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Cascade hydropower plants operation considering comprehensive ecological water demands

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ABSTRACT

Hydropower plants operation may change river flow, thereby degrading the stability of river ecosystems. The primary purpose of this paper is to compute the comprehensive ecological water demand and establish ecological operation models to quantitatively analyze the interactions between power generation and degree of ecological flow satisfaction under different operation modes. The comprehensive ecological water demand takes the river base flow, ecological flow process and ecological water demands of fish habitat during the spawning period into account. The driest monthly streamflow under a 90% frequency method, range of variability approach and two-dimensional depth-averaged finite element model were adopted to obtain the ecological flow. In addition, to study the impacts of the ecological operation of hydropower plants on power generation, three optimal operation models including a maximum power generation model (Model-I), a minimum ecological change model (Model-II) and a multi-objective optimization operation model (Model-III), are established. In model-II, the average annual power generation of the cascade hydropower plants decreased by 10.61% compared with Model-I, and meanwhile the degree of ecological change reduced by 75.41%, which means, the reduction of power generation by 35.66×10^8 kWh could lead to a reduction of 11.4% on the degree of ecological degradation. Afterwards, the multi-objective problem of economic and ecological benefits in model-III was solved by the application of NSGA-II. Among them, scheme 3 is recommended for Model III, and its power generation and degree of ecological change are 311.69×10^8 kWh and 6.64%, respectively. In general, mutual restrictions and conflicts between power generation and ecological demand are inevitable, but they can be optimized through multi-objective ecological operation models to fetch the coordinated development of economy and ecology.

1. Introduction

The primary goals of most of the current hydropower plant group operation models are to reconcile with the benefits of flood control and power generation, with the goals for maximizing the utilization of water resources and economic benefits. There are insufficiencies considering on the ecological protection requirements of downstream rivers in the related operation schemes; as a result, great changes in ecological factors such as river discharge, water temperature and water quality in downstream river have led to different degrees of damage to river ecosystem and evolution. In order to alleviate the ecological changes in the river, many experts and scholars have carried out a series of related research. Yin et al. [1] provided a series of management measures for ecological flow downstream of the dam, and Chen et al. [2] proposed a time-nested method to derive a daily reservoir operation plan considering downstream ecology. Hence, it is of great necessity to study the multi-objective hydropower plants operation based on ecological operation by integrating ecological objectives into the operation process, which also provides key technical support for research on hydropower plant operation [3].

In recent years, the goals for optimal hydropower plant operation are gradually shifting from single objective to multiple objectives. Since the theory that hydropower plants operation should maintain river diversity, firstly proposed by Schluter, some scholars have made different attempts afterwards in this field [4]. Carriaga and Mays simulated the movement of sediment aiming to minimize the changes in the lower reaches of a hydropower station by using a differential dynamic programming method coupled with the HEC-6 model [5]. To restore

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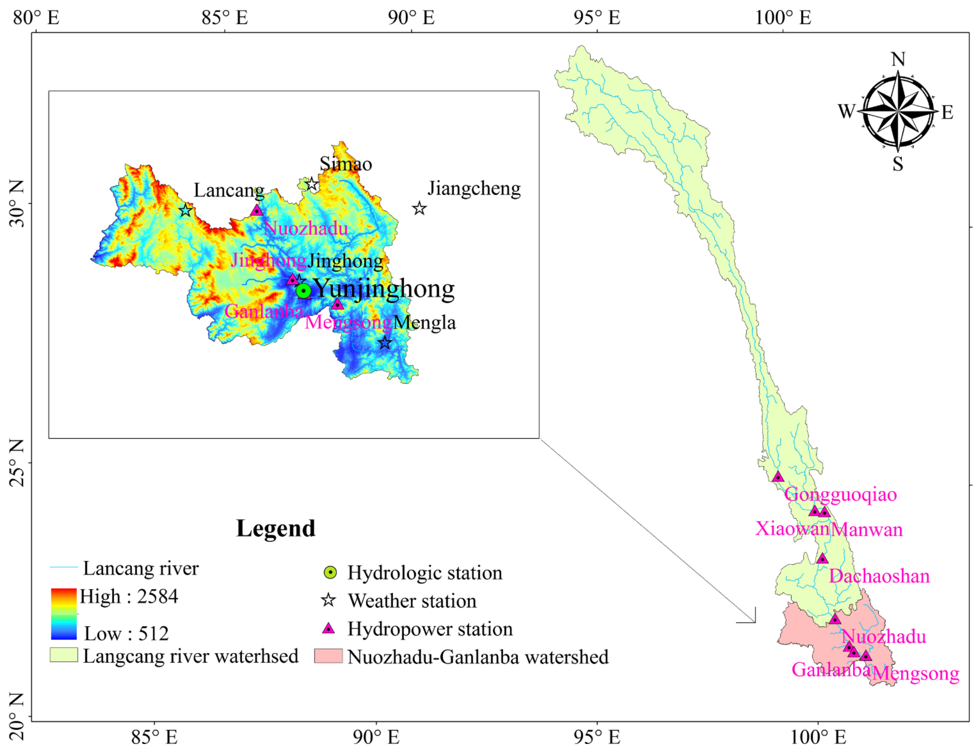


Fig. 1. Location of the study area, hydropower stations and the hydro-meteorological stations.

fish migration routes, some scholars have proposed corresponding countermeasures. In specifically, King [6] proposed artificial flood peaks and Xu [7] proposed an eco-friendly technical operation schemes to ensure that the hydrodynamic characteristics and the discharge water temperature of the hydropower station meet the habitat requirements of fish. The fuzzy set method and artificial intelligence algorithms have been applied to ecological operation to identify the changes in natural streamflow conditions after hydropower plants operation and these methods can provide appropriate streamflow conditions for maintaining the floodplain ecology [8].

As the ecological water demand of a river occupies the prerequisite of ecological operation, scholars have increasingly adopted ecological streamflow to characterize the ecological water demands of rivers. Defined as the river streamflow, the ecological streamflow of rivers is suitable to maintain the health of river ecosystems and ensure the survival and development of human beings. Numerous techniques involving hydrological methods, hydraulic methods, and habitat simulation methods are often used to determine the ecological streamflow of rivers. There are many common hydrological methods, such as Tennant, 7Q10, 10%MAF and RVA methods. Tennant [9] proposed minimum ecological flow standards to assess river health. Boner [10] proposed that the 7Q10 method which uses the driest average streamflow of 7 days under the 90% guarantee rate as the minimum environmental flow required by the river. Operacz [11] proposed an environmental flow method for Polish hydropower stations after comparing several MAFs. Richter [12] put forward RVA method widely used in hydrology change assessments and water resource management. The most frequently used hydraulic methods are the wetted perimeter method and the R2Cross method, which determine the ecological water demands of rivers based on the river parameters [13]. Habitat simulation methods are used to calculate the ecological water demands of habitats based on the instream flow incremental method (IFIM) [14]. Additionally, the two-dimensional depth-averaged finite element model (River2D) [15], which is a type of IFIM, integrates river hydrodynamics and fish habitat simulation software to simulate the ecological water demands of fish. As a commonly used model, Pragana et al. applied the River2D model to obtain a 2D hydrodynamic description under various scheduling schemes [16]. Almeida et al. predicted the velocity suitability index for fish's shelter configurations with the River2D model [17]. Kuriqi adopted River2D model to establish the habitat modeling through hydrodynamic analysis [18].

In virtue of human society and ecosystems are both highly dependent on rivers of existence, water resources are unanimously precious wealth shared by human and ecosystems. Simultaneously, water conservancy projects are one of the threatening factors for river ecosystems. It is essential to establish new principles and develop new technical methods to enable water conservancy projects meeting the needs of human society. At the same time, it is of great significance to build an eco-friendly water conservancy engineering technology system taking the needs of river ecosystem health and sustainability into account. Therefore, in this paper, the lower reaches of the Lancang River were taken as an example, and a multi-objective hydropower plant operation focused on ecology is carried out. The comprehensive ecological water demand of the river is computed in consideration of three ecological factors; namely, the river base flow, the ecological streamflow process and the ecological water demands for fish habitat. The Lancang River basin is an international river and bears the tasks of economic development. Accordingly, it is essential to meet the navigable flow demands for cargo ships and cruise ships. In the light of the navigable flow demands of the Lancang River basin, the navigable streamflow designed for the area downstream of the Jinghong plant is 504 m^3/s [19]. At the same time, in this paper, three operation models are established, i.e., the maximum power generation model, the minimum ecological change model and the multi-objective optimization operation model. These models are established to quantitatively analyze the relationship between power generation and degree of ecological streamflow satisfaction in diverse operation modes, with the purpose of providing a scientific basis for the ecological restoration and protection of the lower reaches of the Lancang River.

