Cooperative Coevolutionary Genetic Algorithm For Water Resources Optimization Model And Its Application

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Abstract

To solve the complexity of multi-public sources water allocation, the optimization model using the multi-objective function and multi-constrained conditions of the cooperative coevolution genetic algorithm (CCGA) was proposed for water resources management. The objective function was the highest benefit to both economy and society, while the constraints included available water supply amount, water demand, water supply projects capacity, ecology protection and non-negativity. Water demand ratio parameters for each public source were proposed which could be optimized by CCGA. The case study in Suibianhe Region showed that the proposed model was capable of allocating water resource efficiently and can provide useful information for water resources integrated management.

1 Introduction

Society benefits immeasurably from water resources and more and more water conservancy projects have improved more and more people's life, especially in the aspect of water supply. But with the rapid development of the economy, the increasing human activities and the changes of the climate, sharp imbalance between insufficient freshwater resources supply and raising water demands is getting more serious and how to allocate the limited water resources among various users becomes much urgent in many regions.

Over the past decade, a number of allocation models were proposed for water resources planning. Among which, the linear programming, objective programming, dynamic programming, genetic algorithms, particle swarm algorithms and neural network method were the most widely used methods. And all these optimal methods could be classified in two kinds as follows: conventional programming methods and modern intelligent methods. However, with the increase in the number of water allocation model variables, the conventional techniques have some disadvantages such as the problem of dimensionality, getting trapped in local optima, huge computational requirements [3] and are less often used for those intricate water resources optimization problems nowadays. Genetic algorithm (GA), based on the concept of natural genetics, is a directed random search technique. And it is one of the increasingly popular modern intelligent methods and has been applied in the field of workshops scheduling, products design, water resources management and so on since it was proposed in the 1960s [7]. Meanwhile, many improved genetic algorithms were also put forward and among which cooperative coevolution genetic algorithm (CCGA) was well received for solving difficult, combinatorial optimization problems and some large-scale optimization problems.

Water resources allocation is usually a multi-water sources, multi-water-using units and multi-objectives problem, which has been of concern for many researchers. And with more and more water conservancy projects' building and operating, the problem how to allocate water to multiple units from two or more public water sources simultaneously and rationally is proposed, especially in the drought years. In this paper, CCGA was introduced into the regional water resources optimization model to solve the problem mentioned above, and the established model was then applied to Suibianhe Region, for the long-term (2030) planning timeframes under the general drought (P=80%) and special drought (P=95) respectively.

2 CCGA

CGGA is a population-based evolution-guided stochastic search technique which inspired by symbiotic interactions where different species live together in a mutually beneficial relationship [8]. And it has been applied in the domains such as job shop scheduling [4], air traffic and capability planning [8] and so on. Comparing to GA, all parameters of the fitness function in CCGA are not encoded and represented by a single chromosome [6]. Instead, the parameters are separated into several subsets. Each subset of the parameters is encoded with one kind of chromosomes, which compose an individual population. Consequently, when fitness value of a chromosome is evaluated, chromosomes in other populations are necessary so that all parameters of the fitness function can be provided. These chromosomes chosen from other populations for fitness value evaluation are referred to as representative chromosomes, which can be chosen randomly

or according to the fitness value [5]. Steps of the CCGA are as follows: (a) Initialize all individual populations; (b) Select representative individuals from other populations and form the complete solution with the evaluated individual, then the fitness will be computed; (c) Generate the offspring of each population by selection, crossover and mutation operations; (d) Stop CCGA if the terminating criteria is reached. Otherwise turn step (b).

3 Water Resources Optimization Model based on CCGA

To realize sustainable utilization of regional water resources, and to promote the harmonious development of the economy, society and environment, the water resources optimization model was developed based on the system analysis and sustainable development principle according to many related studies [2]. The model includes 4 important parts: objective functions, constraint conditions, water supply and receive sequence and optimization Techniques.

Supposing there are J water-using units and M public water sources in the study area. And in each unit, there are K water users and I local independent water sources. A year is also divided into T periods in this model considering the variations in water supply and demand in different periods, and monthly or ten-day scale is often used.

3.1 Objective functions

To exhibit fairness, efficiency and coordination, the maximum comprehensive benefit objective, incorporating economic, social and ecological benefits were often reflected. And in this paper, to highlight the importance of the ecological environment, this model transformed the eco-environmental object into a constraint. Thus, two objectives were constructed. They were minimum relative water deficiency ratio (DR) and maximum regional economic benefits which represented the extent of social object and economic object respectively. Each detailed formulation was shown as follows.

