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Comprehensive model for managing water resources in the Baotou City, Inner Mongolia

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ABSTRACT

Based on the analysis of water resources and water supply conditions of the Baotou City, a multi-objective and comprehensive model for managing water resources is established through the selection of decisive variables, analysis of the balance of water resources demand and supply, and the set-up of the managing districts. The optimal distribution of groundwater is strongly emphasised and a response matrix is used to express the restraint of water level in the model. The model is solved using linear objective programming. The analytical results indicate that the optimised scheme has excellent social, economic, and environmental benefits, and can be used as a reference for the development and planning of the Baotou City.

INTRODUCTION

The Baotou City lies in the mid-western part of Inner Mongolia in North China (Fig. 1). As one of the most important industrial bases, it has a good rate of economic development. In recent decades, the discrepancy between water resources supply and demand has become more and more striking. Consequently, the availability of water has become the main constraint on development in the Baotou City. The improper use of water resources has led to continuous drawdown of the groundwater level within the exploitation area and created some other geological and environmental problems, such as salinisation of irrigation area near the Yellow River.

The water resources in the Baotou City include surface water and groundwater. The surface water includes the water from the Yellow River and Kunhe Reservoir. Mainly the urban population and industry use the Yellow River water through three water supply fields. The groundwater, including unconfined and confined water, can be divided into centralised groundwater resource field of the water supply company, individual wells owned by others, and agricultural irrigation wells. The total volume of water supply was 380 million m^3 in 1998, in which surface water occupied 57% and groundwater shared 43%. According to the development and planning of the Baotou City, the water shortage for drinking and industry will be 50 million m^3. If the actual water supply conditions, pipe network distribution, and agricultural water shortage conditions are all taken into account, the total annual water shortage may reach 150–200 million m^3. Therefore, it is an urgent need in water resources management to solve the water shortage problem by rationally using the limited water resources to ensure the social, economic, and environmental efficiency of the study area. Hence a comprehensive model for managing water resources was established.

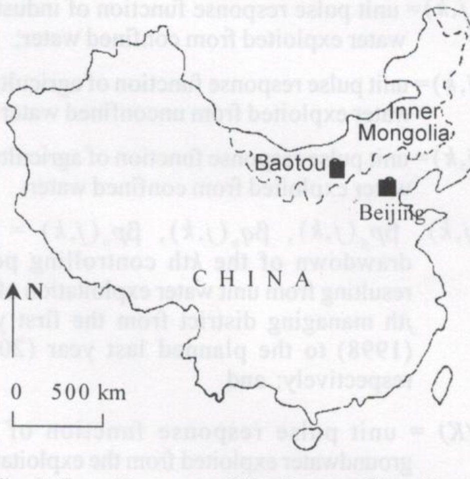

Fig. 1: Location map of the Baotou City, North China

MODELLING PRINCIPLES AND DECISIVE VARIABLES

According to the hydrogeological conditions, features of water supply and consumption, and the distribution of the industry and agriculture in the Baotou City, the administrative area can be divided into 17 managing districts (Fig. 2).

Modelling principles

For the purpose of effective modelling of groundwater, the following principles were set.

