Synergetic Optimization of Water Resources, Energy and grain in the Yellow River Basin

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Abstract: Firstly in this paper an overall analytical framework model of water-energy-grain based on the synergetic theory was established. Secondly, a total partition structure model was built, which is also known as the water-energy-grain synergetic optimization model with internal control feedback function. An intelligent multi-factors balancing algorithm was also studied. Finally, the integration of the synergetic optimization distribution scheme and strategy for grain production, energy and water resources utilization in the Yellow River basin was put forward. The synergetic optimization theories of water resources allocation, grain production, energy resources development as well as models correlation and parameters transfer were systematically dealt with.

1. Introduction
Water, energy and grain are indispensable resources for human survival and development. With the population growth, economic and social development, the system risk of energy, grain and water resources has become increasingly world-wide concern. At the same time, water and eco-environment are becoming more and more worrying. Therefore, it is of great scientific significance to reveal the interaction mechanism and collaboratively optimize the interaction relationship. At the present, it is still in infancy in the field of water-energy-grain synergetic optimization research both in domestic and abroad. There are complex interactions and ties between water, energy and grain, but most of the previous studies focused on the improvement of the relationship between water and energy, water and grain, and neglected the feed-back correlation between water, energy and food. There are few quantitative and integrative optimum researches on the close relationship among them, especially on system optimization method and synergetic modeling technology.

Therefore, in this paper, the relationship among water resources, energy and grain is studied from the viewpoint of system science. The synergetic optimal model of water resources, energy and grain in the Yellow River basin is constructed. The solution method of multi-factor equilibrium is studied.

2. General Situation of Water Resources, Energy and Grain in the Yellow River Basin

2.1 Water Resource Conditions
The Yellow River Basin belongs to continental monsoon climate, most of which are located in arid and semi-arid areas, with less precipitation and large evaporation. The average annual precipitation in the basin is 445.8 mm, while evaporation is 1199.7 mm. The average annual runoff of the Yellow River is $534.8 \times 10^8 \text{m}^3$. According to the statistics of 2015, the per capita water in China was 2100 m$^3$, which
occupies only 28% of the global per capita water resources.

2.2 Grain Production
The total arable land in the basin amounts to 1553.2×10^4 ha. In addition, along the lower reaches of the Yellow River, irrigation areas were developed to 656×10^4 ha. The effective irrigation area amounts to 247.1×10^4 ha. In recent 30 years, the grain output of the river basin has increased continuously. The total grain output reached 4370×10^4 t in 2015.

2.3 Energy Development
The Yellow River basin is known as China's "energy basin" for rich hydro-power resources in the upper reaches, rich coal and natural gas resources in the upper and middle reaches and rich petroleum resources in the middle and lower reaches. It is proven that The Yellow River Basin has 685 coal production areas (or mine fields), reserved deposits are 4492×10^8 tons, accounting for 46.6% of the country's coal reserves.

3. Establishment and Solution of Synergetic Optimization Model

3.1 The Concept of Synergetic Optimization of Water Resources, Energy and Grain in Basin

The basin is a combination of regions with vertical hydraulic connections. Water resources, energy and grain are all the key elements for the survival and development of the basin. It is of great significance to coordinate their internal relations to realize the harmonious development of the basin. The synergetic optimization of water resources, energy and grain in a basin is to realize the overall optimization through the internal optimization of each subsystems (water resources, energy and grain).

3.2 Model Establishment

The general control model is used to identify the direction of the system evolution, to control and guide the optimization direction of the system. The model framework is shown in Fig.1.

![Fig. 1 Framework of Synergetic optimal model of water resources, energy and grain in the Yellow River Basin.](image)

Through coordination of water resources, energy and grain planning goals, the General Control Model could minimize integrated deviation, as follows:

$$\min f = \sum_{i=1}^{3} \omega_i \left( \frac{S_i^t - S_i^*}{S_i^*} \right)$$

where, $f$ represents integrated coordination of water resources, energy and food in basins, $\omega_i$ ($i=1, 2, 3$) are the contribution weights of water resources, energy and food to the overall target of the basin, it is determined by analytic hierarchy process (AHP) according to the criteria of efficient utilization of water resources, protection of energy and food security. $S_i^t, S_i^*$ is water consumption and water resources availability respectively. $S_2, S_2^*$ is actual energy production, energy planning output.
respectively. $S_1, S_2$ is actual grain production and grain planning output respectively.