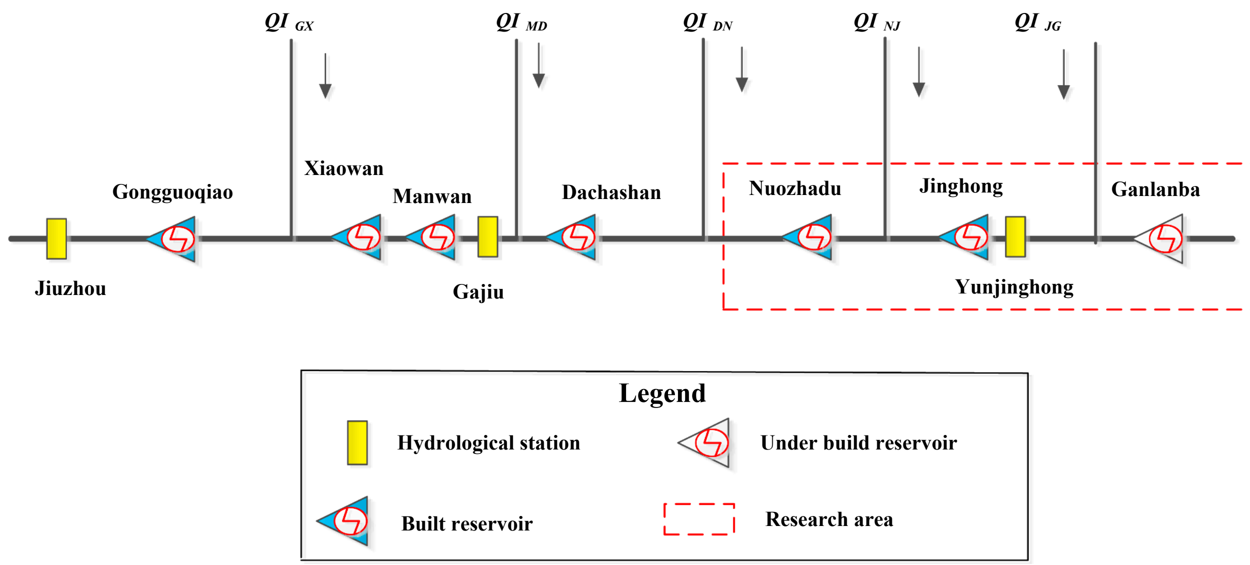


Fig. 2. Node diagram of the mainstream hydropower plants in the lower reaches of the Lancang River. QI stands for interregional inflow, and the corner marks represent the abbreviations of the two hydropower stations, such as GX stands for the abbreviation of Ganlanba and Xiaowan hydropower stations.

2. Study area and data used

The Lancang River (Fig. 1) originates in Qinghai Province of China and flows through Tibet and Yunnan Provinces. The Lancang River flows through Laos and Myanmar, where it is called the Mekong River. The total length of the mainstream is 4880 km, and the length of the Lancang River in China is 2139 km. The watershed area is 16.74×10^4 km^2 [20], and the average annual streamflow is 741.5×10^8 m^3. The mean annual precipitation and temperature are 1161.2 mm and 22 °C, respectively. The Lancang River has abundant water resources and is one of the most important water resources for strategic reserve areas in China. Power generation is one of the main tasks for the utilization of water resources in the Lancang River. The Lancang River is one of the thirteen hydropower bases in China and is the main force of clean energy. In the lower reaches of the Lancang River, eight hydropower plants are have been planned and developed. From upstream to downstream, these plants are Gongguoqiao, Xiaowan, Manwan, Dachaosha, Nuozhadu, Jinghong, Ganlanba and Mengsong (Fig. 2). The total installed capacity of the eight hydropower plants in the lower reaches of the Lancang River is approximately 16000 MW, and the average annual power generation is approximately 700×10^8 kWh. The downstream section of the Lancang River located below the Nuozhadu hydropower plant is selected as the research area, and the characteristic parameters of this region are shown in Table 1.

In this study, the natural monthly streamflow at the Nuozhadu and Jinghong hydropower plants from 1953 to 2013 and the natural daily streamflow (1953–2013) collected from the Yunjinghong hydrologic station are used to investigate and derive the hydropower plant operation and ecological changes. And the daily streamflow from 2010 to 2015 during hydropower plant operation were measured from Jinghong hydropower plant. The inflow of the Nuozhadu hydropower plant is shown in Fig. 3. The reach from the Ganlanba hydropower plant to the river outlet serves as a natural shelter and is a natural location for fish breeding because of the meandering and fast-flowing rivers and the typical canyon-shaped channel with reefs, which are suitable for fish spawning. Therefore, this paper selects the reach with these hydrological and hydraulic conditions as the habitat protection study area. The research area is located approximately 24 km downstream of the Jinghong hydropower plant with a length of approximately 4 km.

Table 1
Characteristics of three hydropower plants.

Indexes	Nuozhadu	Jinghong	Ganlanba
Dead water level (m)	765	591	535.2
Normal pool level (m)	812	602	539
Flood limited water level (m)	804	591	591
Total storage (10^8m^3)	237	11.39	0.313
Regulation ability	Multiyear	Seasonally	Daily
Guaranteed output (10^4kW)	2500	834	78
Installed capacity (MW)	5850	1750	155
Annual power generation (10^8 kW•h)	239.12	63.62	8.7
Maximum flow of unit (m^3/s)	3475.9	3170.3	3170.29

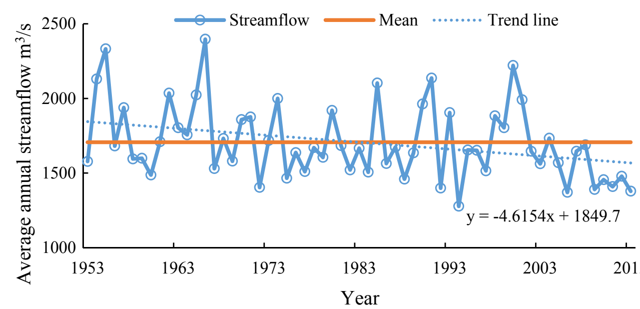


Fig. 3. The average annual streamflow of the Nuozhadu hydropower plant.

3. Methods

This study adopted three kinds of ecological water demand, namely the river base flow, ecological streamflow process line and ecological water demand of the fish habitat, to calculate the comprehensive ecological water demand based on the 7Q10, RVA and River2D models. In addition, for the solution method of the reservoir operation model, the genetic algorithm (GA) and the nondominated sorting genetic algorithm (NSGA-II) were utilized to solve the single-objective and multi-objective operation problems respectively.

3.1. Range of variability approach

During the long-term evolution process of the river ecosystem, aquatic organisms have adapted to the natural fluctuations of the river and are satisfied with these natural changes. Therefore, the integrity of the river system largely depends on the natural hydrological conditions of the river [21]. However, during the process of conquering and transforming nature, human beings have seriously damaged the natural streamflow regimes of rivers, which has resulted in the streamflow changes becoming not entirely dependent on seasonal precipitation [22]. The habitat of some rivers has been radically changed, which has had a profound influence on river ecosystems [23]. The RVA method, which is based on the indicators of hydrologic alteration (IHA), was proposed by Richter in 1996 and has been widely used in hydrology change assessments and water resource management [12]. The core idea of the RVA is to use long-term hydrological data ($\geq$20 years) with little or no human disturbance and essentially natural conditions as the basis for defining the range of changes in hydrological variables, and the mean $\pm$ Δ (standard deviation) or its range of 25–75% (that is, the threshold of the RVA) is taken as the ecological target to evaluate the degree of change in the IHA before and after the construction of hydropower projects [24]. The IHA are divided into five categories(33 indicators), including monthly flow, annual extreme flow and occurrence time, frequencies of high and low flow and flood fluctuations, can reflect the hydrological regimes of the river in a more comprehensive way. In view of the above problems, this paper uses the RVA to evaluate the degree of change in an ecosystem impacted by the operation of a hydropower plant compared with the natural conditions.

The specific hydrological change in each indicator is calculated by the following formula:

$$D_i = \frac{N_i - N_e}{N_e} \times 100\% \tag{1}$$

where D_i is the degree of change in each indicator; N_i is the actual number of years that fall within the range of the RVA threshold when the i index is affected; N_e is the number of years expected to fall within the RVA threshold when the i index is affected. $N_e = r{\cdot}N_T$, where r is the ratio of the indicator that falls within the RVA threshold before it is affected, and N_T is the total number of years after the indicator is affected.

To ensure an objective judgment standard forD_i, Richter suggests that $0\% < |D_i| < 33\%$ represents no change or a low degree of change, $33\% < |D_i| < 67\%$ represents moderate change and $67\% < |D_i| < 100\%$ represents high change [12]. The best conditions occur when the streamflow characteristics of the river are not changed ($D_i = 0\%$). The comprehensive degree of ecological change (D_0) is calculated by the following formula:

$$D_0 = \left[\frac{1}{33}\sum_{i=1}^{33} D_i^2\right]^{1/2} \tag{2}$$

3.2. Habitat simulation method

The River2D model is a two-dimensional hydrodynamic model that was developed by Steffler and Blackburn [15], and this model is based on the method of flow increases in a river channel. The effective habitat area for a target fish under different flow and water level conditions is simulated by River2D model. The River2D model is mainly composed of a two-dimensional hydrodynamic module and a physical habitat module.

3.2.1. Hydrodynamic module

The River2D model was found to be very effective in comparison to the 1D model, especially for spatially distributed phenomena. With the River2D model, Vasquez [25] investigated the patterns of sediment erosion, and Jooheon [26] analyzed the fish habitat quality under low discharge rates. The two-dimensional hydrodynamic model utilizes shallow-water equations based on Saint-Venant equations. The energy conservation equation and the momentum conservation equation in the directions of x and y are satisfied [27].

