits and power generation benefits. As the ecological conservation degree increases, the average annual power generation of LJP reservoir decreases. In general, the ecological conservation degree under DPM is higher than that under SPM when they have the same amount of power generation; correspondingly, the ecological discharge under DPM is slightly larger than SPM. When the operation schemes have the same ecological discharge under DPM and SPM for the de-watered river reach, the ecological protection degree of DPM is usually higher than the ecological protection degree of SPM (for example, the operation schemes with the average annual power generation of 53 million kW·h), which indicate that the ecological flow under DPM is more appropriate to de-watered river reach. In addition, when the operation scheme

Table 2 Calculation results of ecological flow m^3/s

Ecological flow	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Minimum ecological flow	0.31	0.36	0.42	0.52	0.75	0.91	1.03	0.73	0.54	0.41	0.36	0.32
Optimal ecological flow	0.39	0.63	0.78	1.12	1.49	2.35	2.54	1.4	0.87	0.68	0.4	0.41

Table 3 The simulation results of LJP reservoir operation based on different models

Average annual power generation (10^6 kW·h)	Average ecological protection degree		Average ecological discharge (m^3/s)		Incidence rate(R = 0) (%)	
	DPM	SPM	DPM	SPM	DPM	SPM
59	0.16	0.12	0.29	0.24	64.4	80.7
57	0.19	0.16	0.34	0.29	59.3	74.9
55	0.21	0.20	0.37	0.36	53.7	70.7
53	0.25	0.23	0.40	0.40	51.8	66.8
51	0.28	0.27	0.42	0.45	49.3	62.5
49	0.37	0.33	0.49	0.50	26.2	55.6
47	0.41	0.36	0.58	0.55	13.5	53.1
45	0.45	0.40	0.65	0.63	5.6	48.1
43	0.50	0.45	0.70	0.68	4.3	44.9
41	0.53	0.48	0.74	0.73	2.5	41.7

Note: R is the ecological protection degree

focuses on the power generation benefit, the gap between the two models on the downstream ecological protection is not significant, but when the operation scheme focuses on ecological benefits, ecological protection benefits under DPM have improved significantly compared with SPM at the same power generation, as shown in Fig. 4.

The situation in which the ecological protection degree is 0 in this study is referred to ecological damage. Figure 6 shows that when the average annual power generation is above 50 million kW·h, the average ecological protection degree of the two models is close, and the ecological damage frequency of DPM is about 15% lower than that of SPM. With the increase of preference to ecological benefit, the ecological protection degree of the DPM to the de-watered river reach is obviously increased, and the ecological damage frequency can be reduced by 40% compared with SPM. Furthermore, we selected operation schemes of which the power generation are 45 million kW·h for specific analysis.

The DPM results in a 5% increase in annual ecological conservation degree and a 43% decrease in ecological damage frequency compared with SPM. Figure 7 shows that except July, November, and February, the monthly average ecological protection degree of other months under DPM is higher than SPM. In addition, DPM contributes to monthly average ecological protection degree with a smaller difference within a year, with a minimum monthly average ecological protection degree of 0.44, while the minimum monthly average ecological protection degree of SPM is 0.29.

The distribution of ecological conservation degrees in different months among DPM results, SPM results, and natural runoff at LJP river is shown in Fig. 8. There is a steady trend in the ecological conservation degrees of DPM, mostly with the figure from 0.4 to 0.5, except for a few occasions that it was above 0.7 in June, July, and August and below 0.1 in September and December. The distribution of ecological protection degree of SPM results was relatively scattered, and there are many months in which the ecological protection degree is 0, which could not effectively protect the ecological environment of the de-watered river reach. In the case of natural runoff, the scattered extent of ecological protection degree is between that in DPM and that in SPM. The ecological protection degree arrives at a higher level since all incoming water enters into the natural river.

