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Article

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Study on cascade hydropower alternative schemes based on multi-objective particle swarm optimization algorithm

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Abstract

Alternative scheme is the most important section in the environmental impact assessment (EIA). And the optimization of alternative schemes are the focus research fields in EIA. This paper define the content of alternatives of basin hydropower planning EIA (HPEIA), including the alternative generation about development patterns (single high stage dam or multistage dams) and development scales (dam height, installed capacity). The multi-objective model for alternatives generating of HPEIA has been built, which aims to reduce the impacts on socio-economic development and to increase the generated energy. Objectives of the model include ecological landscape change rate, installed capacity, cultivated field inundation area, and resettlement population, and water level is the decision variable. The basic data is obtained by remote sensing images and processed in ARCGIS: (1) obtain the water level-water surface area curve based on the DEM; (2) divide the landscape patterns in submerged area; (3) decide the centralism population distribution scope and their elevation boundary in the map. Moreover, multi-objective particle swarm optimization (PSO), by which the non-inferior solution sets of the multi-objective model are made, and combining with PSO and grey relational analysis. This model is tested in the hydropower planning alternatives-generating in Hei Shanxia reach, Yellow River. The comparative analysis of the three optimal sequences was investigated. One is to get the theoretical solution which presents the highest relativity, the other is obtain the solution on the condition of maximum installed capacity, and the third is to achieve the practical solution that is consistent with the decision objectives. The results of the above analysis show that the multi-objective model of alternatives generating of HPEIA can meet the competitive principle. Application of the PSO is suggested to be a helpful tool that solve the multi-objective model.

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Keywords: Cascade hydropower; Alternative schemes; Particle swarm optimization (PSO)

1. Introduction

The alternative scheme is one of the core components in EIA [3,4]. The generation, comparison and preference of alternative schemes are a comprehensive subject, involving engineering technology, environmental ecology,

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Nomenclature

A_{ji}	i th inundated area corresponding with j th reservoir
c_1	Learning factors [1]
c_2	Learning factors [1]
F_1	Landscape rate of change
F_2	Inundated area
F_3	Immigration amount
F_4	Total generation power
g_d	The global optimal position vector
H_0	Water level in the last reservoir (constant)
H_j	Water level in j th reservoir
H_j^-	The lowest water level
H_j^+	The maximum high-water level
HR	The water head available at the planning river reach
HR_j	The water-head corresponding with N_j
i	Land utilization type number
$iter$	The ordinal number of this iteration
j	Cascading power station number
J	Sequence number
k	The number of objective vector
L	Landscape index number
M_{iter}	Maximum iterations
N_j	Standard power
P_j	Inundated population at j th reservoir
p_d^i	The local optimal position vector
R_1	Random numbers between 0 and 1
R_2	Random numbers between 0 and 1
RWA_j	Water surface area at j th reservoir
S_k	k th landscape index corresponding with a certain water level
SR_k	k th landscape index before exploitation
T_{max}	Maximum iteration number
$v_d^i(k)$	i th velocity vector at k time
$x_d^i(k)$	i th position vector at k time
Y_0	Datum vector sequence
Y_j	Objective vector sequence
ω	Inertial factor which is given by linear drop law [2]
ω_{max}	Initial inertial factor
ω_{min}	Final inertial factor
ζ	Resolution coefficient
ε_0	The grey correlation
γ	The correlation degree
η	Fitness threshold value

environmental economy etc. A considerable amount of research has been carried out on the comparison and selection of alternative schemes. The Rapid Impact Assessment Matrix [5], cost–benefit analysis [6], analytic hierarchy

process (AHP) [7], method of synthesis [8], extension transformation and reasoning [9] are used to recognize, screen and compare the alternative schemes, however, they do not emphasize how to produce the alternative scheme.

At present, in the field of HPEIA, it is more about the optimization of hydropower planning scheme. The AHP [10,11], regional landscape pattern changes [12], TOPSIS method based combination weight [13], improved back propagation (BP) neural network [14] are used to the optimization of hydropower planning scheme.