Energy conservation equation:

$$\frac{\partial H}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_x}{\partial y} = 0 \tag{3}$$

The momentum conservation equation in the directions of x and y:

$$\frac{\partial q_x}{\partial t} + \frac{\partial (Uq_x)}{\partial x} + \frac{\partial (Vq_x)}{\partial y} + \frac{g}{2}\frac{\partial H^2}{\partial x} = gH(S_{0x} - S_{fx}) + \frac{1}{\rho}\frac{\partial (H\tau_{xx})}{\partial x} + \frac{1}{\rho}\frac{\partial (H\tau_{xy})}{\partial y} \tag{4}$$

$$\frac{\partial q_y}{\partial t} + \frac{\partial (Uq_y)}{\partial x} + \frac{\partial (Vq_y)}{\partial y} + \frac{g}{2}\frac{\partial H^2}{\partial y} = gH(S_{0y} - S_{fy}) + \frac{1}{\rho}\frac{\partial (H\tau_{yx})}{\partial x} + \frac{1}{\rho}\frac{\partial (H\tau_{yy})}{\partial y} \tag{5}$$

where H is the water depth, U and V are the average velocities at the bottom in the x and y directions, respectively, q_x and q_y are the directions of flow in the x and y directions, respectively, g is the acceleration of gravity, ρ is the density of water. S_{0x} and S_{0y} are the gradients in the x and y directions of the riverbed. S_{fx} and S_{fy} are the corresponding frictional slopes. τ_{xy}, τ_{xx}, τ_{yx} and τ_{yy} are the components of the horizontal turbulent stress tensor.

3.2.2. Habitat module

The fish habitat component of the River2D Model is based on a two-dimensional simulation program developed by IFIM, and the weighted usable area (WUA) is the core of habitat evaluation in IFIM, representing the appropriate habitat area for fishes [28]. The WUA may not reflect the actual use area by fish, but it is a widely used indicator of the available area under appropriate management.

The habitat model uses the habitat suitability curve (HSC) to quantify the preference of a certain fish for habitat variables (velocity, depth and substrate) at specify life stages. The HSC is represented by the habitat suitability index (HSI). The range of the HSI is [0–1], and 0 indicates that the conditions are not suitable for survival, while 1 indicates that the conditions are very suitable for the survival of fish in the current state.

There are two primary ways to determine the HSC, one is determined by expert opinion or historical data records, and the other is to directly observe the habitat of a specific species at different life stages; that is, the occurrence frequency of the target fish in the area can be used as the basis for establishing a HSC. The combined suitability factor is calculated by using the HSC, and the method is as follows:

Product method:

$$CSF_i = V_i \times D_i \times C_i \tag{6}$$

Finally, the WUA of the habitat is calculated:

$$WUA = \sum_{i=1}^{n} CSF_i \times A_i \tag{7}$$

where CSF_i represents the combined suitability factor at grid i; n indicates the number of grids; A_i is the area of grid i; V_i is velocity indicator, D_i is the depth index, and C_i is the substrate index. This paper only considers the effects of velocity and depth, and does not consider the influence of substrate, so C defaults to 1.

In this paper, the MATLAB fuzzy controller toolbox is used to simulate the HSI of fish, and a fuzzy logic inference system based on Mamdani method is established [29]. The fuzzy set is defined and described by the membership function. The first step in fuzzy modeling is the fuzzification for the selected habitat variables (i.e. velocity and depth) by using the triangular and trapezoidal membership functions in order to describe the membership degree for the variable value in the fuzzy set [30]. Since the fuzzy set boundaries have a characteristic of overlapped, a value for the same habitat variable can come from different sets, in which the membership degree is between 0 and 1. Fish experts often use “very high”, “high”, “medium”, “low” and “very low” to describe fish's habitat preferences [31]. The fuzzy rule then defines the relationship between the habitat variables and the habitat suitability of each species. Finally, after establishing fuzzy habitat variables and fuzzy rules, the Mamdani method is used to defuzzify and obtain the HSI of fish. For more information on the construction of habitat fuzzy systems, please refer to [32].

3.2.3. Model parameters and simulation process

(1) Research area determination: the river section and indicative fish species are determined.
(2) Data input: the riverbank and riverbed terrain data, such as, the coordinates, elevation and roughness of each point, are added to the model.
(3) Boundary definition: the surface elevations (outflow boundaries) of the streamflow (river inflow) and outflow sections and the WUA of target fish under different flow and water level conditions are simulated by the River2D model in the selected modeling area.
(4) Grid division: the triangular meshes in the river section that is within the boundary range are divided.
(5) Boundary condition setting: the available habitat area under the corresponding state is obtained under different streamflow conditions (Fig. 4).

3.3. Optimization algorithm for hydropower plants operation

GA are a new class of optimization search algorithms that were proposed by Holland from the idea that originates from the survival of the fittest in nature and gene heredity [33]. Because of its simple operation and robustness, GA is widely applied in water resources optimization research. Pothiya used GA algorithm and multiple tabu search algorithm to solve the dynamic economic scheduling problem [34]. Yu combined GA and hybrid particle swarm optimization to predict the annual electricity demand [35]. The search space and solution space for solving problems is the mapped genetic space. The mapped genetic space encodes every possible solution as a vector (binary or decimal numeric string) that is called a chromosome or individual, and all chromosomes constitute a group (the number of chromosomes in a group is expressed by population). For the optimal operation of hydropower plants, GA can interpret that the water level during the operation of the hydropower plants can be represented by the random selection of populations as the parents. Then, the fitness function of each chromosome is calculated according to the predetermined objective function, and this function guides the selection, crossover and mutation of all chromosomes to eliminate chromosomes with low fitness and obtain a new population that meets some predetermined optimization and convergence index. In this paper, GA is used to solve Model-I and Model-II, and detailed information on the GA can be found in Chang et al. [36].

In the solutions to multi-objective optimization problems, two or more objectives are conflicting. The optimization of one goal inevitably leads to the deterioration of at least one other goal; that is, no unique best solution exists. Therefore, the optimal solution to a multi-objective optimization problem is usually the Pareto optimum solution, as proposed by Vilfredo Pareto in 1896 [37]. This solution indicates that there is no such solution in the feasible solution space, and any one objective value is better than the others. The NSGA-II used in this paper is a fast and effective multi-objective evolutionary algorithm that was proposed by Deb based on the Pareto optimum solution [38]. This algorithm could reduce the complexity of noninferior sorting GA and has the advantages of a fast running speed and good convergence of the solution set [39]. Han utilized NSGA-II optimization to achieve a multi-objective model of turbine efficiency with a target net power output and system total cost as the objective functions [40].

4. Optimal operation model for cascade hydropower plants

In this paper, three optimal models for the operation of the Nuozhadu, Jinghong and Ganlanba cascade hydropower plants are established to quantitatively analyze the relationship between power generation and degree of ecological streamflow satisfaction in diverse operation modes. The objective functions of the three models involve the maximum power generation model (the largest average annual power generation model) (Model-I), the minimum ecological change model (the maximum ecological benefit model) (Model-II), and the multi-objective optimization operation model (Model-III) that combines the objective functions of Model-I and Model-II. Model-I and Model-II are single-objective decision making problems and are solved by the improved GA. Model-III is a multi-objective decision making problem that is solved by the NSGA-II.

4.1. Objective functions for three optimal models

Model-I: The major objective of hydropower plant operation is to maximize the water resource benefits that are mainly related to power generation, and the optimization variables are the water levels of hydropower plants in computational time intervals. The model takes the maximization of annual power generation as the objective function:

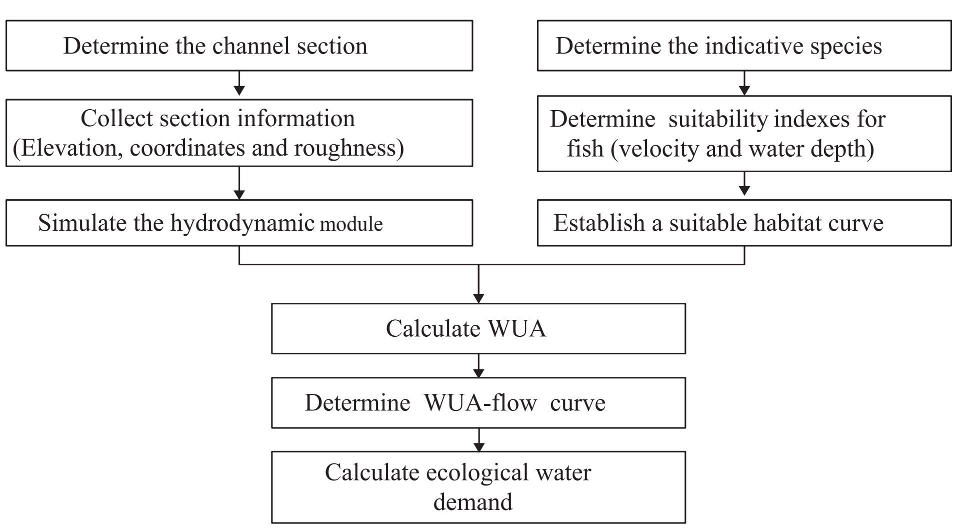


Fig. 4. The flow chart of the River2D model in this paper.

