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Multisource and multiuser water resources allocation based on genetic algorithm

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Abstract

Water resources are one of the important supply factors for urban survival and development. The water demand of a city and the amount of water supplied by the natural environment affect the overall development of the city. In this study, remote sensing image interpretation is used to classify land use and predict ecological water demands. An optimal allocation model of multisource and multiuser water resources has been established. The allocation of water resources in 2020 and 2030 was also forecasted.

Keywords Allocation of water resources · Genetic algorithm · Red line of water resources · Ecological red lines

1 Introduction

Water resources are an important condition for maintaining the economy and society [1]. With the development of urbanization, ecological degradation, river and lake shrinkage, water pollution and groundwater level decline have occurred [2, 3]. At present, studies mainly focus on the types of ecosystems, such as rivers [4, 5], wetlands [6] and terrestrial vegetation [7, 8]. Rijiberman studies systems of evaluation for water resources and how the water capacity can be used as an evaluation factor for water resources and the environment [9]. Madulu studies the Wami River Basin as well as the conflict between human activities and water resources including wildlife survival and the development of animal husbandry [10]. Overall, a complete assessment system has not yet been formed and further in-depth studies are necessary.

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Harbin is located on the banks of the Songhua River. Since the 1960s, the increase in population and industry has overexploited the water resources. Harbin's regional water supply is insufficient, and due to the influence of water pollution, water supply in Harbin is limited. Therefore, this paper forecasts the water demand of Harbin in 2020 and 2030. In traditional algorithms, the ecological red line is integrated into the traditional algorithm. The optimal allocation model for multisource and multiuser water resources is constructed, and the prediction of water resources in 2020 and 2030 is optimized.

2 Study area and data

Harbin (44°04′N–46°40′N, 125°42′E–130°10′E) is located in Heilongjiang Province. As the largest city in the Northeast of China, the total land area of Harbin is 53,068 km^2, and the total population in Harbin is ranked second in China's provincial cities. The research area of this paper has eight areas that include Songhua River mainstream, two rivers and three tributaries.

The Thematic Mapper (TM) is an advanced, multispectral scanning, Earth resources sensor designed to achieve higher image resolution, sharper spectral separation, improved geometric fidelity and greater radiometric accuracy and resolution. The TM image can be downloaded in the official website of the United States Geological Survey (http://glovis.usgs.gov).

The remote sensing images include TM image data from LandSat8 satellite in 2013 and 2014 (June–September), which includes 3 images for each year. The TM image data from the LandSat5 satellite were obtained for 2006–2012 (June–September).

The water resources data are obtained from the "Sustainable Utilization Planning of Water Resources in Harbin (2001–2030)," which is a plan issued by the local government. According to the government announcement, the total water supply in Harbin in 2020 was 980,090,000 m^3, of which the groundwater was 82,490,000 m^3 and the surface water was 897,600,000 m^3. In 2030, the total water supply in Harbin was 1,107,840,000 m^3, of which the groundwater was 82,490,000 m^3 and the surface water was 1,025,350,000 m^3.

3 Methodology

In this paper, ENVI v5.1 is used for band fusion, splicing, clipping and projection of TM images, and then, the available TM images were classified into forestland, cultivated land, residential areas and water bodies. ArcGIS software was used to transform the TM raster data of land-use types into the vector data. By overlapping the vector data of land-use types and the vector data of ecological red line, the range of the ecological red line areas of different land-use types was obtained. The ecological red line is delineated according to the "Guidelines for Delineation of Ecological Protection Red Line" issued by the Ministry of Ecology and Environment of the People's Republic of China [11]. And then the area of the ecological red line area under different land-use types was obtained [12, 13].

To make a prediction with quota, while assuming a reasonable per capita daily water consumption rate, domestic water demands were calculated as:

$$Q = 365 \cdot p_t \cdot a_t \tag{1}$$

where t is the planning year, Q_t is the residents' water consumption for a year, and P_t is the total population of the year. a_t is daily water consumption.