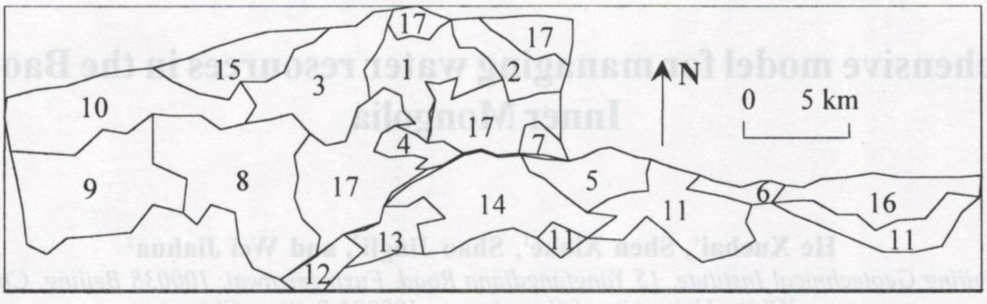

Fig. 2: Distribution of 17 managing districts in the Baotou study area

- To meet the drinking water demand in each managing district.
- Try to accomplish the planned output value of industry in each managing district.
- Minimise the cost of water supply.
- Ensure certain environmental efficiency. For the purpose of controlling continuous decline of groundwater level in the centre of depression cone, the withdrawal of groundwater should be controlled strictly. In order to lower groundwater level, it is necessary to increase groundwater volume and improve soil quality, and the groundwater can be exploited moderately in the area where the groundwater level is shallow.
- Meet the demand of agricultural water in each managing district.

Determination of decisive variables

Based on the modelling principles as well as water supply conditions, pipe network distribution, and water consumption, two types of decisive variable are determined in the comprehensive model (Shao and Cui 1994).

Decisive variables for surface water

The variable W_{ij} expresses the water supply quantity of the *i*th (*i*=1,2,3,4) surface water resources field to the *j*th (*j*=1,2,...,17) managing district for drinking and industrial consumption, and the variable R_j represents the water quantity of agricultural irrigation drawn from surface water resources field to the *j*th (*j*=1,2,..., 17) managing district.

Decisive variables for groundwater

According to the types of water resources and aquifers, the decisive variables for groundwater can be determined as follows:

a) Q_z = the water quantity exploited intensively by water supply company;

b) Qg_j (j=1,2,...,17) = the industrial water quantity exploited from phreatic water in each managing district;

c) Pg_j (j=1,2,...,17) = the industrial water quantity exploited from confined water in each managing district;

d) Qn_j (j=1,2,...,17) = the agricultural water quantity exploited from phreatic water in each managing district; and

e) Pn_j (j=1,2,...,17) = the agricultural water quantity exploited from confined water in each managing district.

Drawdown expression of groundwater exploitation

According to the hydrogeological conditions of the study area, a simulated model of water quantity of groundwater system has been established, and the natural water level (H_k) at water level controlling point and pulse response function have also been solved for the purpose of controlling groundwater level more accurately. Thus, at each water level controlling point, the drawdown due to exploitation can be expressed as follows (Chen and Li 1991):

$$S_k = \beta q_z(k) \cdot Q_z + \sum_{j=1}^{17} \Big[\beta q_g(j,k) \cdot Qg_j + \beta q_j(j,k) \cdot Qn_j + \beta p_g(j,k) \cdot Pg_j + \beta p_n(j,k) \cdot Pn_j \Big] \quad (1)$$

where k = the number of a water controlling point;

$\beta q_g(j,k)$ = unit pulse response function of industrial water exploited from unconfined water;

$\beta p_g(j,k)$ = unit pulse response function of industrial water exploited from confined water;

$\beta q_n(j,k)$ = unit pulse response function of agricultural water exploited from unconfined water;

$\beta p_n(j,k)$ = unit pulse response function of agricultural water exploited from confined water;

$\beta q_g(j,k)$, $\beta p_g(j,k)$, $\beta q_n(j,k)$, $\beta p_n(j,k)$ = the drawdown of the *k*th controlling point resulting from unit water exploitation of the *j*th managing district from the first year (1998) to the planned last year (2010) respectively; and

$\beta q_z(K)$ = unit pulse response function of the groundwater exploited from the exploitation field by water supply company.

COMPREHENSIVE MODEL

The exploitation and consumption of water resources are dealt with issues of many aspects, such as society, economy, environment and technology. Therefore, the problems of water resources management should be solved using multi-objective programming methods (Yang and Lin 1992). Administrative level linear objective programming is one of the multi-objective methods (Qian 1990), which takes each expecting value as an ideal point and turns original "hard constraints" with positive and negative deviation variables into "soft constraints". Optimal solutions can then be reached under the condition of objective programming. Some useful decisive information can be obtained from the positive and negative deviation variables of solutions. The advantages of this method are united mathematics expressions and common computing program. The method can be used to solve large-scale and multi-objective programming problems. This model was solved using the above method.