(1) Social object

$$\min f_1 = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\alpha_{jk}\left(\frac{D_{jkt} - \sum_{i=1}^{I}Q_{ijkt} - \sum_{m=1}^{M}Q_{mjkt}}{D_{jkt}}\right)^2 \quad (1)$$

Where D_{jkt} denotes the water demand by the kth user of the jth unit in the tth period, Q_{ijkt} denotes the water supply to the kth user of the jth unit in the tth period from the ith independent water source, Q_{mjkt} denotes the water supply to the kth user of the jth unit in the tth period from the mth public water source, α_{jk} represents the weight of the kth user of the jth unit.

(2) Economic object

$$\max f_2 = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\left(\sum_{i=1}^{I}b_{jk}Q_{ijkt} + \sum_{m=1}^{M}b_{jk}Q_{mjkt} - \sum_{i=1}^{I}c_{ijk}Q_{ijkt} - \sum_{m=1}^{M}c_{mjk}Q_{mjkt}\right) \quad (2)$$

Where b_{jk} denotes the water supply benefit by the kth user of the jth unit, c_{ijk} denotes the water supply cost to the kth user of the jth unit from the ith independent water source, c_{mjk} denotes the water supply cost to the kth user of the jth unit from the mth public water source.

3.2 Constraint conditions

Five constraints were set for the multi-objective functions. They were available water supply amount, water demand, water supply projects capacity, ecology protection and non-negativity which were expressed by the following equations.

(1) The available water supply amount cannot exceed the maximum water supply amount of a water source project.

$$\sum_{j=1}^{J}\sum_{k=1}^{K}Q_{ijkt} \le W_{it} \quad (3)$$

$$\sum_{j=1}^{J}\sum_{k=1}^{K}Q_{mjkt} \le W_{mt} \quad (4)$$

Where W_{it} and W_{mt} denotes the maximum water supply amount of the ith independent water source and the mth public water source in the tth period respectively.

(2) The water supply amount cannot exceed the water demand.

$$\sum_{i=1}^{I}Q_{ijkt} + \sum_{m=1}^{M}Q_{mjkt} \le D_{jkt} \quad (5)$$

(3) The water supply amount cannot exceed the water supply project's capacity.

$$\sum_{k=1}^{K}Q_{ijkt} \le C_{\max ij} \quad (6)$$

$$\sum_{k=1}^{K}Q_{mjkt} \le C_{\max mj} \quad (7)$$

Where $C_{\max ij}$ and $C_{\max mj}$ denotes the water supply project's capacity to the jth unit from the ith independent water source and the mth public water source respectively.

(4) The water supply amount must exceed the ecological water demand.

$$Q_{ijt} + Q_{mjt} \ge E_{ijt} \quad (8)$$

(5) Nonnegative constraints.

$$Q_{ijkt} \ge 0 \quad (9)$$

$$Q_{mjkt} \ge 0 \quad (10)$$

3.3 Water supply and receive sequence

The sequence of users that received water is ecological sector (E), domestic sector (D), industrial sector (I), third industrial

sector (T) and agricultural sector (A). And the independent water sources supply water first. If local water demand cannot be satisfied by local independent water, then it needs the public sources water supply.

3.4 Optimization Techniques

Optimizing water allocation is complex and often difficult to achieve as some impact relations are nonlinear and interdependent. CCGA is used to solve the optimization model.

(1) Fitness function

There were two objects in this model as mentioned above. And they should be combined into a single fitness function.

$$\max f = \sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{t=1}^{T}\alpha_{jk}$$

$$\left(\sum_{i=1}^{I}b_{jk}Q_{ijkt}+\sum_{m=1}^{M}b_{jk}Q_{mjkt}-\sum_{i=1}^{I}c_{ijk}Q_{ijkt}-\sum_{m=1}^{M}c_{mjk}Q_{mjkt}\right)^{2}\left(\frac{\sum_{i=1}^{I}Q_{ijkt}+\sum_{m=1}^{M}Q_{mjkt}}{D_{jkt}}\right) \quad (11)$$

(2) Optimization variables

In this model, Q_{ijkt} and Q_{mjkt} are the variables. And according to the water supply sequence, the independent sources water supply was not needed to optimize. In general, the public sources often supply water to many units simultaneously. Thus, how to allocate the water to the units from various public sources needs to be optimized. CCGA can be used to solve this problem effectively. For convenience, the parameters n_{mj} were introduced in CCGA (see Equation (12)). And each n_{mj} can be regarded as a chromosome, and each source's set of n_{mj} can be regarded as a population. So in this model a complete solution is divided into M populations and each population has J chromosomes. When a chromosome is evaluated, it should be combined with chromosomes in other populations to form a complete solution. Each population should evolve separately using a standard GA. If the terminating criterion is reached, then stop CCGA. And the optimal water allocation from each public source can be got.

