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Water Resources Allocation Model with Blue Water and Green Water

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ABSTRACT: China has faced many problems about water resources for a long time, such as shortage, uneven distributions among regions, wasting and so on. With rapid development of social economics, the demand of water is pressuring, so optimal allocation of water resources is in critical need. Therefore, to build a harmony water rights system and a mature water market, and then fulfill tradable water rights mechanism, are key parts of the present management of water resources.

Since the initial water rights allocation is the precondition of water rights trade, it is theoretically significant to probe into an allocation model for it. In order to offer an effective theory support for initial water rights allocation, this paper attempts to define measurable criteria on the basis of which water resources can be allocated to the regions in basin in an equitable and reasonable manner.

In this paper, the concept of blue water and green water were discussed in water right allocation. Two models, only blue water and both blue and green water considered, were used to modeling the water resources allocating in proportion to each region's area, population, arable land or the GDP, in order for sustainable development.

The model put more emphasis on transferred water volume, which is in close relationship with the procedure of water transferring, both inside and outside the river basin. A case study was carried out in the Hanjiang River Basin, where the river is bifurcate and the largest branch of Yangtze. The modeling results in sub-districts under different criteria are discussed.

INTRODUCTION

Water resources allocation, especial initial water right allocation, plays a rather important role in water resources management in the river basin scale. In order to pursuing for equitable sharing, an integrated basin management of water resources is required, which is certainly supposed to result in an optimal benefit and sustainable development of eco-environment system. In the premise of assuring the basic demand for water, water use in sub-district will be considered to obtain high efficiency.

The conception, Green Water, was proposed originally by Falkenmark (1995) and was compared with another useful concept, Blue Water, usually stored in river, lake or saturated soil layer. Afterwards, more and more scientists began to introduce Green Water to the study fields of hydrology and ecology-environment. Among them, Rokstrom (1999) deems Green Water as one kind of runoff, which flows back to atmosphere ultimately. Jansson *et al.* (2001) suggested the importance of Green Water to maintaining ecology system. And Hope *et al.* (2004) paid lot of emphasis on influence upon agricultural economy.

Currently, there are two main standpoints with respect to Green Water. In a broad sense, it is the total amount of evaporation and transpiration in the scale of river basin. While in a narrow sense, it is the beneficial transpiration for agricultural production. For former one, all the rainfall in river basin is divided into two parts, namely Blue Water, the liquid water flows out of the river basin, and Green Water, including evaporation and transpiration by crop, pool, soil and others. For latter one, only water infiltrated into the root zone is considered as Green Water, which excluding evaporation and transpiration in pool, soil and others. In any case, Green Water is valuable resources for environment, and both Green Water and Blue Water are in close interrelationship and could transform into the other form conditionally. It is a dynamic process.

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Zaag *et al.* (2002) have established a water resources allocation model of river basin. In that model, Blue Water and Green Water are applied to allot water right for basin scale of linear river, with the definition of allocation criteria. In this paper, new improved models will be proposed, in which extra criteria are taken into account and the studied basin of bifurcate river will be analyzed. Appropriate mathematical expression will represent reasonable allocation of water resources in that certain river basin.

MODEL STRUCTURE

Allocation Criteria

There are two models are advocated in this section, only Blue Water considered and both Blue Water and Green Water considered. The available water resources are allotted for sub-district under the criteria of total area, population, crop area and GDP value (Gross Domestic Production), respectively, to achieve a goal of equity objective. For more detail, the planned criteria are listing as follows:

Criterion 1: The generated water resources in the river basin will be allocated by the proportion of river basin in the sub-district.
Criterion 2: The generated water resources in the river basin will be allocated by the proportion of population in the sub-district.
Criterion 3: The generated water resources in the river basin will be allocated by the proportion of crop area in the sub-district.
Criterion 4: The generated water resources in the river basin will be allocated by the proportion of GDP value in the sub-district.

In practical application, more premise are needed: firstly, two important parameters, the value of Green Water relative to Blue Water and the fraction of reserved water for basic requirement of each sub-district, are equal absolutely; secondly, for every sub-district, it has the exclusive upstream and downstream sub-strict. Of course, the most upstream sub-district has no upstream neighbor and the most downstream sub-strict has no downstream neighbor. Accordingly, the most upstream sub-district has not inflow from outside and the most downstream sub-strict are not entitled to deliver outflow to outside the studied river basin.