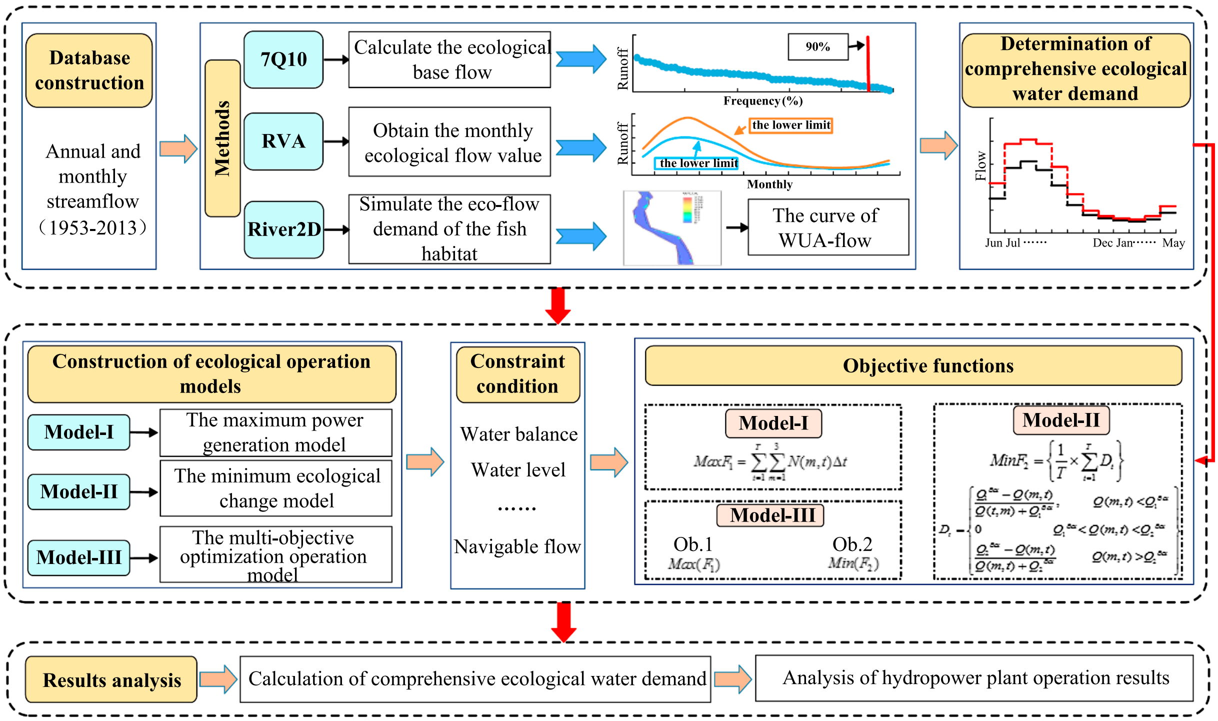


Fig. 5. The flow chart of main research content in this paper.

$$MaxF_1 = \sum_{t=1}^{T}\sum_{m=1}^{3} N(m, t)\Delta t \tag{8}$$

Model-II: The optimization variables are the water levels of hydropower plants in computational time intervals, and the objective of the ecological operation of a hydropower plant is to ensure that the discharge flow meets the water demands of the downstream ecosystems. Therefore, in this study, the ecological benefits of the operation of hydropower stations were expressed by the gap between the discharge from hydropower plants and the suitable ecological water demand. The lowest degree of ecological change is described as follows:

$$MinF_2 = \left\{\frac{1}{T} \times \sum_{t=1}^{T} D_t\right\} \tag{9}$$

$$D_t = \begin{Bmatrix} \frac{Q_1^{\partial\alpha} - Q(m,t)}{Q(t,m) + Q_1^{\partial\alpha}}, & Q(m, t) < \ Q_1^{\partial\alpha} \\ 0 & Q_1^{\partial\alpha} \ < Q(m, t) < \ Q_2^{\partial\alpha} \\ \frac{Q_2^{\partial\alpha} - Q(m,t)}{Q(m,t) + Q_2^{\partial\alpha}} & Q(m, t) > \ Q_2^{\partial\alpha} \end{Bmatrix} \tag{10}$$

Model-III: The multi-objective operation function simultaneously considered both electricity generation and ecology. In this paper, the optimization variables are the water levels of hydropower plants, and the multi-objective operation function is described as follows:

$$\text{Ob.1} \quad Max(F_1) \tag{11}$$

$$\text{Ob.2} \quad Min(F_2) \tag{12}$$

where F_1 = total power generation of cascade hydropower plants (kWh); $N(m, t)$ = the output at node m at time t (MW); T = total time period; Δt = the duration of an operation stage; F_2 = the degree of ecological change; D_t = the distance between the discharge of a hydropower plant and the suitable ecological water demand; $Q(m, t)$ = the discharge flow at node m at time t; $Q_1^{\partial\alpha}$ and $Q_2^{\partial\alpha}$ are the lower and upper limits of the suitable ecological water demand, respectively.

4.2. Constraint condition

The main constraints of these models are described as follows.

(a) Water balance constraint:

$$V(t + \Delta t) = V(t) + [Q_I(t) - Q_0(t)]\Delta t \tag{13}$$

(b) Discharge constraint:

$$Q_{\min}(m, t) \leqslant Q(m, t) \leqslant Q_{\max}(m, t) \tag{14}$$

(c) Water level constraint:

$$Z_{\min}(m, t) \leqslant Z(m, t) \leqslant Z_{\max}(m, t) \tag{15}$$

(d) Output constraint:

$$N_{\min}(m, t) \leqslant N(m, t) \leqslant N_{\max}(m, t) \tag{16}$$

(e) The minimum ecological flow constraints:

$$Q(m, t) \geqslant base(i, t) \tag{17}$$

(f) The minimum navigable flow constraints:

$$Q(m, t) \geqslant Q_m \tag{18}$$

where$V(t + \Delta t)$ = storage capacity in the following period; $V(t)$ = the current hydropower plant storage capacity; $Q_0(t)$ and $Q_I(t)$ are the beginning and end discharges at month t; $Q_{\min}(m, t)$ and $Q_{\max}(m, t)$ are the minimum and the maximum storage outflows; $Z(m, t)$, $Z_{\min}(m, t)$ and $Z_{\max}(m, t)$ are the current water level, lowest water level and the highest water level of hydropower plant i at month t, respectively; $N(m, t)$, $N_{\min}(m, t)$ and $N_{\max}(m, t)$ are the hydropower plant output at month t, the firm output and the installed capacity, respectively; $base(i, t)$ is the ecological base flow at month t of hydropower plant i; Q_m is the minimum navigable flow.

5. Results and discussion

In this section, the 7Q10 method is used to calculate the ecological base flow of the river, the RVA method is used to obtain the monthly ecological flow value, and the River2D model is adopted to simulate the ecological flow demand of the fish habitat, respectively. Then these three ecological flows and navigable streamflow requirement are considered comprehensively to determine the comprehensive ecological water demand threshold of the study area. Finally, the relationship between power generation and ecosystem protection based on three different ecological operation models is quantitatively analyzed. The flow chart of the main research contents of this paper is shown in Fig. 5.

5.1. Calculation of comprehensive ecological water demand

In this paper, three ecological factors were adopted to calculate the comprehensive ecological water demand. The three ecological factors are the river base flow, ecological streamflow process and the ecological water demands of the fish habitat, and these factors are computed with the 7Q10 method, the RVA method and the River2D model, respectively.

5.1.1. The ecological base flow

The 7Q10 method adopts the 90% guarantee rate of the driest average streamflow for 7 days as the minimum design flow of the river, which has been modified in China; that is, the minimum average monthly streamflow over the 10 most recent years is used as the river base flow or the driest monthly streamflow under a 90% frequency. Therefore, in this paper, the river base flow that was maintained downstream of the Jinghong hydropower plant was 443 m^3/s, as shown in Fig. 6.

5.1.2. The ecological streamflow process

The RVA was utilized to evaluate the river health in the study area. In addition, the ecological streamflow process was figured out based on the threshold of the RVA. The results of the hydrological evaluation indexes based on RVA are shown in Table 2. According to the results of the degree of ecological change of each indicator, the comprehensive degree of ecological change in the study area is 68%, which represents a high degree of change.

The construction of hydropower plants in the downstream portions of the Lancang River has resulted in a certain degree of damage to the ecosystem. To coordinate the contradiction between power generation and ecological demand, the hydropower plant operation must meet as many of the ecological needs as possible in the lower reaches. In this paper, the threshold of the monthly average flow is calculated based on the RVA, and these results are used as the river ecological streamflow. First, the monthly average streamflows before hydropower plant operation in the lower reaches of the Lancang River are ranked, and then, the 25% and 75% occurrence frequencies of the monthly average streamflow are calculated as the lower and upper limits of the ecological streamflow process, respectively. Table 3 shows the minimum and maximum ecological streamflow process based on the RVA.

5.1.3. Habitat ecological streamflow

The fish population in the lower reaches of the Lancang River is dominated by Cyprinidae, and the most common species is Tor douronensis. Therefore, this paper selects Tor douronensis as the target fish and analyzes the ecological streamflow that maintains the habitat stability. Since the construction of the cascade hydropower plants on the lower reaches of the Lancang River, the habitat that is suitable for the survival and breeding of fish in the mainstream has been greatly damaged. In particular, migratory fish, such as Tor douronensis and other indigenous fish, have suffered from serious impacts. Because of migratory access barriers, indigenous fish cannot normally reach their original spawning grounds, and the fish downstream of the cascade hydropower plants can only adapt to new spawning environments and habitats. In this paper, the average streamflow during the spawning period (July-September) is 3615 m^3/s, so the streamflow ranging from 1500 m^3/s to 5000 m^3/s is selected to simulate the hydraulic state of the river section, and the corresponding WUA values (Fig. 7) under different streamflow conditions are calculated.

