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Multi-Objective Optimal Allocation for Regional Water Resources Based On Ant Colony Optimization Algorithm

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Abstract

The extremely imbalance of water resources distribution all over the world has brough the water shortage problem to many countries and regions, especially in developing countries such as China. In his paper, we study on the problem of water resources allocation, with the objective to produce more benefits in economic, ecological and social aspects. Specifically, we formulate the water resources allocation as a multi-objective optimization problem, and propose to employ Ant Colony Optimization (ACO) based algorithm as a solution. We also use the water resources dataset of Beijing city to evaluate the effectivity of our method.

Keywords: *Water resource allocation, Ant Colony Optimization (ACO)*

1. Introduction

The extremely imbalance of water resources distribution all over the world has brough the water shortage problem too many countries and regions [1]. Nowadays, water resources allocation has become a worldwide focus topic. In China, the total amount of water resources ranks 6th in the world, but the average per person is only 1/4 of the world average level, and therefore, China has been listed as one of the 13 water-poor countries in the world [2]. It is predicted that there would emerge a peak of water shortage in 2010 to 2020, and by then there might be a large area of water scarcity in China.

To this end, we study on the problem of water resources allocation. Indeed, the research on water resources approximately started from 1960s. In 1962, Maass et al. [3] developed a water-resource system using single objective nonlinear static planning. Loucks et al. [4] tried to employ system planning method to solve complex water resource problem. Later on, some new algorithms such as Genetic Algorithm (GA), Simulated Annealing (SA) have been applied to optimize the allocation of water resources. For example, Tokuda et al. [5] designed an adaptive annealing with chaotic optimization algorithm to optimize the water resource allocation. Also, the problem has evolved into a multi-object optimization problem. For example, Haimes et al. [6] formulated the water resource allocation problem as a multi-objective optimization and provided some solutions.

In this paper, we aim to optimize the planning of limited water resources, in order to produce more benefits in economic, ecological and social aspects. The allocation of water resources is to produce an optimal deployment among water consumption regions and departments. The objective is to obtain a balance between economic, ecological and social development, that is, to achieve economic benefit, promote social progress, and maintain the ecological balance of the environment. Therefore, we formulate it as a multi-objective

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optimization problem. Along this line, we propose to employ a method based on Ant Colony Optimization (ACO) algorithm [7] to solve the water resources allocation problem.

To remain of this paper is organized as follows. Section 2 presents the water resources allocation algorithm based on ACO. In Section 4 we conduct some experiments based on the water resources situation in Beijing. Finally, the paper is concluded in Section 4.

2. Water Resources Allocation Model

2.1 Objective Function

We partition the target region into K areas. Suppose the set of water resources includes surface water, ground water, reused water, and transferred water, etc., notated as $i(i=1,2,...,I)$. The water consumption of users includes daily use, agricultural use, industrial use, and environmental use, etc., notated as $j(j=1,2,...,J)$. Let x_{0j} be the amount of water demand of user j, x_{ij} be the amount of water supply of resource i to user j.

Now we define the objective functions. Recall that we consider three different objectives, that is, economic, ecological and social benefits of water resources allocation. Our goal is to maximize the following function:

$$F(X)=\max(Z_1,Z_2,Z_3), X\in G(X), \tag{1}$$

Where Z_1,Z_2,Z_3 are the objective functions of economic, ecological and social benefits respectively, and $G(X)$ is the set of constraints.

First, the objective function of economic benefit is defined as:

$$Z_1=\max\sum_{j=1}^{J}\sum_{i=1}^{I}(b_{ij}-c_{ij})x_{ij}\alpha_i\beta_j, \tag{2}$$

Where b_{ij} is the benefit factor, c_{ij} is the cost factor, α_i is the coefficient for sequential water supply, and β_j is the coefficient for equitable water use.

We define the objective function for social benefit based on the degree of coordination of water supply and demand, which refers to the coordination situation of all water resources supplies and consumptions within the whole water system in a year. Inspired by [8], we define the degree of coordination as follows:

$$DOC=\sum_{k=1}^{K}\sum_{j=1}^{J}\frac{1}{12}\times\sum_{t=1}^{12}\left\{\xi_i(t)\left[x_{0j}^k(t)-x_{ij}^k(t)\right]\right\}, \tag{3}$$

where $x_{0j}^k(t),x_{ij}^k(t)$ are the amount of water demand and water supply for user j at time t within a year in area k respectively, and $\xi_i(t)$ is the grey relation coefficient [9] of $x_{ij}(t)$ and $x_{0j}(t)$ at t, which is calculated as:

$$\xi_i(t)=\frac{\min\limits_i\min\limits_t\left|x_{0j}(t)-x_{ij}(t)\right|+\rho\max\limits_i\max\limits_t\left|x_{0j}(t)-x_{ij}(t)\right|}{\left|x_{0j}(t)-x_{ij}(t)\right|+\rho\max\limits_i\max\limits_t\left|x_{0j}(t)-x_{ij}(t)\right|}, \tag{4}$$

Where ρ is the resolution factor, and $\rho \in (0,1)$. In this study, we set $\rho = 0.5$ [10].