The content of alternatives of basin hydropower planning EIA (HPEIA) includes the alternatives' generation about development patterns (single high stage dam or multistage dams) and development scales (dam height, installed capacity). Considering the fact that the hydropower development is limited by the geographical space, the restricted selection of development patterns, this paper but the regulative goal of dam height and installed capacity may be achieved by adjusting the normal store water level, therefore this paper studies the generation method of alternative scheme of development scale.

2. Multi-objective model for the generation and optimization of alternative schemes in basin hydropower planning EIA based on environmental restraint

Choosing the normal water level which is suitable for basin environmental capacities are essence of the alternatives about HPEIA. The targets of the model are to reduce the influencing of socio-economic development from hydropower planning, to increase the generated energy, and to reduce the submergence farming quantity, which is based on regional environmental capacities and the restricted conditions such as the change rate of the landscape patterns and the discrete water level. The multi-objective programming on alternatives of HPEIA (MOPA-HPEIA) is showed in Fig. 1.

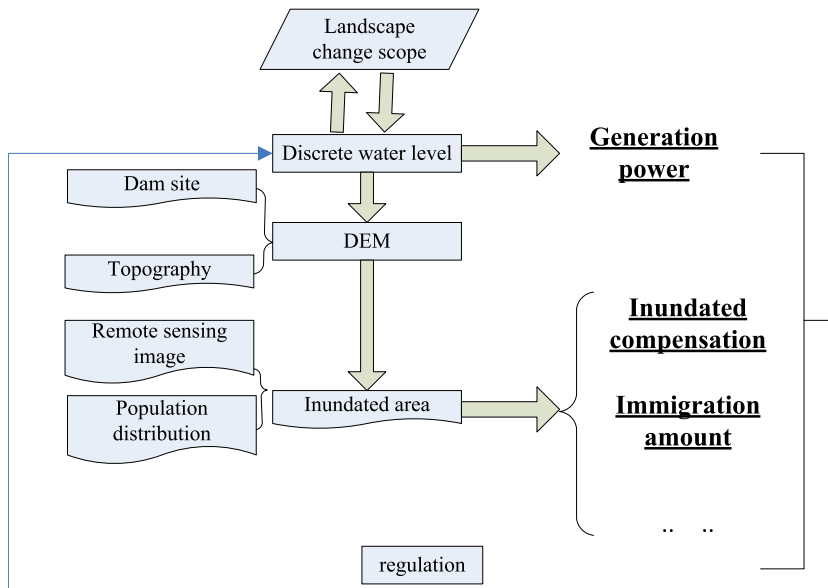


Fig. 1. MOPA-HPEIA model.

2.1. Objective function

Objectives of MOPA-HPEIA include ecological landscape change rate, installed capacity, cultivated field inundation area, and resettlement population. Its decision variable is water level. The first objective function is the maximum changes in landscape pattern indices, the second is the submergence land cover types, the third is the minimum submergence immigration quantity, and the fourth is the installed capacity summation of multistage power stations.

The detailed information of MOPA-HPEIA represents in Table 1.

Table 1. MOPA-HPEIA model.

Index	Objective function/constraint condition
Landscape rate of change	$Min F_1 = \max \{ S_1 - SR_1 /SR_1, S_2 - SR_2 /SR_2, \dots, S_L - SR_L /SR_L\}^\dagger$
Inundated area	$Min F_2 = \sum_{j=1}^m \sum_{i=1}^n A_{ji}$
Immigration amount	$Min F_3 = \sum_{j=1}^m P_j$
Total generation power	$Max F_4 = \sum_{j=1}^m N_j (H_j - H_{j-1} /HR_j)$
Water level constraint	$\sum_{j=1}^m H_j \leq HR$
Water level amplitude	$H_j \in (H_j^-, H_j^+)$

2.2. Functional relationship

The functional relationship of $A_{ji} \sim H_j$, $P_j \sim H_j$, and $Q_j \sim H_j$ must be established before the application of MOPA-HPEIA. The DEM in the study area is obtained from <http://datamirror.csdb.cn/index.jsp>, and processed in ARCGIS. The water surface area water level curve and t landscape patterns in different water levels are obtained.

The functional relation of the water level and the immigrant population is got by spot investigation. The centralism population distribution scope i, and the elevation boundary are analysed by DEM model.