The optimal ecological streamflow can be estimated by the relationship between streamflow and WUA; that is, the streamflow corresponding to the maximum WUA is the optimum ecological streamflow for fish. However, during the actual operation of cascade hydropower plants, it is impossible to achieve the ideal optimal ecological streamflow. Therefore, this paper puts forward an optimal ecological streamflow range, and sets the streamflow range corresponding to the WUA under the 90% guarantee rate as an ecological

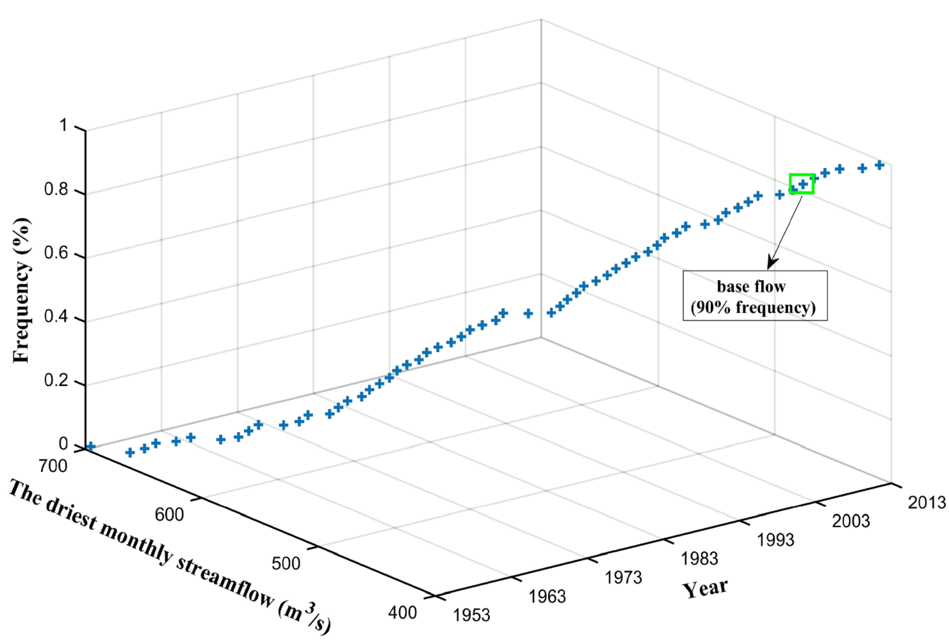


Fig. 6. The frequency distribution of the driest monthly streamflow (1953–2013) at the Jinghong hydropower plant. Green marks the ecological base flow under 90% frequency.

Table 2
Statistics of IHA at the Jinghong hydropower plant.

IHA		1960–1983 (1960–1983)		2010–2015 (2010–2015)		Threshold based on RVA		Degree of ecological change (%)
		Median	Coefficient of variation	Median	Coefficient of variation	Lower	Higher	
Monthly streamflow	January	687.9	0.51	955.5	0.56	515.7	868.4	33.33
	February	701	0.52	778.3	0.90	527.5	891.8	33.33
	March	687.2	0.51	864.5	1.74	521.8	875.5	33.33
	April	650.4	0.52	1007	1.17	502.8	842.1	33.33
	May	672.6	0.53	1360	0.66	471.4	830.2	33.33
	June	1553	0.63	1457	0.60	1156	2130	33.33
	July	2895	0.22	1437	0.96	2590	3225	100
	August	3787	0.48	2006	0.74	3154	4979	100
	September	3315	0.35	1681	0.78	2698	3857	100
	October	1967	0.35	1569	0.57	1522	2215	33.33
	November	1094	0.55	1135	0.69	741.7	1341	33.33
	December	748	0.44	965	0.88	583.1	908.6	33.33
Magnitude and duration of annual extreme water conditions	Annual minima 1-day means	545.6	0.61	579.5	0.63	381.9	717.1	0
	Annual minima 3-day means	568	0.55	590.5	0.64	422.5	734.7	0
	Annual minima 7-day means	622.9	0.53	601.4	0.62	448.6	778.2	0
	Annual minima 30-day means	638.5	0.52	738.1	0.55	491.1	824.4	0
	Annual minima 90-day means	667.9	0.49	857.7	0.57	536.6	863.3	66.67
	Annual maxima 1-day means	9374	0.23	3086	0.18	8383	10,570	100
	Annual maxima 3-day means	7230	0.20	2953	0.19	6530	7986	100
	Annual maxima 7-day means	6267	0.26	2695	0.16	5423	7057	100
	Annual maxima 30-day means	4525	0.24	2444	0.14	4056	5157	100
	Annual maxima 90-day means	3685	0.22	2048	0.23	3434	4257	100
	The number of break-off discharge	0	0	0	0	0	0	0
	Base flow coefficient	0.33	0.48	0.49	0.35	0.25	0.41	100
Timing of annual extreme water conditions	The date of each annual 1-day minima	153	0.04	69.5	0.32	144.8	161	100
	The date of each annual 1-day maxima	231.5	0.06	270.5	0.20	221	244	66.67
Frequency and duration of high and low pulses	Number of low pulses each year	7	2.54	1	4.75	0	17.75	33.33
	Mean duration of low pulses within each year	2	1.00	10	1.31	1	3	66.67
	Number of high pulses each year	23.5	0.46	7.5	0.87	19.25	30	100
	Mean duration of high pulses within each year	2	0.44	2.5	0.40	1.125	2	50
The rate and frequency of water condition changes	Means of all positive differences between consecutive daily means (rise rate)	189.5	0.71	29	1.59	123.2	258.6	100
	Means of all negative differences between consecutive daily means (fall rate)	-64.9	-1.73	-37.5	-1.15	-138.5	-26.03	33.33
	Number of reversals	181.5	0.09	163.5	0.15	174.3	189.8	66.67

Note: the units for streamflow, time, and rate of change are m^3/s, d, and %, respectively.

Table 3
Ecological streamflow threshold of each hydropower plant in the lower reaches of the Lancang River (m^3/s).

Hydropower plants	Nuozhadu		Jinghong		Ganlanba	
Threshold value	Maximum	Minimum	Maximum	Minimum	Maximum	Minimum
June	2120	1470	2150	1510	2190	1540
July	3740	2720	3870	2820	3940	2870
August	4460	2940	4670	3110	4750	3170
September	3760	2640	3910	2750	3980	2800
October	2750	1930	2880	2060	2930	2100
November	1600	1160	1700	1200	1730	1220
December	949	764	999	801	1020	816
January	706	615	746	643	760	655
February	602	511	623	533	634	543
March	580	469	598	486	609	495
April	727	596	735	610	748	621
May	1150	886	1170	898	1190	914

Note: the minimums and maximums are the streamflow corresponding to the 75% and 25% occurrence frequencies of the monthly average streamflow, respectively.