Model I: only Blue Water considered

(a) Calculate generated Blue Water of each sub-district using rainfall coefficient method,

$$Q_{b,i} = C_i A_i \max[P_i - I_i, 0] \quad i = 1, 2, \cdots n \qquad \ldots (1)$$

Where $Q_{b,\,i}$ is the generated Blue Water in the i^{th} sub-district ($10^6\ m^3/a$), A_i is the area of the i^{th} sub-district (Km^2), C_i is the rainfall coefficient of i^{th} sub-district, P_i is the average annual runoff of i^{th} sub-district(m/a) and I_i is the average annual interception of i^{th} sub-district (m/a).

(b) From the most upstream sub-district to downstream, the rightful sharing of water resources is given in sequence, excluding the reserved Blue Water,

$$Q_{r,i} = \left(Q_{t,i-1} + (1 - R_b) \sum_{k=i}^{k=n} Q_{b,k} \right) \frac{A_i}{\sum_{k=i}^{k=n} A_k} \qquad \ldots (2)$$

$$k = 1, 2 \cdots n \quad i = 1, 2, \cdots n$$

Where $Q_{r,\,i}$ is the rightful sharing of water resources excluding the reserved Blue Water of i^{th} sub-district ($10^6\ m^3/a$); $Q_{t,\,i-1}$ is the delivered water resources (Blue Water) of i^{th} sub-district from the upstream ($10^6\ m^3/a$) and R_b is the proportion coefficient of reserved Blue Water.

In this study, $R_b = 0.25$, which assumes that a quarter of generated Blue Water will be reserved in the original sub-district for fulfilling the basic demand for water. For the most upstream, in Equation (2), $Q_{t,\,i-1} = 0$.

(c) Compare the available water resources, including non-reserved Blue Water and transferred water from upstream. The surplus water will be transferred to downstream,

$$Q'_{t,i} = Q_{t,i-1} + (1 - R_b) Q_{b,i} - Q_{r,i} \qquad \ldots (3)$$

$$Q_{t,i} = \max[Q_{t,i-1} + (1 - R_b) Q_{b,i} - Q_{r,i}, 0] \; i = 1, 2 \cdots n \qquad \ldots (4)$$

(d) The allocation water right is the relative value of generated Blue Water, transferred water from upstream and transferred to downstream (water transfer from outside of river basin is un-allowed and allowed, respectively),

$$Q_i = Q'_{t,i-1} + Q_{b,i} - Q'_{t,i} \qquad i = 1, 2, \cdots, n \qquad \ldots (5)$$

$$Q_i = Q_{t,i-1} + Q_{b,i} - Q'_{t,i} \qquad i = 1, 2, \cdots n \qquad \ldots (6)$$

(e) Go back to Step (b), to allocate for the next sub-district. Above allocation is under the criterion of river area equity. Replace the variable A_i in Equation (2) with population, crop area or GDP of i^{th} sub-district, the corresponding results will present clearly.

Model II: both Blue and Green Water considered

In this suggested model, Green Water allocation is introduced to improve the equal sharing of water resources. Generally, Green Water will be converted to Blue Water through another parameter, W_g, which is the value of Green Water relative to Blue Water. In this study, $W_g = 0.5$, that means one unit Green Water equals to half unit Blue Green, from the viewpoint of utility.

(a) Estimate the generated Blue Water and Green Water. The former is decided by Equation (1) and the latter one is computed as,

$$Q_{g,i} = (1 - C_i)A_i \max[P_i - I_i, 0] \quad i = 1, 2, \cdots n \quad \ldots (7)$$

(b) From the most upstream to downstream, the rightful sharing of water resources is calculated in sequence, excluding the reserved Blue Water,

$$Q_{r,i} = \left(Q_{t,i-1} + W_g \sum_{k=i}^{k=n} Q_{g,k} + (1 - R_b) \sum_{k=i}^{k=n} Q_{b,k} \right) \frac{A_i}{\sum_{k=i}^{k=n} A_k} \quad k = 1, 2 \cdots n \; i = 1, 2, \cdots n \quad \ldots (8)$$

Where W_g is the weight of Green Water relative to Blue Water.