$$D'_{mjkt} = n_{mj}\sum_{k=1}^{K}\left(D_{jkt}-\sum_{i=1}^{I}Q_{ijkt}\right) \quad (12)$$

Where n_{mj} denotes the water demand ratio parameters the jth unit, D'_{mjkt} denotes the new water demand for the mth public water source by the kth user of the jth unit in the tth period.

4 Its Application

Suibianhe Region, located in the mountain-river-lake region (western part of Jiangsu Province) at the middle reaches of Huaihe River is selected as the study area. The mean annual precipitation is 894 mm and is concentrated between June and September. The average annual water resources total quantity is 2.58×10^{8} m^{3}, among which surface water resources is 1.71×10^{8} m^{3}, groundwater resources is 1.04×10^{8} m^{3} and the repeated calculation is 1.70×10^{7} m^{3}. Although water resources in the region is totally abundant, seasonal and pollution-induced water shortage still exists [5]. And with the increase of population, the development of economy and urbanization, the problems of water resources shortage are becoming increasingly prominent in this area. Consequently, water resources management especially the reasonable and optimal allocation of water resources is particularly important in the context of the regional sustainable development.

In this study, based on the administrative districts, the region was divided into 8 water-using units for modelling (see Fig. 1). And each unit could also be divided into 5 sectors, and they were ecology, domesticity, industry, third industry, and agriculture. The data and information for estimating sectoral water demands were collected for every studied zone. In 2030, considering the general drought (P=80%) and special drought (P=95%), the water demand of the five sectors were shown in Table 1 respectively. According to the analysis of the region's water supply system, the small-sized reservoirs (SR), underground water (GW), reclaimed water (RW) and other local surface water (OW) were classified as the local independent water sources. The passing-by rivers (PR) were generalized into 6 main rivers. And these rivers and Hongze Lake (PL) formed the two main public water sources. So the parameters n_{1j} ($j=1,2,\cdots,8$) and n_{2j} ($j=1,2,\cdots,8$) could represent the public rivers water supply and lake water supply respectively and they could be optimized by CCGA.
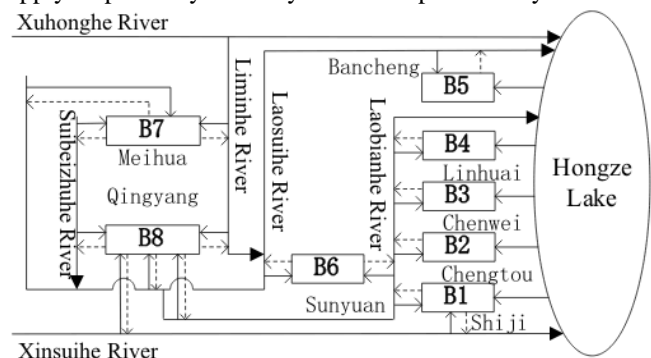

Figure 1: Sketch of water resources system

In this case, α_{jk} in the equation (12) were set as 1.0 with the equal weight method according to the experts' advice. The termination criterion was set to perform 200 generations of GA simulation. And based on the algorithm of CCGA, the water allocation optimal results were calculated and shown in Table 2. From Table 2, we could find that, in the general drought condition, water supply and demand were balanced in each unit of the region. While in the special drought condition, water demand of B5 was fully guaranteed. And except B5, the water supply was insufficient at different degrees in other 7 unties, among which the largest water deficient ratio was 5.18% in B8. It indicated that the DR was relatively balanced in the regional spatial distribution. And the model by CCGA could be applied in water optimal allocation reasonably.