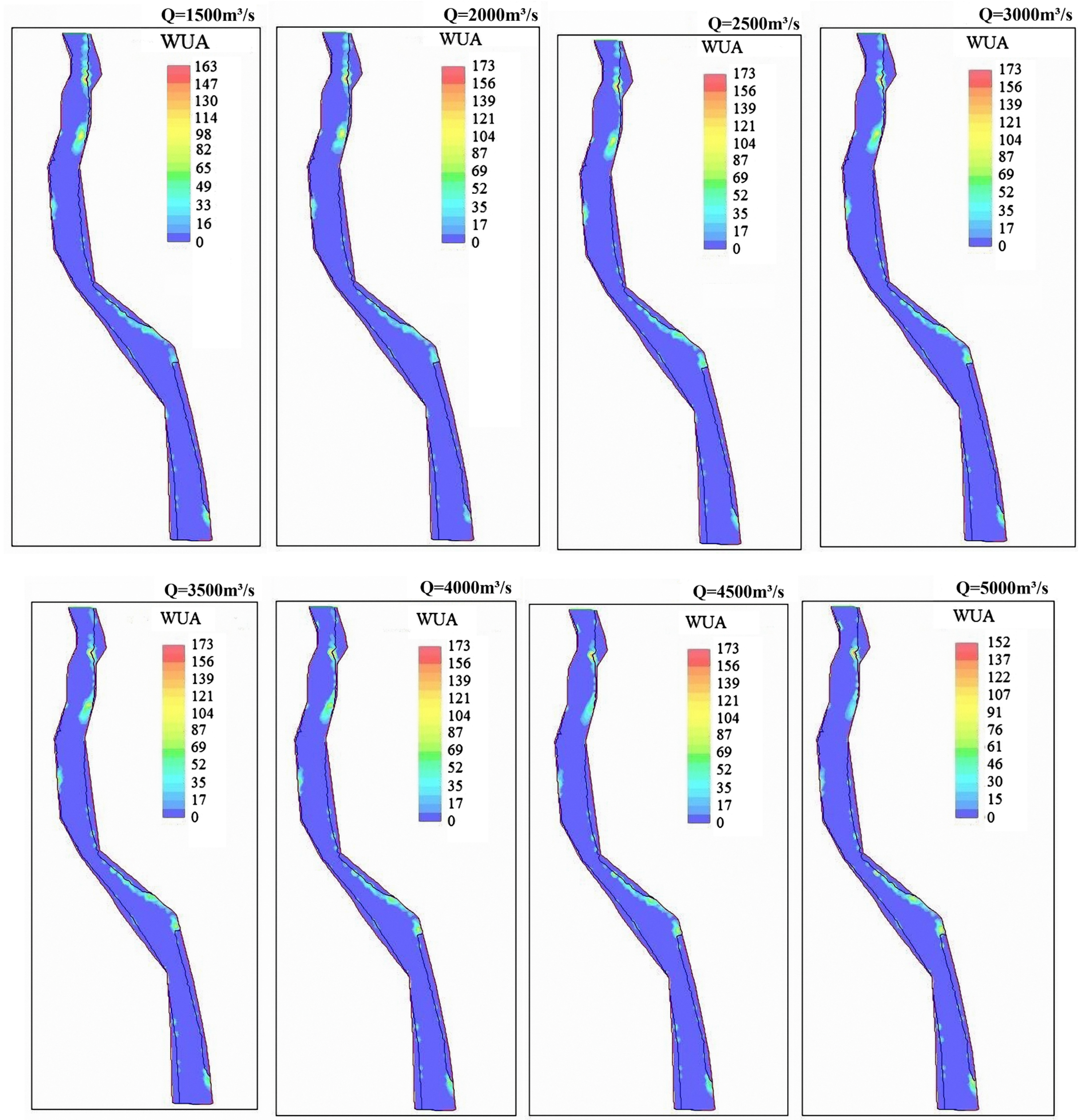


Fig. 7. The distribution map of WUA under different streamflow (Q) conditions.

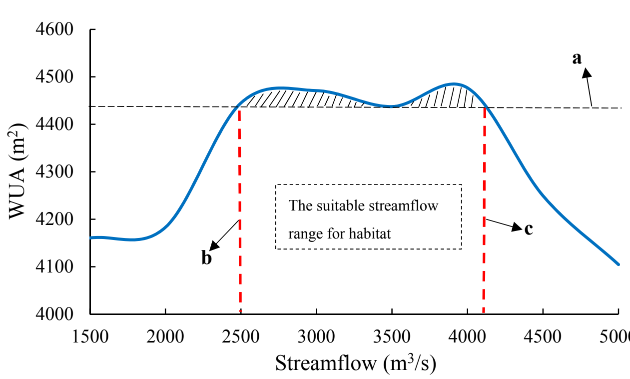


Fig. 8. The relation curve between WUA and streamflow. a represents the WUA with 90% guarantee rate, and b and c represent the lower and upper limits of streamflow corresponding to 90% WUA respectively.

constraint. The optimal ecological demand was described as the specific process that incorporates the ecological requirements into the hydropower plant operation under a certain recovery level, which provides greater flexibility for the balance of hydropower and ecological conservation objectives. Under the conditions of optimal hydropower plant operation, the ecological target is difficult to reach, but the optimization technology can ensure that the streamflow is closer to the ecological target. In addition, the determination of the degree of protection is a dynamic process, which should be adjusted according to the current and required conditions to maintain the good condition of the entire basin, and the trade-offs between hydropower generation and the degree of habitat protection should be explored. According to the standardization of the WUA, the corresponding streamflow range of the 90% WUA was selected as the threshold, and finally, the suitable streamflow range for the Tor douronensis spawning period was approximately 2500 ~ 4100 m^3/s. The relationship curve of the WUA of habitat and streamflow in the study area is shown in Fig. 8.

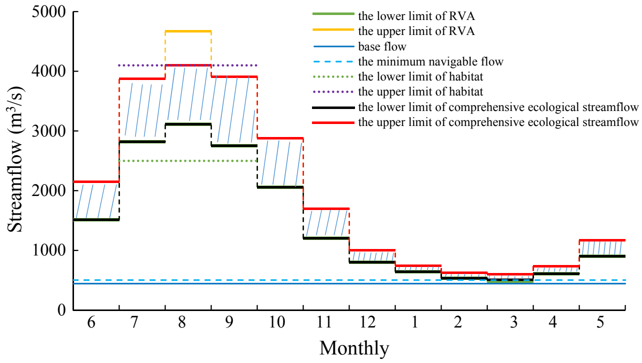


Fig. 9. The monthly comprehensive ecological streamflow. The blue shades represent the threshold of monthly comprehensive ecological streamflow.

In accordance with the principle of ecological compatibility and priority, the known navigable flow, the calculated ecological base flow and the fish habitat water demand are combined with the river ecological streamflow process line to determine the comprehensive ecological water demand in the lower reaches of the Lancang River (Fig. 9), which provides a basis for further hydropower plant operation models.

5.2. Analysis of hydropower plant operation results

As the construction of large-scale hydropower plants in the lower reaches of the Lancang River was completed and these plants were put into operation, the structures of the cascade hydropower plants underwent profound changes. The downstream cascade of hydropower plants plays a role in obviously regulating the streamflow while exerting power generation benefits. This regulation function reduces the flood peak discharge during the flood season and increases the streamflow during the dry season. The results of the Lancang River health assessment indicate that the regulation and storage of hydropower plants in the lower reaches of the Lancang River at the present stage have destroyed the ecological health of the natural rivers. Presently, the goal for the optimal operation of cascade hydropower plants is to quantitatively assess the mutual feedback between power generation and ecology and ensure economic benefits while maintaining the ecological health of rivers. In other words, the purpose of the study is to satisfy the ecological water demands under the conditions that improve the hydropower benefits by regulating the discharge flow of the Nuozhadu hydropower plant and changing the operation of the cascade power station.

Five typical years were selected based on the streamflow data from the cascade hydropower plants from 1954 to 2010, i.e., wet year (1962), relatively wet year (1957), normal year (2007), relatively dry year (1959) and dry year (1975). The selecting of typical years ensures the reasonableness of the operation results for certain periods of inflow after the calculation of a long series of hydropower plant regulations. The typical year means that the measured annual streamflow is similar to the designed annual runoff that is calculated by the P-III curve. The results are shown in Table 4.

5.2.1. Results of single-objective hydropower plants operation

The single-objective hydropower plant operation models (Model-I and Model-II) are utilized to investigate the changes in power generation and the degree of ecological change. Ecological constraints are considered over the long series of hydropower plant operation and during five typical years. The long-term operation results that were computed with measured data are shown in Table 5. In Model-II, the average annual power generation of the cascade hydropower plants is 300.28×10^8 kWh, which decreased by 10.61% compared with the results of Model-I (335.94×10^8 kWh). Additionally, the average annual power generation of the Nuozhadu, Jinghong and Ganlanba

Table 4
The streamflow of the Nuozhadu hydropower plant under different typical years.

Typical year	Dry year (P = 90%)	Relatively dry year (P = 75%)	Normal year (P = 50%)	Relatively wet year (P = 25%)	Wet year (P = 10%)
Year	1975	1959	2007	1957	1962
Design streamflow based on P-III curve ($10^8 m^3$)	457.62	479.83	529.94	592.35	631.26
Observed streamflow ($10^8 m^3$)	464.51	478.86	528.66	593.16	629.64

Table 5
The comparison of the results from the single-objective model over a long series.

Model	Hydropower plants	Average annual power generation (10^8kWh)	Average annual output during the dry season (10^4kW)	Average annual degree of ecological change (%)
Model-I	Nuozhadu	250.06	214.91	15.1
(Maximum power generation)	Jinghong	77.04	68.86	
	Ganlanba	8.84	8.25	
	Cascade	335.94	292.02	
Model-II	Nuozhadu	224.67	141.78	3.7
(Minimum ecological change degree)	Jinghong	67.38	44.52	
	Ganlanba	8.22	5.80	
	Cascade	300.28	191.09	

hydropower plants decreased by 11.15%, 12.54% and 7.06%, respectively, compared with the results of Model-I. The average output of the cascade hydropower plants during the dry season (November-May) in Model-II was 192.09 × 10^4 kW, which represents a decrease of 34.22% compared with the results of Model-I (292.02 × 10^4 kW). Moreover, the average outputs of the Nuozhadu, Jinghong and Ganlanba hydropower plants decreased by 34.03%, 35.35% and 29.75%, respectively, compared to the results of Model-I. The reason for these discrepancies is that the amount of water redistributed within the year when maximum power generation is the target. Model-II is based on the objective function of minimum ecological change, so less water is used for power generation.

To more clearly express the impacts of power generation on the degree of ecological change, Fig. 10 shows the trends of the monthly average degree of ecological change and power generation for Model-I and Model-II. Fig. 10(a) indicates that the power generation during the flood season is relatively large and the degree of ecological change is smaller, while during the dry season, the opposite is true. Model-I predicts a relatively large degree of ecological change during the dry season (December-February) and in June of the flood season, with a maximum of 46.03% in February. The reason for this result is that Model-I searches for the largest amount of power generation, and not all of the discharge flow is within the scope of comprehensive ecological streamflow, so the degree of ecological change is high (Fig. 10(b)). In contrast, the objective function of Model-II is minimum ecological change, and the discharge flow remains within the threshold of comprehensive ecological streamflow. Thus, the degree of monthly ecological change is low, and the maximum occurs in January (10.59%), but this comes at the expense of power generation that is obviously lower than that in Model-I. To minimize the degree of ecological change, it is difficult to guarantee the economic benefits while minimizing the degree of ecological change. The average annual ecological change calculated by Model-II was 3.7%, which decreased by 75.41% compared with the results of Model-I (15.1%).