(c) Compare the surplus water which is more than the rightful sharing, and the transferred water to downstream. As Green Water could not be transferred, the actual transferring is the smaller one of the above two,

$$Q'_{t,i} = \min[Q_{t,i-1} + W_g Q_{g,i} + (1 - R_b)Q_{b,i} - Q_{r,i}, Q_{t,i-1} + (1 - R_b)Q_{b,i}] \; i = 1, 2, \cdots n \quad \ldots (9)$$

$$Q_{t,i} = \max[Q'_{t,i}, 0] \; i = 1, 2, \cdots n \quad \ldots (10)$$

(d) The allocated water right is (water transfer from outside is un-allowed and allowed, respectively),

$$Q_i = Q'_{t,\, i-1} + W_g Q_{g,i} + Q_{b,i} - Q'_{t,i} \; i = 1, 2, \cdots n \quad \ldots (11)$$

$$Q_i = Q_{t,i-1} + W_g Q_{g,i} + Q_{b,i} - Q'_{t,i} \; i = 1, 2, \cdots n \quad \ldots (12)$$

(e) Go back to Step (b). Continue to allocate water for the next sub-district.

Analogously, replace the variable A_i in Equation (8) with population, crop area or GDP of i^{th} sub-district, the corresponding results will present clearly.

Discussion of Transferred Water

Actually, Model I is a special form of Model α: $W_g = 0$ or Green Water is omitted completely. Equation (9) denotes that, the value of $W_g Q_{g,\,i} - Q_{r,i}$ is a benchmark. When $W_g Q_{g,\,i} \geq Q_{r,\,i}$ then the surplus water resources $Q_{t,\,i-1} + (1 - R_b)Q_{b,\,i}$ will be transferred to downstream. Otherwise, all Green Water and partial Blue Water are used full and the surplus water $Q_{t,\,i-1} + W_g Q_{g,\,i} + (1-R_b) Q_{b,\,i} - Q_{r,\,i}$ will be transferred. The mathematical expression guarantees the Green Water will never be transferred.

Besides, the transferring water $Q_{t,\,i}$ is a positive variable in Equation (10). If the rightful sharing water, $Q_{r,\,i}$, is relative larger and more than the summation of generated Blue Water, Green Water and transferred water from upstream, $Q'_{t,\,i}$ will be negative by Eqn. (9). Therefore, this sub-district is short of water resources and unable to supply water resources to downstream. It needs inflow water from outside. Thus, two conditions are discussed, water transfer from outside is un-allowed and allowed. When it is allowed, the amount water after allocation is not equal to the original situation. On the other way round, the water is always transferred in the river basin inside and the water resources volume is balanced at all time.

CASE STUDY OF HANJIANG RIVER BASIN

Studied River Basin

The studied area is Hanjiang River Basin. Hanjiang River is the largest branch of Yangtze River. It has a whole length of 1,577 Km and covers an area of 159 × 10^3 Km^2. The average annual rainfall ranges from 800 to 1,300 mm and the average annual evaporation is 893 mm (water surface) or ranges from 550 to 600 mm (land surface).

The sub-districts for water resources are divided by administrative division. For simplicity, mainly according to topological structure of Hanjiang River and Tangbaihe River (branch river of Hanjiang River), five sub-districts are divided throughout the entire river basin:

Sub-district A and B are located in Hanjiang River, where Sub-district A includes Hanzhong City, Ankang City and Shangluo City, and Sub-district B consists of Shiyan City and Shenlongjia forest district. Symmetrically, Sub-district C and D are located in Tangbaihe River, where Sub-district C includes Anyang City only, and Sub-district D consists of Xiangfan City and Shuizhou City. Danjiangkou City is the confluence point of the two rivers, and the below area is Sub-district E, including Shiyan City, Xiangfan City, Jingmen City, Qianjiang City, Tianmen City, Xiantai City, Shenlongjia forest district, Hanchuan City and Wuhan City. Note that different parts of Shiyan City, Xiangfan City and Shenlongjia forest district are belong to different water resources sub-district.

For the sake of avoiding producing repeated water resources and optimizing water allocation for bifurcate river, the existing structure is to be reshaped and Sub-district E s divided to E1 and E2. Consequently, the improved structures are A-B-E1 and C-D-E2. The ultimate allocated water for Sub-district E will be added by E1 and E2. As seen in Figure 1. The parameters of this study are list in Table 1.