Industrial output value constraints

In the programming, the practical annual industrial output value in each managing district equals the unit industrial output value of per water supply volume multiplying corresponding water supply quantity and adding positive and negative deviation variable. The equation is as follows:

$$\alpha_j\left(\sum_{i=1}^{n} w_{ij} + \eta_j Q_z + Qg_j - Sh_j\right) - \delta v_j^+ + \delta v_j^- = V_j \qquad (2)$$

where

j = the number of seventeen managing districts, $j = 1,2,\ldots,17$;

α_j = unit output value of per water supply volume;

η_j = ratio of groundwater exploitation volume of water supply company to the total centralised groundwater exploitation volume(Q_z), $\sum_{j=1}^{17} \eta_j = 1$;

Sh_j = demand volume of drinking water;

V_j = value of planned industrial output; and

n = the number of surface water fields supplying to the jth managing district (n=4).

Cost constraint of industrial water

In this model, the cost of water supply mainly takes city living and industry into account, but the cost of agricultural water supply is not involved in. The total cost of water supply is equal to the unit cost of water supply multiplied by the volume of water supply.

$$\sum_{i=1}^{n}\sum_{j=1}^{17}(\theta\omega_{ij}\cdot W_{ij}) + \lambda z\cdot Q_z + \sum_{j=1}^{17}(\lambda_q\cdot Qg_j + \lambda_p\cdot Pg_j) - \delta f^+ + \delta f^- = F \qquad (3)$$

where

$\theta\omega_{ij}$ = cost coefficient of the ith surface water supply field offered unit water volume to the jth managing district;

λ_z, λ_q, λ_p, = cost coefficient of unit exploitation water of the groundwater field of the water supply company, unconfined water and confined water exploited by industry respectively; and

F = total cost quota of industrial water supply.

Constraint of agriculture water demand

$$Qn_j + Pn_j + R_j - \delta a_j^+ + \delta a_j^- = A_j \quad j=1,2,\ldots,17 \qquad (4)$$

where A_j = agricultural water demand of the jth managing district.

Constraint of resources

a) The total water supply volume of surface water fields cannot exceed the water volume that can be supplied, that is,

$$\sum_{j=1}^{17} W_{ij} \le W_i \quad i=1,2,3,4 \qquad (5)$$

where

W_i = the water volume that can be supplied by the ith surface water field.

b) The volume of surface water used by agricultural irrigation of each managing district cannot exceed the total water volume that can be used.

$$\sum_{j=1}^{17} R_{ij} \le R \qquad (6)$$

where

R = the total water volume of surface water that can be used by agricultural irrigation.

c) The volume of unconfined water exploitation cannot exceed the capacity of the resources.

$$kq\cdot Q_z + \sum_{j=1}^{17}(Qg_j + Qn_j) \le Q \qquad (7)$$

where

Q = the water resources that can be exploited from unconfined water; and

kq = ratio of unconfined water to the total groundwater exploited by water supply company.

d) The volume of confined water exploitation cannot exceed the resources that can be exploited.

$$kp\cdot Q_z + \sum_{j=1}^{17}(Pg_j + Pn_j) \le P \qquad (8)$$

where

P = the water resources that can be exploited from confined water; and

kp = ratio of confined water to the total groundwater exploited by water supply company, $kq+kp=1$.

Environmental constraint

Due to unreasonable exploitation, the volume of groundwater exploitation has been optimised in order to control groundwater level and improve water environment in this model. The following principles are taken into account in order to select groundwater level controlling points.

(a) At the centre of depression cone and the site of groundwater exploitation intensity, groundwater level of those areas should rise or at least remain constant.

(b) The unconfined water level should be lowered in those areas that unconfined water level is too high.