The above functional relationships are summarized below.

$$RWA_j = RWA_j(H_j) \tag{1}$$

$$A_{ji} = A_{ji}(H_j) \tag{2}$$

$$P_j = P_j(H_j) \tag{3}$$

3. Model solution

3.1. The introduction of particle swarm algorithm

The MOPA-HPEIA is solved by the algorithm of multi-objected particle swarm. Kenedy and Eberhart [15] proposed the particle swarm optimization (PSO) that is a random optimization algorithm based on swarm intelligence [16].

The position of particle No. i is expressed by $X_i = (x_{i1}, x_{i2}, \dots, x_{iD})$, and its velocity by $V_i = (v_{i1}, v_{i2}, \dots, v_{iD})$ being $i = 1, 2, \dots, m$. Each particle has a fitness value decided by function, knows its best position (pbest) thus far and current position X_i , this may be regard as the particle own flight experience. Moreover, each particle also knows the global best of particle swarm (gbest). At the same time, this may be regard as the particle fellow flight experience [17]. The particle regulates its own “flight” to search the optimal solution according to the following two equations after it found the pbest and gbest [18].

$$v_d^i(k+1) = \omega \times v_d^i(k) + c_1 \times R_1 \times (p_d^i - x_d^i(k)) + c_2 \times R_2 \times (g_d - x_d^i(k)) \tag{4}$$

$$x_d^i(k+1) = x_d^i(k) + v_d^i(k+1) \tag{5}$$

ω is inertial factor which is given by linear drop law.

$$\omega = \omega_{max} - \frac{\omega_{max} - \omega_{min}}{M_{iter}} iter \tag{6}$$

3.2. Multi-objected particle swarm algorithm

The PSO is a global random search optimization algorithm, and the degree of solution is determined by the fitness function [19]. The PSO has good performance on the single objective optimization problem, but the algorithm cannot be directly applied to the multi-objective problem, because the particle swarm optimization algorithm needs to update its own by tracking individual extremum and global extremum to determine the pbest and gbest [20]. The multi-objective question Pareto optimal solution’s evaluation criteria are composed of two parts: (1) the non-poor optimal solution set obtained should be as close as possible to the real Pareto front; (2) the non-poor optimal solution should distribute uniformly along the Pareto front as far as possible [21].

In this paper, scholars proposed the grey correlation method to evaluate the advantages and disadvantages of Pareto solution set [20,22]. Grey relational analysis can better analyse the closeness between each non-inferior solution and the ideal solution, and can grasp the whole picture of the solution space. The grey correlation degree is used to determine the individual extremum and global extremum of the PSO. The PSO is used to optimize the high-dimensional multi-objective problem.

The grey correlation is given by

$$\varepsilon_{0J}(k) = \frac{\min_J \min_k |y_0(k) - y_J(k)| + \zeta \max_J \max_k |y_0(k) - y_J(k)|}{|y_0(k) - y_J(k)| + \zeta \max_J \max_k |y_0(k) - y_J(k)|} \quad (7)$$

The correlation degree is given by

$$\gamma = \frac{1}{n} \sum_{k=1}^n \varepsilon_{0J}(k) \quad (8)$$

The detail steps that the Pareto solution set is valued by the grey correlation method is: (1) extract the optimum value of each objective function used by the basic particle swarm and take these optimum values as the datum vector sequence; (2) substitute the complete particles into the objective function, and form each one vector which are taken as the goal vector sequence. The correlation degree of the datum vector sequence and the goal vector one is computed by Eqs. (7) and (8), and the particle corresponding with the biggest correlation degree is taken as the gbest; (3) substitute the single particle into the objective function, and take the goal vectors which are formed by each flight process of the particle as the goal vector sequence. The correlation degree of the datum vector sequence and the goal vector one is computed by Eqs. (7) and (8), and the particle corresponding with the biggest correlation degree is taken as the pbest.

3.3. Algorithm flow of multi-objected particle swarm

The algorithm flow of multi-objected particle swarm is as follows:

Step1: initialization: particle position X , velocity V , swarm number m , learning factor c_1 and c_2 , inertial factor ω , fitness threshold value η , maximum iteration number T_{max} , and objective function number n .

Step2: extracting the optimum value of each objective function used by the basic particle swarm and take these optimum values as the datum vector sequence.