(1) Water resources allocation model

Through reasonable water resources development, optimized allocation and scientific distribution, the comprehensive benefit of water supply in the basin can be maximized, and reasonable water distribution in different areas and sectors could be realized, i.e.

$$B(\omega) = \max \sum_{j=1}^{J} \sum_{t=1}^{T} [\theta(j, t) - C(j, t)] Q(j, t)$$

In which, B ($w$) is the comprehensive benefit of water supply; $\theta(j, t), C(j, t)$ is benefit and cost of water supply during t period in j area; $Q(j, t)$ is water supply in t period; J is the total number of fraction areas in the basin; T is the total period of water supply.

(2) Grain production model

Through rational planning, grain species combination and optimization, as well as planting pattern structural selection, the requirement of grain security and yield stability could be met. The purpose of the model is to maximize grain production and realize self supply in the basin.

$$T_F = \max \sum_{j=1}^{J} \sum_{k=1}^{K} \sum_{l=1}^{L} [P_F(j, k, l) A_S(j, k, l)]$$

In which, $T_F$ is the total grain yield in the basin; $P_F(j, k, l)$ is unit yield of grain in j area, k crop and l planning pattern; $A_S$ is crop planting area; L is the total number of planting patterns.

(3) Energy optimization model

Through reasonable scale, patterns combination and scientific layout, the national energy security and stable supply could be met. The goal is to maximize the energy output of the basin and to improve the support capacity of energy security.

$$T_E = \max \sum_{j=1}^{J} \sum_{m=1}^{M} \sum_{n=1}^{N} [P_E(j, m, n) E_0(j, m, n)]$$

In which, $T_E$ is the energy output of the basin; $P_E(j, m, n)$ is unit energy output in the j area under m energy and n technology level; $E_0(j, m, n)$ is energy production scale in the j area under m energy and n technology level; M is the number of energy types in the basins, and N is the number of energy production modes.

(4) Model correlation and Parameter transfer

The water resources allocation model optimizes the water supply areas and the water allocation in different sectors through regulation of water resources availability and the project scale, as follows;

$$Q_F(j, k, l) = f[E_Tc(j, k, l), P_e(j, k, l), G_E(j, k, l), \Delta W] / \eta_g(j, k, l)$$

In which, $Q_F(j, k, l)$ is the water demand quota during the growth period under the cropping pattern l and k crop in j area, which is affected by water demand $E_Tc$, effective precipitation $P_e$, groundwater recharge $G_E$ and the change of groundwater level $\Delta W$ during the growing period. The water demand $E_Tc$ of growth period is determined by crop coefficient $K_c$ and crop evapotranspiration $E_T0$, that is,

$$E_Tc = K_c E_T0$$

The crop coefficient $K_c$ is obtained from the field measurement. The evapotranspiration of crop $E_T0$ is usually calculated by Penman's formula. $\eta_g$ is the utilization coefficient of irrigation water, which consists of canal water utilization coefficient and field water utilization coefficient. If $Q_F(j, k, l)$ is expressed by the crop water consumption $w$, then, the water production function of crop growth period can be changed as follows;

$$P_F(j, k, l) = a + bw + cw^2$$

In which, w is water consumption during crop growth period; a, b, c is a constant and different values are taken for different crops in different regions. The relationship between water resource allocation model and energy optimization model is set up through energy production process, water demand and energy input-output function, etc.

$$Q_E(j, m, n) = X_{in}(j, m, n) / \eta_E$$

In which, $Q_E(j, m, n)$ is water demand quota per unit product for energy type $m$ and technology level $n$ in j area; $X_{in}(j, m, n)$ is the water requirement per unit energy production and usually affected by energy types, production process, technical level, etc. $\eta_E$ is the water use efficiency coefficient of
energy industry and determined by industrial water supply system. If we use energy production water consumption \( w \) to express \( Q_E(j, m, n) \), then, the Cobb-Douglas production function of energy industry with water as input factor is given as follows:

\[
P_E(j, m, n) = AK^\alpha L^\beta W^\gamma
\]  

(9)

In which, \( A \) is the technical level; \( K \) is capital investment; \( L \) is labor input; \( W \) is water consumption for energy production; \( \alpha, \beta, \gamma \) are constants, different regions and different energy production takes different values.