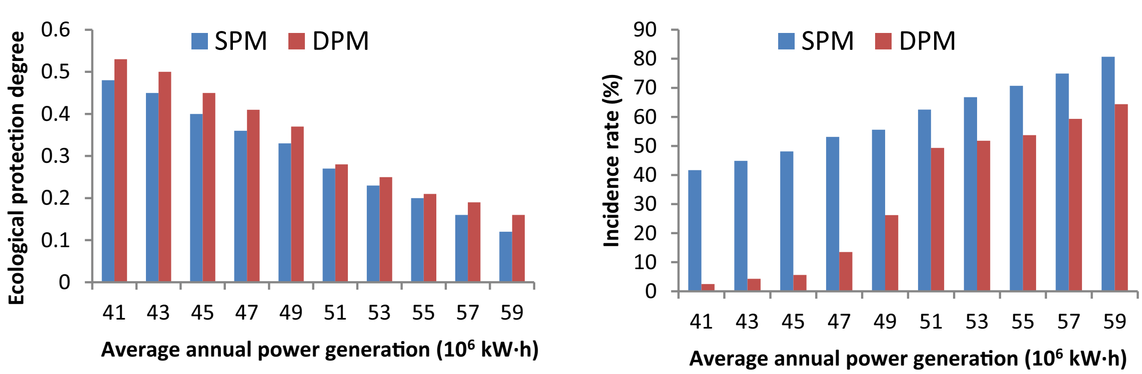


Fig. 6 The relationship among average annual power generation, ecological protection degree, and ecological damage frequency of LJP

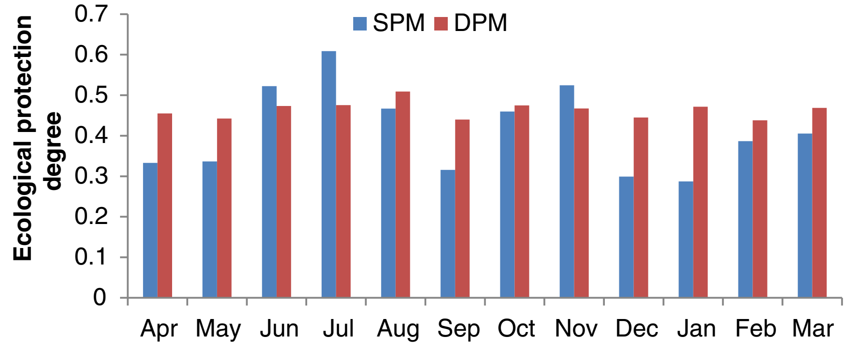


Fig. 7 Monthly average ecological protection degree of different schemes

The ecological flows under different models are shown in Fig. 9. It shows that ecological flow is rarely more than the optimal ecological flow both under DPM and SPM, because the ecological flow of de-watered river reach does not enter the turbine. During the whole study period, the ecological flow under DPM generally satisfies the requirement of minimum ecological flow and is closer to the optimal ecological runoff compared with SPM. The ecological flow obtained by