The results from the different typical years of the cascade hydropower plants in Model-I (Table 6) show that the power generation of

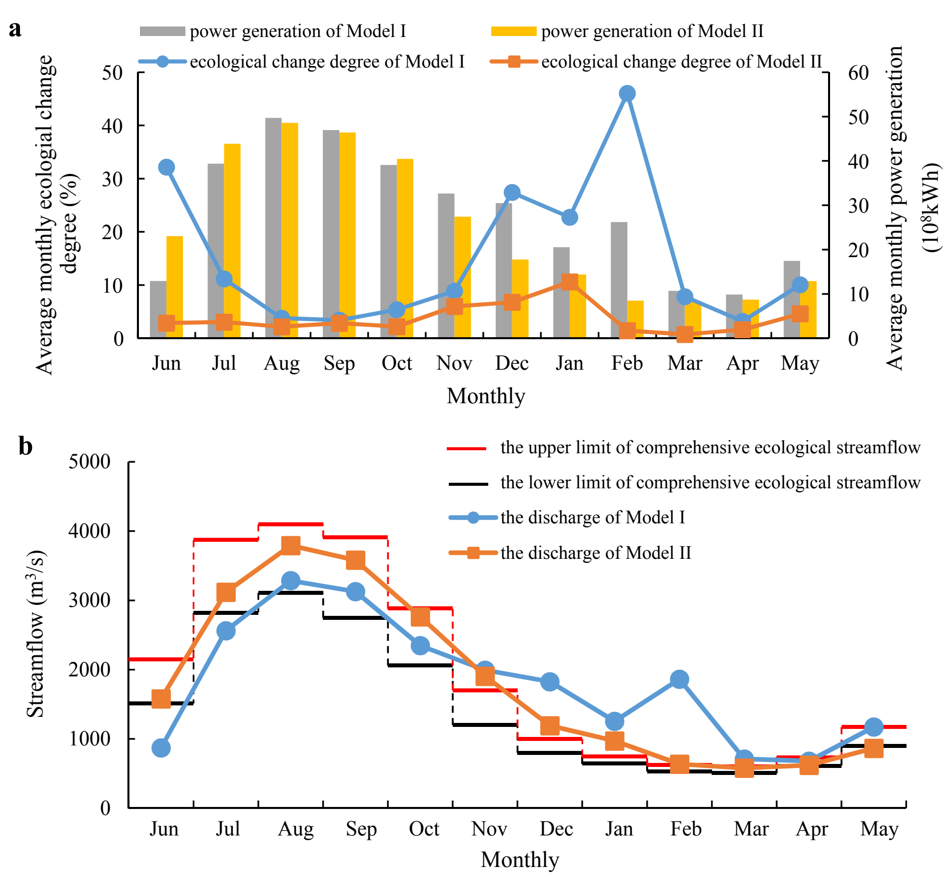


Fig. 10. Comparison of the results of Model I and Model II.

Table 6
The results of each typical year under Model-I and Model-II.

Model	Time	Power generation (10^8kWh)				Output of cascade hydropower plants during the dry season (10^4 kW)	Degree of ecological change (%)
		Cascade hydropower plants	Nuozhadu	Jinghong	Ganlanba		
Model-I	Dry year	298.79	221.39	69.13	8.28	297.13	16
	Relatively dry year	305.37	225.50	71.45	8.42	278.67	17.9
	Normal year	339.96	252.37	78.49	9.09	298.57	14.1
	Relatively wet year	371.14	275.07	86.62	9.45	275.92	10.4
	Wet year	368.35	274.40	84.53	9.42	275.61	10.1
Model-II	Dry year	274.23	202.83	63.30	8.10	202.04	4.1
	Relatively dry year	291.36	215.53	67.75	8.07	203.46	4.6
	Normal year	291.87	215.73	67.95	8.19	186.60	3.9
	Relatively wet year	319.98	239.12	72.29	8.57	179.14	1.7
	Wet year	333.77	251.28	74.00	8.50	210.12	2.9

cascade hydropower plants gradually increased with the increase in inflow; that is, the minimum value appeared during the dry year, and the maximum value appeared during the wet year. The same pattern was observed at the Nuozhadu, Jinghong and Ganlanba hydropower plants. However, with the increase in the inflow, the average output of the cascade hydropower plants during dry season did not show a decreasing trend. The main reason for this pattern is that the target of maximum power generation in Model-I would lead to an uneven distribution of output during some years. When only the optimal economic benefits were pursued without considering the ecological benefits, the range of the degree of ecological change over the five typical years was 10–18%, and the degree of ecological change in was largest during the dry year and smallest during the wet year.

5.2.2. Multi-objective hydropower plants operation results

To better reflect the mutual feedback between power generation and the ecosystem of hydropower plants, Model-III was used to study how to improve the comprehensive benefits of hydropower plants by using a multi-objective operation model and optimization algorithm and compensate for the shortcomings of conventional operation methods. During the calculation process for the NSGA-II algorithm, the inflow of the Nuozhadu hydropower plant is taken as the input variable. First, the generated water level of the Nuozhadu hydropower plant is set as the initial solution for the gene operation, which are divided into selection, crossover, mutation and other processes, and then the evolutionary population is calculated using nondominated sorting and crowding degrees, and finally, the calculation ends when the iteration conditions are satisfied. The multi-objective operation model for a typical year is solved, and the Pareto optimal solution set of five typical years is shown in Fig. 11(a)–(e). The results show that the power generation and degree of ecological change of cascade hydropower plants restrict and conflict with each other, showing a clear positive relationship. With the increase in power generation, the degree of ecological change also shows an increasing trend; that is, the ecological benefits decrease as the economic benefits increase.

In this paper, a normal year is analyzed as a representative, and four schemes are selected as the recommended programs. As shown in Fig. 11(f) and Table 7, the power generation and the degree of ecological change of the cascade hydropower plants in scheme 1 are 337.51×10^8 kWh and 20.49%, respectively, while these values are respectively 326.06×10^8 kWh and 11.31% in scheme 2, 311.69×10^8 kWh and 6.64% in scheme 3 and 295.48×10^8 kWh and 2.57% in scheme 4. The results show that there is an obvious competitive relationship between ecological benefits and power generation benefits during the joint operation of the cascade hydropower plants in the lower reaches of the Lancang River. The increase in power generation comes at the expense of changing the natural eco-hydrological situation. As the Nuozhadu is a carryover storage hydropower plant that substantially changes the hydrological situation of the natural streamflow, it plays a dominant role in coordinating the relationship between power generation and the ecosystem.

According to the monthly power generation (Fig. 12(a)) and degree of ecological change (Fig. 12(b)) from the cascade hydropower plants, the differences among the schemes are mainly reflected during the dry season. In particular, the degree of ecological change is distinctly different among the schemes during the dry season. As shown in Fig. 12(c) and (d), the hydropower plants are required to maintain high water levels to ensure power generation benefits; therefore, the amplitude of the variation in flow increases, and the natural streamflow in the river basin substantially changes, leading to the obvious confliction between cascade generation benefits and ecological benefits.

In scheme 1, the water level is high to ensure the maximum power generation, but the degree of ecological change is also the largest. The degree of ecological change in each month in scheme 4 remained less than 10%, but its operating head was low, so the power generation was the smallest, which reduced the economic benefits of the cascade hydropower plants. However, in scheme 2, the degree of ecological change in February was close to 70%, which indicated serious damage to the ecological environment. Thus, these three schemes are not suitable to be selected as the recommended schemes. Therefore, after a comprehensive comparison of the power generation, ecological changes and water level processes of the cascade hydropower plants and consideration of other factors of the four programs, scheme 3 is selected as the recommended program for a normal year.

The power generation of the Nuozhadu hydropower station (252.37×10^8 kWh) calculated from Model-I in normal year of this paper is close to that of Niu et al. (258×10^8 kWh), while Jinghong hydropower station is about 10×10^8 kWh higher than that of Niu et al., which is due to the different algorithms of reservoir operation model [41]. In general, the researches of other scholars are limited to the traditional power generation optimization operation, ignoring the ecological impact. Or some scholars only qualitatively analyzed the impact of hydropower development for the lower reaches of the Lancang River on the environment. For example, Fan et al. proposed that the water quality of the Nuozhadu hydropower station deteriorated, and the hydropower plants operation had a negative impact on the aquatic organisms [42]. Yi et al. pointed out that Tor douronensis has to find another suitable habitat in the lower reaches of the Lancang River due to hydropower plants operation [43]. However, these studies have not combined ecology with operation to quantitatively analyze the relationship between hydropower plants operation and ecological satisfaction while which is the main purpose of this study. In addition, this work is not perfect enough, and the researches on the migration path of aquatic organisms in the lower reaches of the Lancang River and