Table 1: Parameters of Studied Area

	Area/10^4 Km^2	Crop Area /10^3 ha	Population /10^4	GDP/10^8 RMB	Rainfall (mm)	Rainfall coefficient	Interception /m	R_b	W_g
A	5.94	538.9	771.7	207.2	847	0.32	0.32	0.25	0.5
B	2.43	182.7	342.2	178.5	1079	0.35	0.3	0.25	0.5
C	2.01	660.7	792.7	96.9	1172	0.3	0.3	0.25	0.5
D	0.45	93.7	131.8	93.2	1103	0.35	0.3	0.25	0.5
E1	2.92	709.4	1039.6	777.8	1103	0.4	0.32	0.25	0.5
E2	1.14	278.2	407.6	304.9	1103	0.4	0.32	0.25	0.5

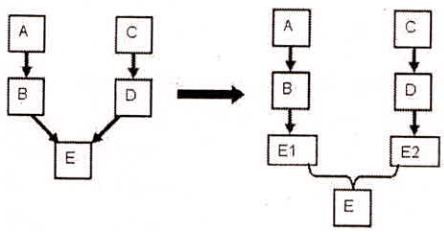

Fig. 1: Studied Area: Hanjiang River basin

Simulation Results

On the basis of the mathematical functions and the parameters, water resources have been allocated under the provided criteria (Table 2, Table 3, where TY stands for transferred water from outside is allowed and TN for not allowed).

The results of Table 2 and Table 3 show that, the proportion of allocated water resources of each sub-district are stable whatever the criterion is. Take the data of Year 2000 for example. 35.8391 billion m^3 Blue Water and 67.294 billion m^3 Green Water are generated, which leads to a total number of 69.538 billion m^3 water resources in the river basin after the Green Water converted. Allocated water resources are depicted as Figure 2 and Figure 3. Evidently, whatever the criterion (Area, crop Area, Population or GDP) is, the allocation of water resources of Sub-district E is the very largest one, approximately more than 40%, as it has an outstanding index of the criteria. And Sub-district A follows next, obtaining a second sharing, about 30%. Sub-district B and C enjoy a less allocation, probably 10%~15%. The residual part is belonged to Sub-district D, without any doubt.

For any certain sub-district, criterion choosing will influence the allocation results greatly. Specifically, Sub-district E is located in the end of the river basin, covering a wide area, affording a larger population and developing a promising economy.

Table 2: Allocation Results under Four Criteria (Blue Water only, 10^8 m^3)

	Blue Water	Area (TN)	Area (TY)	Crop Area (TN)	Crop Area (TY)	Population (TN)	Population (TY)	GDP (TN)	GDP (TY)
A	100.12	126.77	126.77	97.85	97.85	94.32	94.32	59.46	59.46
B	66.25	43.65	70.30	41.25	41.25	47.29	47.29	46.23	46.23
C	52.59	55.43	55.43	61.66	61.66	58.26	58.26	27.99	27.99
D	12.64	10.59	13.43	3.25	12.32	6.38	12.05	17.43	17.43
E	127.30	122.46	127.30	154.89	154.89	152.66	152.66	207.80	207.80
Sum	358.91	358.91	393.24	358.91	367.98	358.91	364.58	358.91	358.91

Table 3: Allocation Results under Four Criteria (Blue and Green Water, 10^8 m^3)

	Blue Water	Green Water	Area (TN)	Area (TY)	Crop Area (TN)	Crop Area (TY)	Population (TN)	Population (TY)	GDP (TN)	GDP (TY)
A	100.12	212.76	251.20	251.20	186.90	186.90	179.06	179.06	131.41	131.41
B	66.25	123.03	84.71	129.41	78.08	78.08	84.87	84.87	78.08	78.08
C	52.59	122.72	111.19	111.19	125.65	125.65	117.76	117.76	74.51	74.51
D	12.64	23.47	25.11	25.11	10.36	22.05	17.68	21.49	29.95	29.95
E	127.30	190.96	223.16	224.81	294.40	294.40	296.00	296.00	381.43	381.43
Sum	358.91	672.94	695.38	741.73	695.38	707.07	695.38	699.19	695.38	695.38