The *agricultural water demand* is predicted according to the water consumption quota and agricultural irrigation quota for Heilongjiang Province as well as the farmland planning of Harbin.

$$D_t = \sum_{j=1}^{8} \sum_{k=2}^{4} s_{kj} q_{kj} \tag{2}$$

where j is area code, k is the sequence number of agricultural product variety, D_t is agricultural water demand, S_{kj} is the planting area of agricultural product variety of k in j area, and q_{kj} is water consumption quota of agricultural product variety of k in j area.

The *industrial water demand* is predicted as follows:

$$W_{t,I} = a_{t,I} \times I_t \tag{3}$$

where $W_{t,I}$ is the demand of industrial water, $a_{t,I}$ is the water demand of industrial output per ten thousand yuan in planning year, and I_t is industrial output for the planning year.

3.1 Ecological water demand

The river eco-environmental water demand is composed of river base flow, which maintains the ecological function of rivers, the evaporative water demand and the water requirement for sediment transport:

$$W_B = W_M + W_E + W_S \tag{4}$$

where W_B is urban river eco-environmental water demand, W_M is the basic river ecological water requirement, W_E is the evaporation water requirement of the river, and W_S represents the water requirement of river leakage.

The ecological water requirement formula for green space is calculated by the limit method as follows:

$$L_{\mathrm{g}} = \frac{1}{1000} d_{\mathrm{g}} \times M_{\mathrm{g}} \tag{5}$$

where L_{g} is the ecological water requirement of green space, d_{g} is the water demand quota of green space in the study area, and M_{g} is the area of green space.

Using the dive evaporation method to calculate ecological water demand of forest-land [14], the formula is as follows:

$$Q_i = A_i \times \varepsilon_i \times k \tag{6}$$

where Q_i is the demand of ecological water of i and i represents different vegetation types. K is vegetation coefficient, ε_i is dive evaporation, and A_i is vegetation area.

According to the industry water quota for landscaping, the following formula was used for calculating ecological water demand:

$$G_t = s_t q_t \tag{7}$$

where S_t is the area of green space and q_t is water demand quota for green space irrigation per unit area.

3.2 Allocation of water resources

Water resources in this area include industry, agriculture, ecological environment and residents' life. The resulting function should include economic benefits, social benefits and environmental water benefits based on the following formulas:

$$\left\{\begin{array}{l} F(x) = \text{opt}\{f_1(x), f_2(x), f_3(x)\} \\ G(x) \le 0, x \ge 0 \end{array}\right\} \tag{8}$$

$G(x)$ is the set of conditions that use the model to meet the following conditions: The total amount of water allocated to various water departments should not exceed the total water supply of all kinds of water sources, and the amount of water allocated to various water departments should not exceed the total amount of water [15].

(1) Economic benefit target

$$f_1(x) = \max \sum_{l=1}^{8} \sum_{p=1}^{4} \sum_{m=1}^{2} \left(a_p^l \cdot x_{mp}^l \right) \tag{9}$$

where a_p^l is the coefficient of the output value of a unit of a cubic meter of water;

(2) Society benefit target

$$f_2(x) = \min \sum_{l=1}^{8} \sum_{p=1}^{4} \sum_{m=1}^{2} c_p \left(b_p^l \cdot x_{mp}^l \right) \tag{10}$$

where c_p is the water shortage weight for water users and b_p^l is the water requirement for the water sector;

(3) Water environment benefit target

$$f_3(x) = \min \sum_{l=1}^{8} \sum_{p=1}^{4} \sum_{m=1}^{2} w_p^l \cdot x_{mp}^l \tag{11}$$

where W_p^l is the discharge coefficient of pollutant and general selection of the chemical oxygen demand.

Quantitative constraints of water mainly consider two aspects, water supply and water demand, where

(1) Water source supply

$$\sum_{m=1}^{2} \sum_{p=1}^{4} \sum_{l=1}^{8} x_{mp}^l \leq W \tag{12}$$

W is the sum of two types of water resources.

(2) Water requirement constraints of various water-use departments.

Water requirement constraints indicate that the total amount of water allocated by each water department cannot exceed its water requirements.

$$\sum_{m=1}^{2} x_{mp}^l \leq D_p^l \tag{13}$$

where D_p^l is the water requirement for the water users, and the variable constraint is not negative.