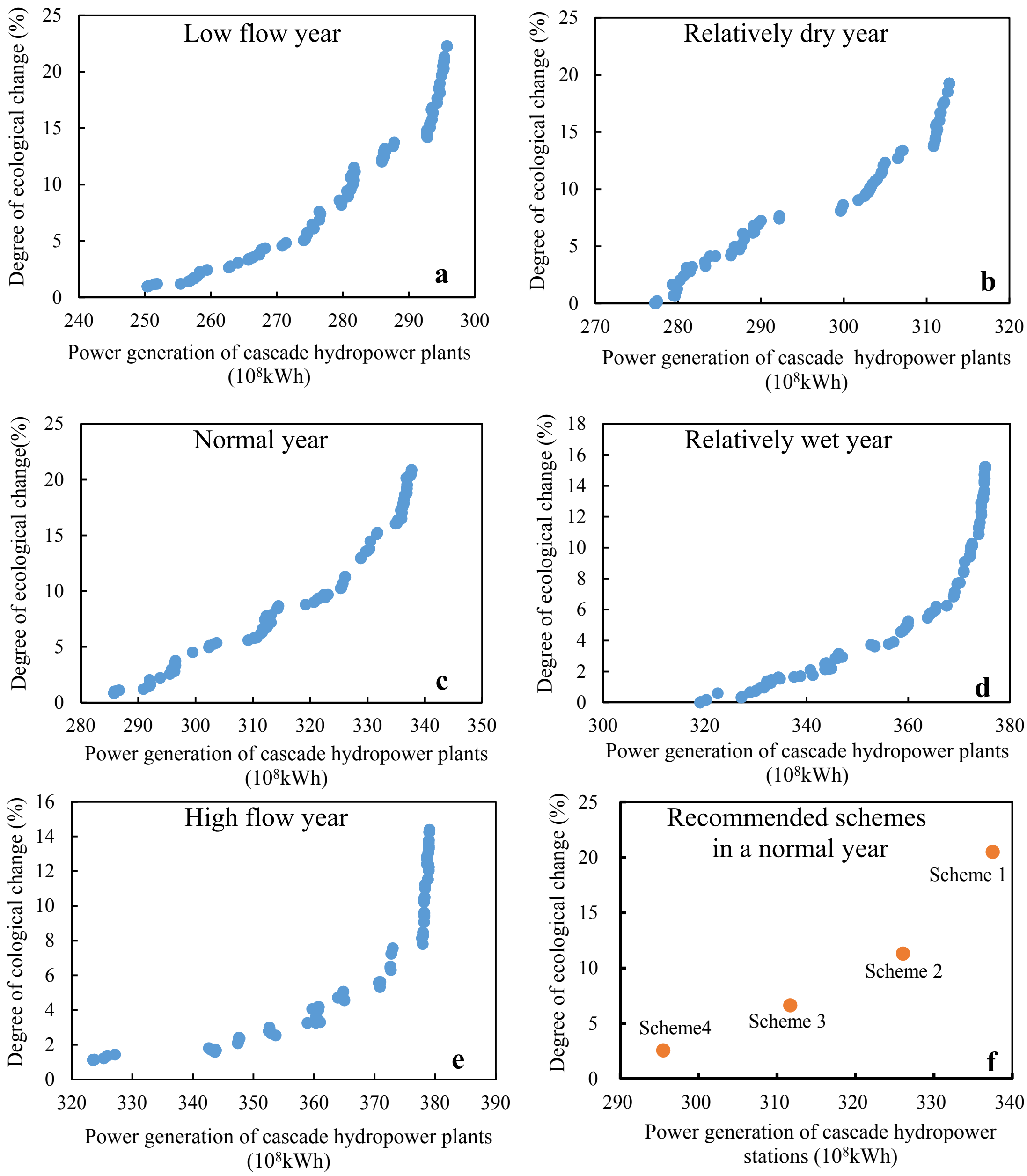


Fig. 11. The Pareto optimal solution sets for different typical years under Model-III.

Table 7
The results of the four schemes during the normal year.

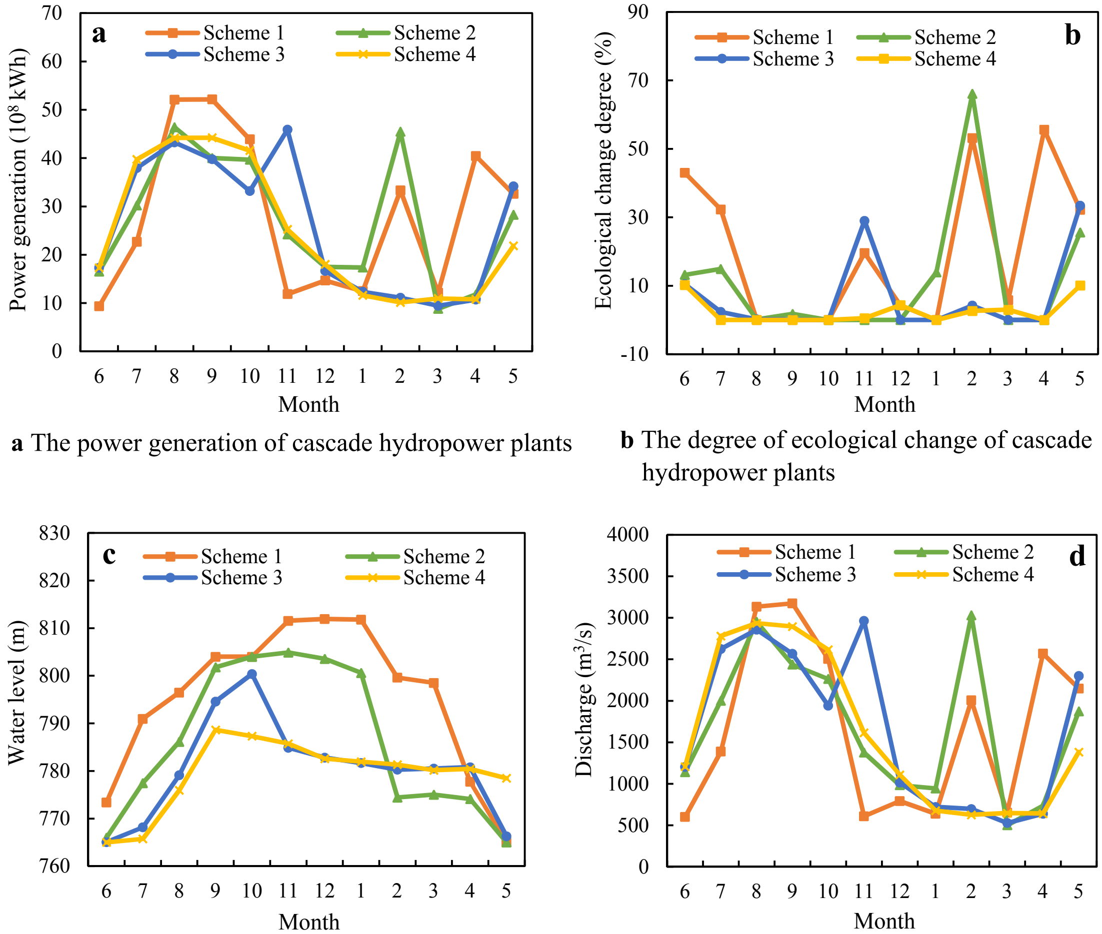
Scheme	Scheme 1	Scheme 2	Scheme 3	Scheme 4
Power generation (10^8kWh)	337.51	326.06	311.69	295.48
Ecological change degree (%)	20.49	11.31	6.64	2.57

the impact of reservoir discharge temperature on fish habitats will be further analyzed in the future.

6. Conclusions

Three ecological factors are considered in this paper to determine the comprehensive ecological water demand in the lower reaches of the Lancang River. In addition, aiming at the contradiction between power generation and ecosystem demands during the operation of hydropower plants, three optimized operation models considering the ecological benefits are constructed to analyze the impacts of different operation modes on ecosystem. The results are as follows:

(1) Based on the RVA method, the overall degree of ecological change of this study area was estimated to be 68%, which indicates a high degree of change in the lower reaches of the Lancang River. Therefore, it is urgent to solve this phenomenon as far as possible through reservoir operation.
(2) The ecological base flow was evaluated with the 7Q10 method to be 443 m^3/s. And based on the RVA method, the threshold (25% and 75%) of monthly average flow was used as the ecological flow process. Then, the appropriate ecological flow of the tor douronensis in the spawning period (July-September) simulated by River2D model was about 2500 m^3/s -4100 m^3/s. Finally, the three ecological flows and navigation flow are used to determine the comprehensive ecological flow as an ecological constraint for hydropower operations.
(3) The average annual power generation of the cascade hydropower



a The power generation of cascade hydropower plants

b The degree of ecological change of cascade hydropower plants

c The water level of Nuozhadu hydropower plant.

d The discharge of Nuozhadu hydropower plant.

Fig. 12. The operation results of cascade hydropower plants with four schemes in a normal year under Model-III.

plants in Model-II (300.28×10^8 kWh) decreased by 10.61% compared to that in the Model-I (335.94×10^8 kWh), while the average annual degree of ecological change that was calculated by Model-II (3.7%) decreased by 75.41% compared with that calculated by Model-I (15.1%). In general, the reduction of power generation by 35.66×10^8 kWh could lead to a reduction of 11.4% on the degree of ecological degradation. Therefore, the increase in power generation is at the expense of ecological degradation.

(4) Although the mutual restrictions and conflicts between power generation and ecological demand are inevitable, this problem can be solved as much as possible through a multi-objective ecological operation model. Therefore, this paper constructs a multi-objective ecological operation model based on NSGA-II algorithm to obtain the Pareto optimal solution set of five typical years to make economy and ecology coordinately develop as much as possible. Among them, scheme 3 is recommended for Model III, with a power generation and degree of ecological change of 311.69×10^8 kWh and 6.64%, respectively.

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