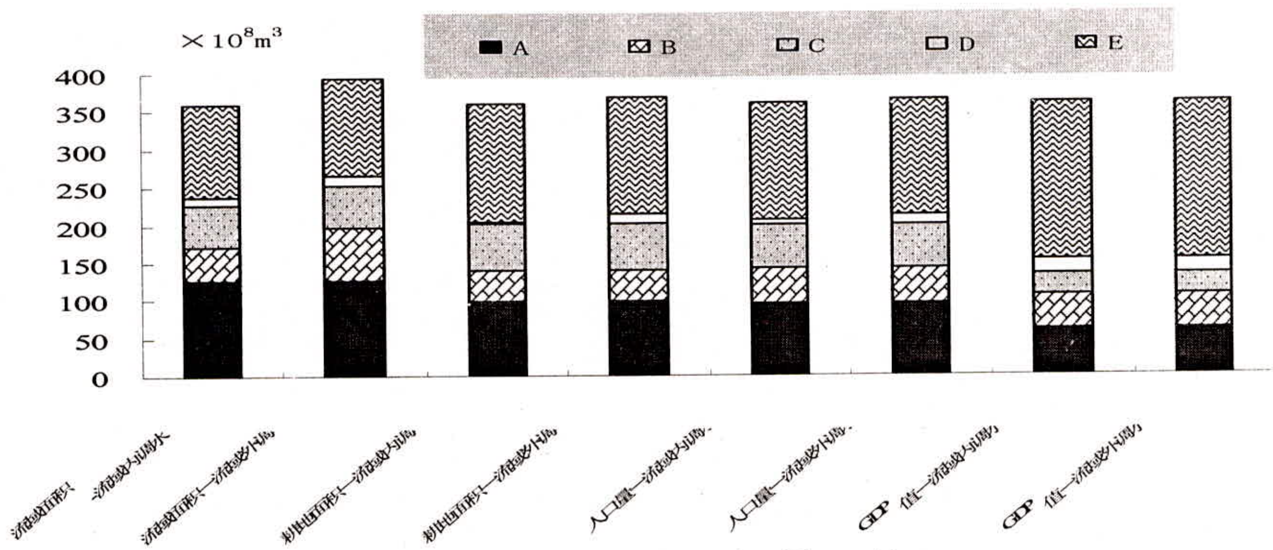

Fig. 2: Water Allocation Proportion (Blue only)

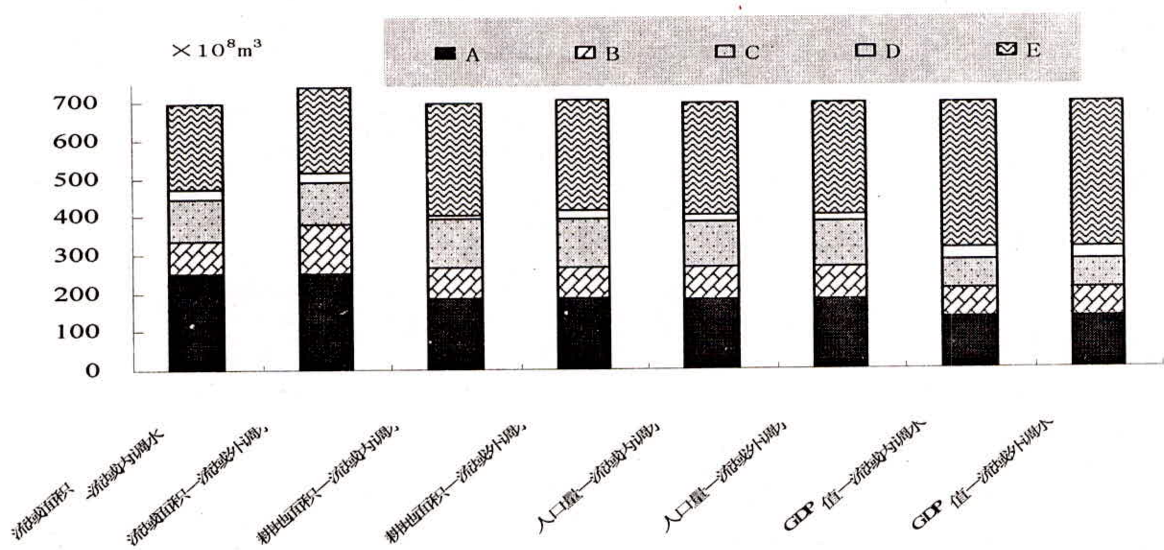

Fig. 3: Water Allocation Proportion (Blue and Green)