Step3: While (fitness value $> \eta$ & iteration number $< T_{max}$)

Step4: For $i = 1 : m$

For $j = 1 : n$

Substitute particle position X into the objective function and compute its value

Endfor

Form the goal vector sequence by the above objective function values

Endfor

Step5: Computing the correlation degree of the datum vector sequence and the goal vector one is by Eqs. (7) and (8).

Step6: Obtaining the pbest and gbest.

Step7: Refreshing the particle swarm position by Eqs. (4) and (5).

End while

The research indicated that 10 particles has been possible to obtain the good result regarding the majority of optimized question [3,4].

4. Example analysis

The Black Gorge in Yellow River which located at the intersection of Gansu and Ningxia province, is the last canyon section of Yellow River. The third-level development programs are used, including Xiao guanyin reservoir, Wu fu one, and Hong shanxia one, from downstream to upstream, respectively. The Jing tai County, Jing yuan County, and the Ping chuan district are the immigration resettlement area.

4.1. Model solution

The response relations of the Xiao guanyin water level and Wu fu one to landscape diversity indices, submergence area, immigrant population, power generation are studied by MOPA-HPEIA under the conditions of the given discharge. In view of the relatively small threshold range of water level changes (3 ~ 5 m), we selects 10 particles. The biggest iterative number is 10 times. The partial parameters of multi-objective particle swarm algorithm are shown in [Table 2](#).

Table 2. MOPA-HPEIA partial initial parameter.

Parameter	Hongshanxia	Wufu	Xiaoguanyin
Normal pool level (m)	1374	1338	1302
Designed water head (m)	39	43	22
Designed install capacity (MW)	420	360	400

Due to the limitation of the length of the article and the convenience of the analysis of the results, the 10 iterations of a particle are randomly output. See the result of 10th iteration of the 10th particle. As are showed in [Table 3](#).

Table 3. MOPA-HPEIA results.

Order number	Xiao water level [m]	Wu water level [m]	Generation power [MW]	Inundated area [mu]	Immigration population	Landscape diversity indices	Landscape change rate [%]	Correlation degree
1	1298.00	1335.00	1002.49	17 631.58	10 749	1.2095	0.12	0.3612
2	1298.43	1335.26	1006.05	17 712.87	10 883	1.2155	0.62	0.4511
3	1298.77	1335.46	1008.90	17 775.40	10 992	1.2203	1.02	0.5475
4	1299.02	1335.61	1011.03	17 820.84	11 074	1.2239	1.32	0.5394
5	1299.20	1335.72	1012.53	17 851.91	11 132	1.2265	1.53	0.4950
6	1299.31	1335.79	1013.50	17 871.78	11 170	1.2281	1.67	0.4699
7	1299.38	1335.83	1014.08	17 883.58	11 193	1.2291	1.75	0.4560
8	1299.42	1335.85	1014.40	17 890.03	11 205	1.2297	1.79	0.4486
9	1299.44	1335.86	1014.56	17 893.23	11 212	1.2299	1.82	0.4450
10	1299.45	1335.87	1014.64	17 894.68	11 214	1.2301	1.83	0.4434

4.2. Results and discussions

[Table 3](#) showed, with the unceasing rise of the Xiao guanyin water level and the Wu fu one, the generation power has been enhanced, but the submergence cultivated area and immigrant quantity have also proportional increased, and the region landscape has been disarranged.

As shown in [Fig. 2](#), there is a peak curve between the correlation degree with the Xiao guanyin water level and the Wu fu one. Because the generation power will be raised with the increment of the two reservoirs water level, the objective sequence draws close the ideal one, but the submergence and immigration will be aggravated when their water levels elevate over some limit, the objective sequence will deviate the ideal one.

As shown in [Table 4](#) and [Fig. 3](#), the correlation degree of the theoretical optimum sequence is 0.7173. This plan compares with the design proposal sequence: (1) the generation power reduced by 12.96%; (2) the submergence cultivated area increased by 1.89%; (3) the immigration population increased by 2.89%; (4) the landscape multiple indices changed by 1.98%.