Unit	General drought (P=80%)						Special drought (P=95%)					
	E	D	I	T	A	Total	E	D	I	T	A	Total
B1	4.9	83.9	76.6	82	3223.9	3471.3	4.9	83.9	76.6	82	3938.1	4185.5
B2	4.4	75.4	175.1	73.1	4658.8	4986.8	4.4	75.4	175.1	73.1	5690.6	6018.6
B3	7.6	130.9	177.8	194.8	2906.2	3417.3	7.6	130.9	126.6	64.5	3619.4	3949
B4	12.3	79.3	126.6	64.5	97.6	380.3	12.3	79.3	177.8	194.8	118	582.2
B5	11.2	87.2	151.5	107.4	638.2	995.5	11.2	87.2	151.5	107.4	781.7	1139
B6	15.1	190.5	188.4	193.6	4523.8	5111.4	15.1	190.5	188.4	193.6	5533.2	6120.8
B7	9.7	152.4	214.3	97.3	1724.4	2198.1	9.7	152.4	214.3	97.3	2282.9	2756.6
B8	614.8	3309	2168.6	2257.6	7211.2	15561.2	614.8	3309	2168.6	2257.6	9066.9	17416.9

Table 1: Water demand by sectors in 2030 ($\times 10^4$ m^3).

Unit	General drought (P=80%)							Special drought (P=95%)						
	Independent sources				Public sources		DR	Independent sources				Public sources		DR
	SR	GR	RW	OW	PR	PL		SR	GR	RW	OW	PR	PL	
B1	0	13	185.3	746.5	1872.3	654.2	0.00%	0	13	575.7	185.3	1924.6	1381.5	2.52%
B2	0	8.8	3.7	766.8	1419.6	2787.9	0.00%	0	8.8	633.3	3.7	1690.6	3673.4	0.15%
B3	90.9	15.5	6.5	892.6	983.8	1428.1	0.00%	63.8	15.5	796.6	6.5	1115.4	2080.4	1.27%
B4	0	4.9	10.5	86.7	187.7	90.5	0.00%	0	4.9	111.4	10.5	178.6	94.1	0.30%
B5	17.1	12.4	9.5	244.9	398.9	312.7	0.00%	12	12.4	205.1	9.5	422.1	477.9	0.00%
B6	240.7	19.9	304.7	667.4	2016.7	1862	0.00%	170.2	19.9	554	304.7	2877.1	1952.5	3.96%
B7	399.7	13.3	447.6	520.5	678.8	138.2	0.00%	298.8	13.3	582.2	447.6	877.9	448.5	3.20%
B8	165.3	574.4	2283.1	1935.6	9318.1	1284.7	0.00%	123.5	574.4	1721.6	2283.1	9614	2197.6	5.18%
Total	913.7	662.2	3250.9	5861	16875.9	8558.3	0.00%	668.3	662.2	5179.9	3250.9	18700.3	12305.9	3.32%

Table 2: Allocated water results based on CCGA in 2030 ($\times 10^4$ m^3).

5 Conclusions

This paper aimed to solve the allocation problem of multi-public sources optimization of water resources, and based on CCGA a water resource optimal allocation model was set up and applied in the Suibianhe Region. The model had a comprehensive object function and 5 constraints which considered the fairness, efficiency, ecology and coordination. Water demand ratio parameters for each public source were proposed which could be optimized by CCGA The optimization model of water allocation based on CCGA is capable of allocating water among different users in different water-using units with two or more public water sources. The model could provide a useful tool for decision-makers in aspects such as water resources projects planning and integrated water resource management.

Acknowledgements

References

[1] Y. Chen, H. Huang. "Coevolutionary genetic watermarking for owner identification", *Neural Computing and Applications*, **26**, pp. 291-298, (2015).

[2] Z. Dong. Water Resources Planning and Management, China Water Power Press, China, pp. 106-108, (2008).

[3] J. Hou, W. Mi, J. Sun. "Optimal spatial allocation of water resources based on Pareto ant colony algorithm", *International Journal of Geographical Information Science*, **28**, pp. 213-233, (2014).

[4] P. Husbands, F. Mill. "Simulated co-evolution as the mechanism for emergent planning and scheduling", *International Conference on Genetic Algorithms*, **68**, pp. 264-270, (1991).

[5] W. Xu, Z. Dong, Z. Zhu, et al. "Water-saving potential at county level", *Journal of Economics of Water Resources*, **34**, pp. 59-61, (2016).

[6] Y. Yang, X. Yu. "Cooperative coevolutionary genetic algorithm for digital IIR filter design", *IEEE Transactions on Industrial Electronics*, **54**, pp.1311-1318, (2007).

[7] H. Zhao, S. Ding. "Study of automated PCNN system based on fruit fly optimization algorithm", *Journal of Computational Information Systems*, **10**, pp. 6635-6642, (2014).

[8] W. Zhao, S. Alam, H.A. Abbass. "MOCCA-II: A multi-objective co-operative co-evolutionary algorithm", *Applied Soft Computing*, **23**, pp. 407-416, (2014).