(c) The places where confined water can turn into unconfined water easily should also be controlled. According these principles mentioned above, 104 water level controlling points (Fig. 3) were chosen in the study area.

If h_k is the optimal controlling water level of the kth point, the following formula can be established:

$$S_k - \delta h_k^+ + \delta h_k^- = H_k - h_k \qquad k=1,2,3,\ldots,104 \qquad (9)$$

Upper and lower boundary limit constraints of decisive variables

In order to rationalise the optimal result, some decisive variables should be controlled by upper and lower boundary limits for the comprehensive model. Also drinking water demand in each managing district should meet the demand of hard constraints for the purpose of ensuring social efficiency of the water resources.

Objective function

In terms of the model criterion and constraint conditions mentioned above, the objective functions of the model can be determined as follows.

Objective of industrial output value

The optimal industrial output value should be as close as possible to the planned industrial output value in each managing district. According to expression (2), we can know that the positive and negative deviations should be minimum, namely:

$$\min Z_1 = \sum_{j=1}^{17}(\delta v_j^+ + \delta v_j^-) \qquad (10)$$

Objective of industrial water supply cost

The lower the water supply cost is, the better the result is. That is to say, the positive deviation should be minimised, namely:

$$\min Z_2 = \delta f^+ \qquad (11)$$

Environmental objective

The environmental objective is to control groundwater level strictly and try to make groundwater level close to the best-limited level:

$$\min Z_3 = \sum_{k=1}^{104}(\delta h_k^+ + \delta h_k^-) \qquad (12)$$

Agricultural water demand objective

For the purpose of meeting the demand of planned agricultural water supply in each managing district, it is required that the negative deviation in expression (4) should be minimised:

$$\min Z_4 = \sum_{j=1}^{17}\delta\alpha_j^- \qquad (13)$$

The constraint conditions consist of expressions (1) through (9) and upper/lower boundary limits of decisive variables. The objective functions are composed by

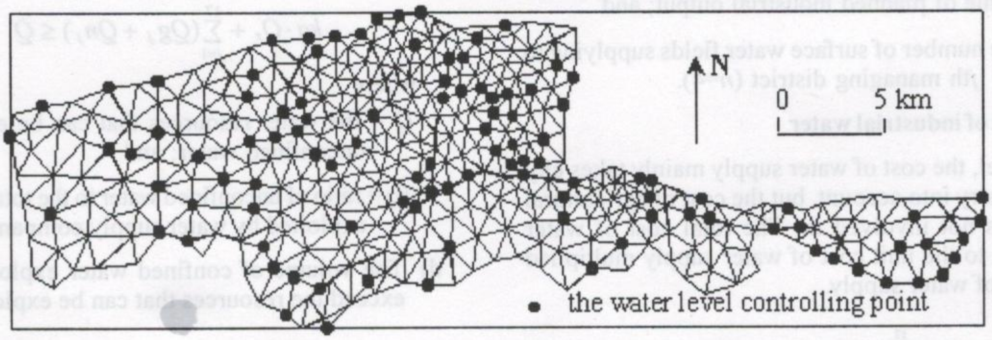

Fig. 3: The computing grids and location of the water level controlling points

expressions (10) through (13). The constraint conditions and objective functions make up the comprehensive model for managing water resources in the Baotou City. There are 69 decisive variables and 286 constraints in the model. The model is solved using the linear objective program.

RESULTS AND DISCUSSIONS

The computing results of the model include the optimal water supply quantity, industrial output, the changes of the groundwater level etc. Part of the computing results is listed in Table 1.

The total water supply quantity of the optimal planning in programming is 661 million m^3/a, and the water shortage is 140 million m^3/a. The No. 3 managing district (the Baotou Steel Factory) is the main consumer. Surface water takes up 80 per cent of the total water supply quantity, and groundwater occupies 20 per cent. As the Yellow River is the main source of surface water, its exploitation plays a decisive role in economic development of the Baotou City.