4. Results discussion

4.1 Basin Generalization

The node is an important basic calculation unit of water resources allocation, grain production and energy optimization. The generalized nodes in the Yellow River Basin are shown in Fig. 2.

4.2 Basic data input

Basic data includes water resources availability, economic and social development, grain production level, energy water production efficiency, total water demand in the basin, etc.

4.3 Synergetic optimization results

(1) Water resources allocation

The results of coordinated optimization of water resources in the Basin are shown in Table 1.

| Provinces   | Water demand | Surface water | Ground water | Un-conventional water | Domestic water | Energy Indus. | General indu. | Grain Prod. | Other Agri. | Ecology water |
|-------------|--------------|---------------|--------------|------------------------|---------------|---------------|---------------|-------------|-------------|---------------|
| Qinghai     | 27.67        | 16.77         | 3.270        | 0.40                   | 2.67          | 1.800         | 3.500         | 6.250       | 4.200       | 2.020         |
| Sichuan     | 0.36         | 0.330         | 0.020        | 0                      | 0.03          | 0             | 0             | 0.200       | 0.070       | 0.050         |
| Gansu       | 67.61        | 36.31         | 5.680        | 3.56                   | 9.81          | 5.350         | 12.42         | 7.930       | 9.010       | 1.030         |
| Ningxia     | 91.16        | 59.88         | 7.680        | 1.34                   | 3.53          | 4.940         | 3.860         | 38.75       | 14.91       | 2.910         |
| Inner Mong   | 108.9        | 63.45         | 25.08        | 2.24                   | 5.59          | 11.21         | 3.16          | 36.87       | 28.06       | 5.880         |
| Shaanxi     | 2.240        | 38.60         | 29.51        | 5.68                   | 17.62         | 13.35         | 9.50          | 16.40       | 15.91       | 1.010         |
| Shanxi      | 5.680        | 45.91         | 21.06        | 3.02                   | 11.64         | 11.22         | 5.500         | 26.99       | 14.19       | 0.450         |
| Henan       | 88.98        | 55.91         | 21.55        | 2.780                  | 9.680         | 8.840         | 5.760         | 44.26       | 11.39       | 0.310         |
| Shandong    | 85.48        | 66.59         | 11.44        | 1.330                  | 4.620         | 2.430         | 4.670         | 63.25       | 4.270       | 0.120         |
| Hebei       | 6.200        | 6.200         | 0            | 0                      | 0             | 0             | 0             | 6.200       | 0           | 0             |
| The basin   | 649.9        | 390.0         | 125.3        | 20.35                  | 65.19         | 59.14         | 48.37         | 247.1       | 102.0       | 13.78         |

(2) Grain production

The optimization scheme for grain production in the Yellow River Basin is shown in Table 2.
Table 2 Land use and grain production optimization of Yellow River basin in different planning years