Formula 8 is the objective function of the genetic algorithm. l represents the subregion, with a total of eight subregions. P represents the four water sectors, including domestic water demand, agricultural water demand, industrial water demand and ecological water demand. m indicates the surface water supply and the groundwater supply. According to historical data, the range of water demand of each district and water sector was set. The random number is selected as the initial input parameter in the range of values. The random number was converted to binary number and optimized by crossover and mutation.

4 Results and discussion

The prediction results show that domestic water demand will increase. The total domestic water demand in 2020 is 360,677,000 m^3, while the total domestic water demand in 2030 is 491,580,400 m^3. The prediction results show that with the implementation of water-saving transformation projects, the total demand of agricultural water decreases, and the ecological water demand will increase.

The water allocation in different regions across two planning years was obtained. Tables 1 and 2 show the balance of water supply and demand for 2020 and 2030,

Table 1 Water balance in 2020

District	Water category (10,000 m^3)								Shortage rate (%)
	Domestic		Agricultural		Industrial		Ecological		
	Requirement	Supply	Requirement	Supply	Requirement	Supply	Requirement	Supply	
Nangang	8058	7709	781	340	1485	1448	900	575	10
Daoli	5577	5335	2881	1255	647	631	3942	2518	25
Daowai	4674	4472	7493	3266	859	838	2059	1315	34
Songbei	1711	1637	4580	1995	1200	1170	5331	3405	36
Xiangfang	5593	5350	2329	1015	1857	1811	1618	1033	19
Pingfang	1110	1062	288	125	484	472	674	431	18
Hulan	5163	4939	29,240	12,739	1260	1229	10,658	6807	44
Acheng	4182	4001	17,998	7841	981	957	16,050	10,251	41

Table 2 Water balance in 2030

District	Water category (10,000 m^3)								Shortage rate (%)
	Domestic		Agricultural		Industrial		Ecological		
	Requirement	Supply	Requirement	Supply	Requirement	Supply	Requirement	Supply	
Nangang	11,826	11,518	586	250	292	273	915	406	9
Daoli	7149	6963	2167	923	122	114	4026	1785	27
Daowai	4986	4856	5624	2395	154	144	2226	987	35
Songbei	2890	2815	3442	1466	311	291	5331	2364	42
Xiangfang	7177	6990	1752	746	365	341	1715	760	20
Pingfang	1148	1118	484	206	91	85	683	303	29
Hulan	8630	8406	21,945	9345	255	238	11,218	4974	45
Acheng	5352	5213	13,542	5767	184	172	16,447	7292	48

Table 3 Water balance summary

Compare items	Planning year	Domestic water	Agricultural water	Industrial water	Ecological water
Water supply prediction	2020	98,009			
	2030	110,784			
Water requirement prediction	2020	36,068	65,590	8772	41,232
	2030	49,158	49,541	1774	42,562
Actual configuration	2020	34,504	28,577	8557	26,336
	2030	47,879	21,098	1658	18,871
Water shortage rate	2020	4.34%	56.43%	2.45%	36.13%
	2030	2.60%	57.41%	6.52%	55.66%

respectively. Table 3 shows that agricultural water consumption and water shortage are the greatest at all levels in Harbin, where the rate of agricultural water shortage is above 55%. Apart from agriculture, the rate of water shortage in industry is also increasing. Domestic water demand is not fully met in the planning year. The eco-environmental water requirement is also not satisfied in the planning year.

From the results of supply and demand of water resources, the water demand cannot be satisfied for future conditions, and there is a tendency for the ecological environment to deteriorate in Harbin.

5 Conclusions

The ecological red line of water resources of the Harbin section of Songhua River is delineated. Water consumption and water demand in 2020 and 2030 were predicted. A genetic algorithm is used to solve the model, and the results for two planning levels in 2020 and 2030 are obtained. The domestic water demand showed an increasing trend, while the agricultural and industrial requirement showed a downward trend. The demand of ecological water was balanced. The areas with high water shortage rates are Hulan, Acheng, Daowai and Songbei Districts, and there is no significant improvement over the next 15 years. There is a large amount of water shortage in agricultural water and ecological water use; there is an increasing trend in ecological water shortages; and the trend in agricultural water shortage is changing slowly.

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