Therefore, the objective function for social benefit is defined as:

$$Z_2 = \max DOC. \tag{5}$$

The environmental benefit is calculated based on the amount of main pollutant emissions. In this paper, we suppose Chemical Oxygen Demand (COD) as the main pollutant factor. Therefore, the objective function for environmental benefit is defined as:

$$Z_3 = -\min \sum_{j=1}^{J} 0.01 d_j p_j \sum_{i=1}^{I} x_{ij},$$

(6)

Where d_j is the amount of COD in the waste discharge of user j, measured in mg/L, and p_j is the coefficient of waste discharge of user j.

The constraints of the optimization problem are as follows.

The bearing capacity of water resources: the demand of water supply should not be larger than the potential usage of water resources:

$$\sum_{i=1}^{I}\sum_{j=1}^{J} x_{ij} \le \sum_{i=1}^{I} W_i, \tag{7}$$

Where W_i is the available supply of water source i.

Water demand limit of users: the amount of user demand of water resources should be stable, that is

$$Q_{\min.j} \le \sum_{j=1}^{J} x_{0j} \le Q_{\max.j}, \tag{8}$$

Where $Q_{\min.j}, Q_{\max.j}$ are the minimum and maximum demands of water for user j.

(1) Non-negative constraint: the demand and supply of water should be non-negative, i.e. :

$$x_{0j} \ge 0, x_{ij} \ge 0. \tag{9}$$

2.2 Allocation Algorithm based on ACO

In this section, we adapt the ACO algorithm to solve the water resources allocation problem. First of all, we define a tabu list where ant h does not satisfy the constraints mentioned before, notated as $tabu_h$.

Suppose the phenomenon of ant h on the path from node i to j at time t is notated as $\tau_{ij}{}^{h}(t)$, and the initial value is $\tau_{ij}{}^{h}(0)=c$, where c is a constant. Notate the probability of ant h transferring from node i to j at time t as $p_{ij}{}^{h}(t)$, which is calculated as:

$$p_{ij}{}^{h}(t)=\begin{cases}\dfrac{\tau_{ij}{}^{h}(t)^{\alpha}\left(1/d_{ij}{}^{h}\right)^{\beta}}{\sum\limits_{s\in allowed_h}\tau_{ij}{}^{s}(t)^{\alpha}\left(1/d_{ij}{}^{s}\right)^{\beta}}, & j\in allowed_h; \\ 0, & otherwise.\end{cases} \tag{10}$$

where $allowed_h=\{A-tabu_h\}$, A is the set of nodes, α is the heuristic factor, meaning the importance of path with remaining pheromones, β is the heuristic factor for $1/d_{ij}^{h}$, denoting the effect of heuristic information, and d_{ij}^{h} is the value of Equation (1).

At time $t+1$, the phenomenon at pah (i,j) is updated as follows:

$$\tau_{ij}(t+1)=(1-\rho)\tau_{ij}(t)+\Delta\tau_{ij}(t), \tag{11}$$

$$\tau_{ij}(t)=\sum_{h=1}^{m}\Delta\tau_{ij}^{h}(t), \tag{12}$$

Where $1-\rho$ is the residual coefficient of pheromones, $\rho\subset[0,1)$, and m is the number of ants. $\Delta\tau_{ij}^{h}(t)$ is the amount of pheromones remaining on the path at current iteration for ant h, which can be calculated as:

$$\Delta\tau_{ij}^{h}(t)=\begin{cases}\dfrac{Q}{L_h}, & \text{if ant } h \text{ passes} (i,j) \text{ at current iteration;} \\ 0, & \text{otherwise.}\end{cases} \tag{13}$$

Where Q is a constant, and L_h is the total length of ant h's tour.

Furthermore, in order to avoid the local optimal solution of the algorithm, we design an adaptable strategy to adjust ρ. That is, when there is no improvement of the local solutions within N iterations, ρ is adjusted by:

$$\rho(t+1)=\begin{cases}0.95\rho(t), & \text{if } 0.95\rho(t)\geq\rho_{\min}; \\ \rho_{\min}, & \text{otherwise.}\end{cases} \tag{14}$$

Where $\rho_{\min}$ is the minimum value of ρ. The goal is avoid the low convergence speed caused by small ρ.