The generated Blue Water inside is 12.73 billion m^3 (Blue Water considered only). The allocation water is 20.78 billion m^3 in the view of GDP criterion but the number is 12.246 billion m^3 according to Area criterion and transferred water from outside is not allowed, reducing by 41%. For another main agriculture region, Sub-district C, when both Blue Water and Green Water considered, allocation water by Crop Area (12.565 billion m^3) is increasing about 40.7% than allocation by GDP (74.51 billion m^3). Therefore, in order to a reasonable and sound water resources allocation, decision-makers should discuss with local government adequately and think over the practicality.

Figure 4 and Figure 5 show the interrelationship of allocated and generated water resources, when outside transfer is not allowed. Positive value means allocated water is more than generated and this sub-district has benefited from this behavior. Vice versa, negative value indicated the loss and it should transfer water to downstream. Compared with Figure 4, when both Blue Water and Green Water considered, Figure 5 shows that the transferred water to downstream are increased for every sub-district. The allocated water of Sub-district E is rather larger for it needn't transfer to downstream and the gap between generated and allocated will be broadened. The relative of benefit and loss is nearly the same.

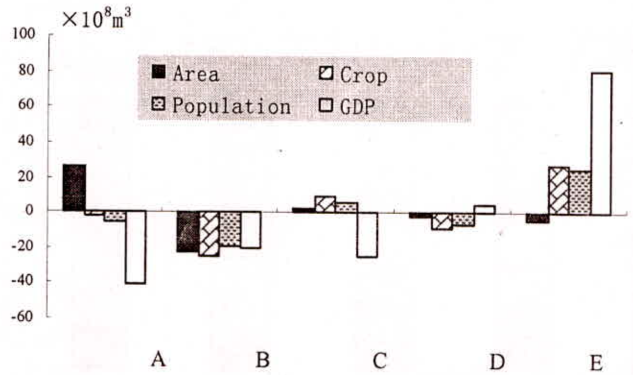

Fig. 4: Gap of Water Generated and Allocated (Blue only)

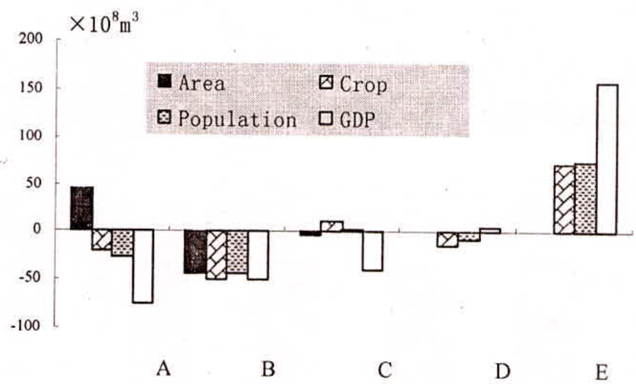

Fig. 5: Gap of Water Generated and Allocated (Blue and Green)

CONCLUSIONS

Water resources scarcity is a more and more serious problem around the world. Water resources allocation models will instruct human beings to optimally allocate water resources. In this paper, two mathematical models, considering Blue Water and Green Water have been constructed and a case study in Hanjiang River Basin in China has been carried out.

1. Firstly, the concept of Blue Water and Green Water are introduced. Then, two correlative models were proposed, in which only Blue Water considered and both Blue and Green Water considered, respectively, with a detailed boundary condition and theory basis. Employing the two useful models, different water allocation according to four logical criteria, Area, Crop Area, Population and GDP, were calculated. Meanwhile, from the viewpoint of criteria, the important management patterns have been analyzed.
2. The models have been extended to the application of water resources allocation in bifurcate river basin. The transferred water resources between adjacent sub-districts were discussed deeply in accordance with boundary condition and several assumptions. This variable is in close relationship with the practical strategy when allocation occurs.
3. The models were employed in Hanjiang River Basin which is one important part of Yangtze River Basin. Five sub-districts for water resources allocation have been divided and the all sorts of simulation results have been given under the panned criteria. Kindly note that some premises and parameter are so simplified that more work should be done to validate the rationality.

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