Industrial output value of each managing district can be fulfilled, except that only 7.5 billion RMB among 12 billion RMB planned by the No. 3 managing district (the Baotou Steel Factory) can be reached. It is difficult to fulfil the planned industrial output value using the available water supply facilities and production technology of the Baotou Steel Factory district. Therefore, in view of water resources and water supply capacity, the planned industrial output value in the Baotou Steel Factory district is higher than practical.

The quality of water will be distinctly improved for the decrease of total optimal groundwater exploitation, which has been reduced by 18 per cent (30 million m^3/a). According to the optimal exploitation scheme, unconfined groundwater level in the centre of depression cone will rise 1–2 m by the year 2010. While in the upper area irrigated by the Yellow River, the groundwater level will decrease 1–2 m by that time. Because of lowering of the groundwater level, the occurrence of salinisation can be controlled effectively, the quantity of usable groundwater can be increased, and ecological environment can also be improved. At present, big depression cones are developing in confined aquifers due to overpumping. According to the optimal exploitation scheme, the water level of confined aquifer will recover 9 m by the year 2010. For the purpose of comparison, the simulated model of groundwater established above was calculated under current exploitation conditions. The results showed that, by the end of year 2010, unconfined and confined water level will drop by 1–3 m and 11 m, respectively. This proved the efficiency of the optimal management.

Table 1: Part of the computing results

No. of the managing district	Planned total water demand (million m^3/a)	Optimised total water supply (million m^3/a)	Optimised surface water supply (million m^3/a)	Optimised groundwater supply (million m^3/a)	Planned output value (billion RMB)	Optimised output value (billion RMB)	Changes of unconfined water level (m)	Changes of confined water level (m)
1	78.70	71.32	48.98	22.34	2.1	2.1	1.10	7.20
2	54.69	53.93	49.78	4.16	4.0	4.0	1.21	3.32
3	296.78	184.87	173.30	11.57	12.0	7.5	0.03	10.34
4	67.62	66.34	62.10	4.24	2.5	2.5	-0.96	10.45
5	60.23	57.48	52.37	5.10	2.5	2.5	0.74	7.41
6	28.14	24.68	17.37	7.31	2.7	2.7	0.53	
7	2.28	1.80	1.75	0.05	0.2	0.2	-2.18	0.18
8	20.16	13.48	10.00	3.48			-1.35	9.07
9	29.42	25.75	25.00	0.75			-0.99	8.31
10	17.02	17.02	10.96	6.05			0.59	9.69
11	24.34	24.34	14.38	9.95			-0.13	7.58
12	1.86	2.39	0.00	2.39			-0.09	
13	1.91	0.86	0.00	0.86			-1.84	
14	30.21	30.21	8.67	21.54			-1.92	
15	5.67	3.26	0.00	3.26			0.17	10.27
16	32.56	32.56	20.24	12.33			0.35	
17	50.75	50.75	34.10	16.64			0.07	4.23
Total	801.61	661.04	529.01	132.03	26.0	21.5		

CONCLUSIONS

Although the water resources of the Baotou City have been optimised through the comprehensive model, the water resources supply will still fall short of demand. The ways to resolve those problems include:

(a) Finding new water resources: To meet the water demand of the Baotou Steel Factory, a water supply project, which can ease the water supply pressure, should be established at the southern outskirts where groundwater resource is abundant.

(b) Reducing expenditure: The measures include improving water supply technology, reducing output value of using water, raising the rate of water reuse, strengthening the consciousness of water conservation.

(c) Adjusting the structure of the industry: The water-consuming industry should properly be limited and the water-conserving industry should be developed rapidly.

According to the optimal programming, under the current water resources and supply conditions, the drinking water is ensured and the water demand of industry and agriculture can be satisfied as far as possible. The output value planned can also be accomplished at minimum water supply cost at the same time. The purpose of controlling and improving environment can be obtained by optimising groundwater exploitation. The optimal programming can provide a reference basis for the social and economic development of the Baotou City in view of the water resources.

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