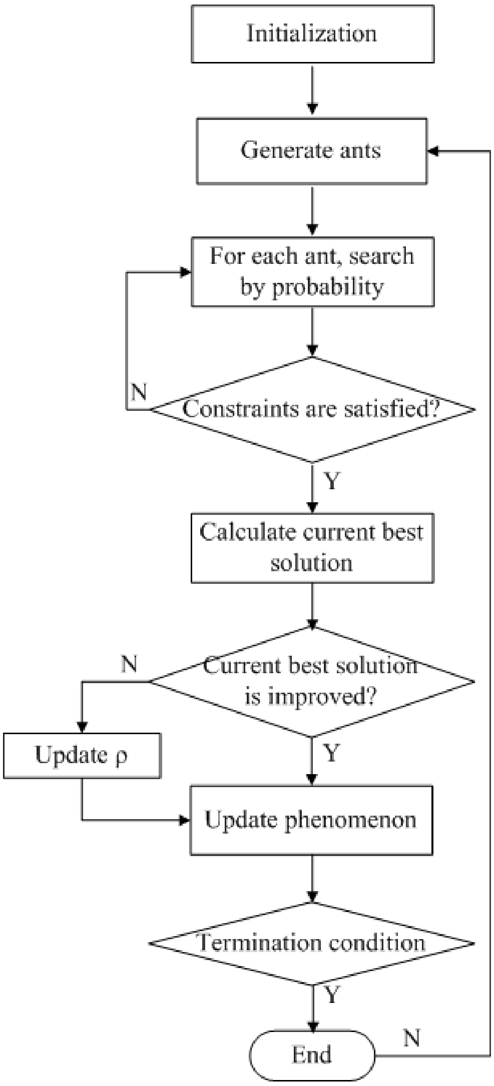

Figure1. Flow Chart of ACO based Algorithm for Water Resources Allocation

Now we present the workflow of water resources allocation based on modified ACO algorithm, as shown in Figure 1. The steps of the whole process are as follows:

Step 1: Initialize the parameters and constraints settings, as well as the termination condition of the algorithm;

Step 2: Generate m ants, and randomly put them on nodes;

Step 3: For each ant h, do the following:

3.1 Transfer to the next node j with the probability of $p_{ij}^{h}(t)$, and

3.2 If the constraints are not satisfied, put the current node into $tabu_h$, and choose other nodes;

Step 4: Calculate the best solution at current iteration, notated as S_t^*;

Step 5: If S_t^* is not better than the best solution of earlier N iterations, adjust ρ as Equation (14). Otherwise, go to Step 6;

Step 6: Update $\Delta\tau_{ij}, \tau_{ij}$, and then set $\Delta\tau_{ij} = 0$;

Step 7: If the number of iterations is smaller than the maximum iteration, go to Step 2. Otherwise, algorithm ends.

3. Experiment

We employ the water resources data of Beijing for experiment. The data is obtained from Beijing Water Authority [11], as listed in Table 1.

Table 1. Water Resources Data of Beijing from 2002 to 2011 (Water amount: billion m^3, population: million)

Year	Total amount of water resources	Reused water	Total water use	Agricultural water use	Industrial water use	Daily water user	Environmental water use	Permanent resident population
2002	16.10		34.63	15.50	7.50	5.40	0.80	142.3
2003	18.40		35.80	13.80	8.40	6.38	0.60	145.6
2004	21.40	2.04	34.19	13.50	7.70	5.70	0.61	149.3
2005	23.20	2.60	34.50	13.20	6.80	5.80	1.10	153.8
2006	24.50	3.60	34.32	12.80	6.20	6.00	1.62	158.1
2007	23.80	4.95	34.81	12.40	5.80	6.20	2.72	163.3
2008	34.20	6.00	35.10	12.00	5.20	6.43	3.20	169.5
2009	21.84	6.50	35.50	12.00	5.20	6.66	3.60	175.5
2010	23.08	6.80	35.29	11.40	5.10	6.59	4.00	196.1
2011	26.81	7.00	36.00	10.90	5.00	7.54	4.50	201.9

The prediction results of water resources situation of Beijing in 2015 is shown in Table 2. As indicated in [12], the increasing development of the agriculture and the steady progress of industry contribute to a stable with a slight decline trend of the total water consumption from 1990 to 2002. We can see that our results are consistent with that finding. Specifically, the agricultural water use is decreasing, and the industrial water use tends to be stable. Generally, our results tally with the Beijing government report [13].

Table2. Water Resources Optimal Allocation Results of Beijing in 2015 (Water amount: billion m^3)

Year	Total amount of water resources	Reused water	Total water use	Agricultural water use	Industrial water use	Daily water user	Environmental water use
2015	21.45	11.96	33.41	6.91	4.40	7.09	5.14

4. Conclusion

In this paper, we focus on the problem of water resource allocation problem, with the objective to maximize the economic, environmental and social benefits. To solve this multi-objective task, we adapt the ACO algorithm and present the workflow of the model. Besides, based on the water resources of in Beijing from 2002 to 2011, we predict the future water resource allocation in 2015 using the proposed method. Our results are consistent with the Beijing government report, which proves the efficiencies of our model.

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