| Provinces  | planting area×10^4ha. | Irrigation area×10^4ha. | Planting index | Grain output10^4t | planting area×10^4ha. | Irrigation area×10^4ha. | Planting Index | Grain output10^4t. |
|------------|----------------------|-----------------------|----------------|-------------------|----------------------|-----------------------|----------------|-------------------|
| Qinghai    | 22.7                 | 14.1                  | 1.0            | 85.0              | 23.7                 | 14.7                  | 1.0            | 98.0              |
| Sichuan    | 0.7                  | 0.1                   | 1.00           | 2.00              | 0.7                  | 0.1                   | 1.00           | 3.00              |
| Gansu      | 203.0                | 41.5                  | 1.16           | 583               | 223.3                | 40.7                  | 1.20           | 670               |
| Ningxia    | 84.4                 | 40.7                  | 1.11           | 359               | 88.8                 | 37.8                  | 1.15           | 413               |
| Inner Mongolia | 101.1            | 98.7                  | 1.00           | 528               | 104.9                | 92.5                  | 1.00           | 607               |
| Shaanxi    | 198.3                | 90.4                  | 1.56           | 815               | 213.8                | 97.5                  | 1.61           | 994               |
| Shanxi     | 227.3                | 74.2                  | 1.36           | 737               | 241.0                | 78.4                  | 1.42           | 892               |
| Henan      | 164.2                | 65.2                  | 1.87           | 883               | 175.5                | 79.7                  | 1.88           | 1204              |
| Shandong   | 45.3                 | 29.7                  | 1.54           | 378               | 48.5                 | 41.8                  | 1.67           | 573               |
| The basin  | 1 047.0              | 454.6                 | 1.46           | 4 370             | 1 119.2              | 483.2                 | 1.49           | 5454              |

5. Conclusions

A collaborative analysis framework based on water was constructed, and the synergetic optimization model of water resources, energy and grain was established under the general framework. Large scale system decomposition and coordination technique, hierarchy optimization method and nested genetic algorithm are used to solve the optimization of complex giant system.

Taking the 2030 level year of the Yellow River Basin as an example, it is concluded that the water supply of the basin can reach 535.6 ×10^8 m^3 through synergetic optimization of water resources, energy and grain, an increase of 23.98 ×10^8 m^3, in which agricultural water is 349.1 ×10^8 m^3, an increase of 19.85 ×10^8 m^3 over the actual agricultural water use in the current year. By optimizing the distribution of grain production, the total amount of grain in the basin will reach 5 453 ×10^4 tons, and the per capita grain output will be increased by 12%. Allocation of energy industry water consumption is 59.14 ×10^8 m^3. By optimizing the scale and distribution of energy resources, coal mining will reach 29.7 ×10^8 tons, petroleum production and processing will be 2.43 ×10^8 t, thermal power installation capacity will be 21.73×10^8 MW. Compared with the current year, coal mining will be increased by 2.86 times, petroleum production will be increased by 4.08 times, the total installation of thermal power will be increased by 0.8 times. On the basis of ensuring living and ecological environment water consumption, the grain income and energy production are increased, and the carrying capacity of water resources in the Yellow River basin is improved significantly.

Reference

[1] DECLAN C, EMMA A G, DELPHINED, et al.(2015) Climate and southern Africa's water-
energy-food nexus [J]. Nature Climate Change, 5(9): 837-846.

[2] SMAJGL A, WARD J, PLUSCHKE L.(2016) The water-food-energy nexus-realizing a new paradigm [J]. Journal of Hydrology, 533: 533-540.

[3] SCANLON B R, RUDDELL B L, REEDPM, et al.(2017) The food-energy-water nexus: transforming science for society [J]. Water Resources Research, 53(5): 3550-3556.

[4] JALILOV S M, KESKINEN M, VARIS O, et al.(2016) Managing the water-energy-food nexus: gains and losses from new water development in Amu Darya River basin [J]. Journal of Hydrology, 539: 648-661.

[5] HERMANN S, WELSCH M, SEGERSTROM R, et al.(2012) Climate, land, energy and water interlinkages in Burkina Faso: an analysis of agricultural intensification and bioenergy production [J]. Natural Resources Forum. 36(4): 245-262.

[6] HOWELLS M, HERMANN S, WELSCH M, et al.(2013) Integrated analysis of climate change, land-use, energy and water strategies [J]. Nature Climate Change. 3(7): 621-626.

[7] HERTEL T, STEINBUKS J, BALDOS U.(2012) Competition for land in the global bio-economy [J]. Agricultural Economics. 44(s1): 129-138.

[8] RINGLER C, WILLENBOCKE D, PEREZ N, et al.(2016) Global linkages among energy, food and water: an economic assessment [J]. Journal of Environmental Studies & Sciences, 6(1): 161-171.

[9] JESWANI H K, BKINSHAW, AZAPAGIC A.(2015) Environmental sustainability issues in the food-energy-water nexus [J]. Sustainable Production and Consumption. 2: 17-28.