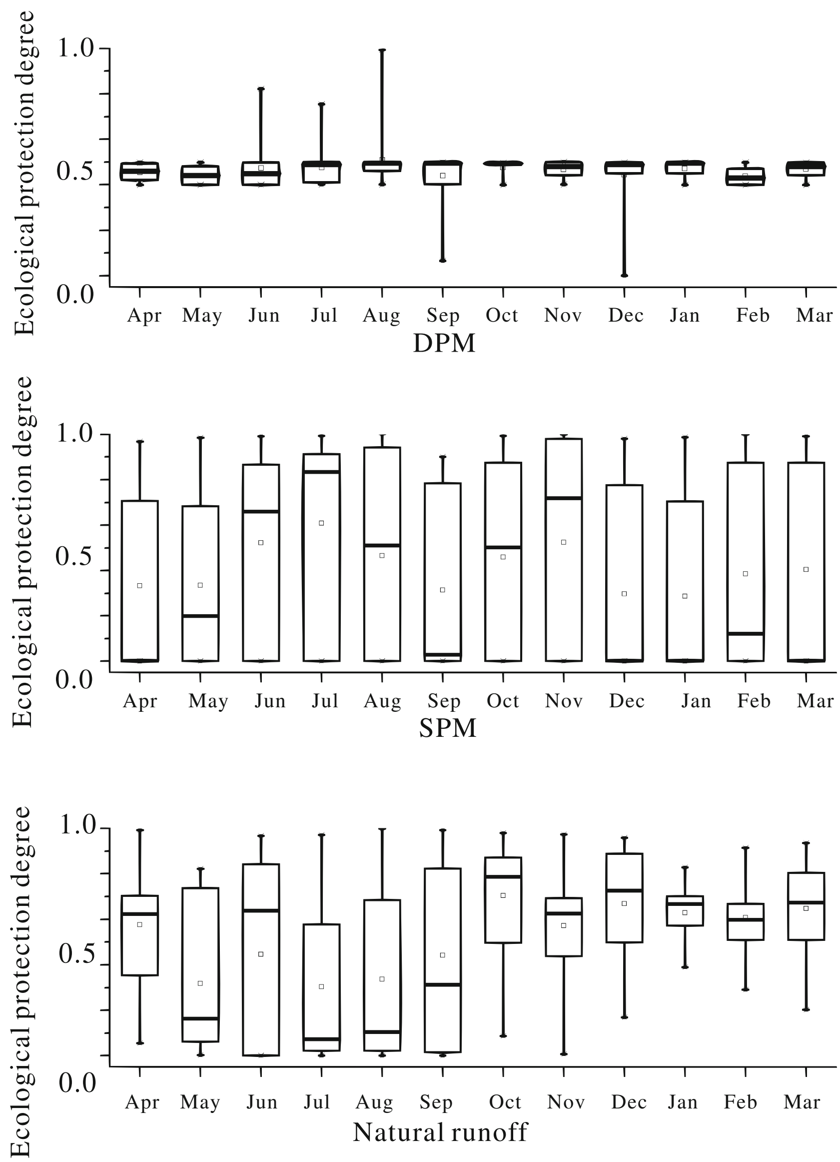


Fig. 8 The distribution of ecological conservation degrees in different months

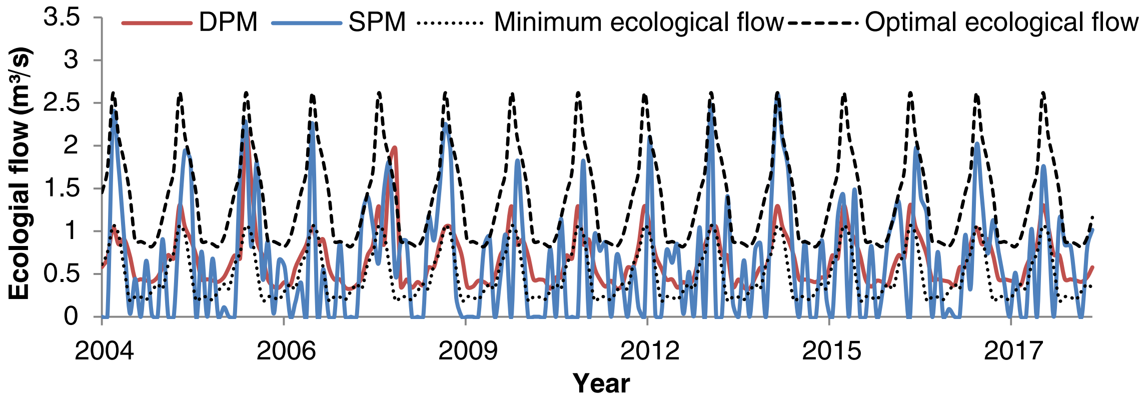


Fig. 9 The ecological flow under different models

SPM varied greatly within a year. There are several months of ecological flow that optimal ecological flow can be achieved, while more than a few months cannot meet the minimum ecological flow requirements, especially in dry period, the phenomenon of non-ecological flow frequently appears.

Considering the ecological objective of the minimum ecological water shortage, SPM only focuses on the minimum ecological water shortage during the whole dispatch period without taking ecological water shortage in the specific time period into consideration. Therefore, there will be no ecological flow in some months. For DPM, ecological protection degree is a segmentation function of ecological flow. When the ecological discharge is lower than the minimum ecological flow, the degree of ecological protection directly falls to 0, which will have an obvious effect on the overall ecological protection level. Therefore, when the scheduling scheme focuses on ecological benefits, the ecological discharge could meet the minimum ecological flow requirements. So that the DPM is better than the SPM in protecting the ecological environment of de-watered river reach in the same power generation efficiency.

Conclusions

For the hydropower reservoir lacking ecological data, compared with SPM, the ecological objective of DPM is maximizing ecological protection degree rather than minimizing ecological water shortage, which can effectively reduce the situations of non-ecological flow of rivers, and is more conducive to the ecological protection of rivers. A case study was performed with LJP reservoir, some important conclusions can be drawn from this study.

(1) With the increasing emphasis on the ecological benefits of the power station, the ecological protection degree increased, correspondingly, the ecological water supply increased, while the power generation decreased.
(2) For the diversion hydropower station, there is a competitive relationship between the generating flow and the discharge flow of the reservoir to de-watered river reach, which causes the ecological flow rarely exceeds the optimal ecological flow.
(3) When the operation focuses on ecological benefits, ecological protection degree under DPM has improved significantly compared with SPM at the same power generation. In addition, the ecological flow under DPM generally satisfies the requirement of minimum ecological flow and is closer to the optimal ecological runoff compared with SPM. In a word, DPM is better than the SPM in protecting the ecological environment of de-watered river reach in the same power generation.

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