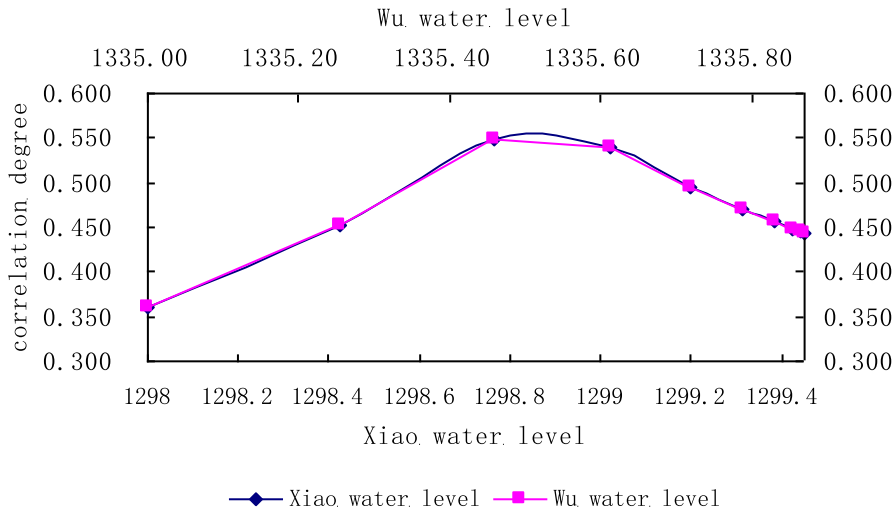


Fig. 2. Dynamic relationship between correlation degree with water level.

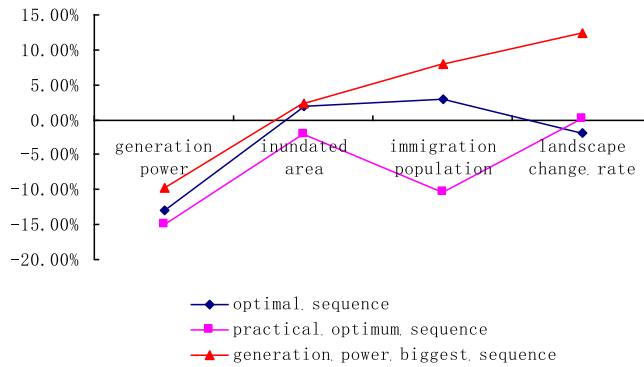


Fig. 3. MOPA-HPEIA model different objective sequences.

Table 4. Extreme point.

Type	Generation power [MW]	Inundated area [mu]	Immigration population	Landscape diversity indices	Correlation degree	Landscape change rate [%]
Designed proposal sequence	1180	18 000	12 000	1.208		
Generation power maximum	1063.97	18 413.69	12 949	1.3585	0.4613	12.46
Inundated area minimum	1002.49	17 631.58	10 749	1.2095	0.3612	0.12
Inundated population minimum	1002.49	17 631.58	10 749	1.2095	0.3612	0.12
Landscape change rate minimum	1002.49	17 631.58	10 749	1.2095	0.3612	0.12
Optimal sequence	1027.06	18 340.31	12 347	1.1841	0.7173	1.98

The correlation degree of the practical optimum sequence is 0.3612. This plan compares with the design proposal sequence: (1) the generation power reduced by 15.04%; (2) the submergence cultivated area reduced by 2.05%; (3) Immigration depopulation by 10.43%; (4) the landscape multiple indices changed by 0.12%.

The contrast of the theoretical optimum sequence to the practical optimum one indicates that although the generation power has drop at small amplitude, the farming has been protected, the immigration quantity reduced, and the local landscape multiplicity protected.

As shown in Table 4 and Fig. 3, the correlation degree of the generation power biggest sequence is 0.4613, which compares with the design proposal sequence: (1) the generation power reduced by 9.83%; (2) the submergence cultivated area increased by 2.30%; (3) the immigration population increased by 7.91%; (4) the landscape multiple indices increased changed by 12.46%.

5. Conclusions

This paper established MOPA-HPEIA model, applied it to the case study, and obtained the following two conclusions: (1) the multi-objective programming model is used to generate alternatives for basin hydropower planning with clear concepts and high credibility; (2) although the correlation coefficient is small, since the main purpose of this paper is to conduct comparison, that is, to develop relativity analysis, not absolute analysis, the correlation coefficient is suitable as the basis for judging the merits and demerits of the scheme.

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