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Mutual optimization of water utilization structure and industrial structure in arid inland river basins of Northwest China

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Abstract: Water is a key restricting factor of the economic development and eco-environmental protection in arid inland river basins of Northwest China. Although water supplies are short, the water utilization structure and the corresponding industrial structure are unbalanced. We constructed a System Dynamic Model for mutual optimization based on the mechanism of their interaction. This model is applied to the Heihe River Basin where the share of limited water resources among ecosystem, production and human living is optimized. Results show that, by mutual optimization, the water utilization structure and the industrial structures fit in with each other. And the relationships between the upper, middle and lower reaches of the Heihe River Basin can be harmonized. Mutual benefits of ecology, society and economy can be reached, and a sustainable ecology-production-living system can be obtained. This study gives a new insight and method for the sustainable utilization of water resources in arid inland river basins.
Key words: water utilization structure; industrial structure; mutual optimization; System Dynamic Model; arid inland river basins; Northwest China
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1 Introduction

The great development of western China greatly increases the demand for water. However, in arid inland river basins of Northwest China, water resources are very limited. Shortage of water has been one of the key restricting factors of eco-environmental and economic development (Cheng, 2000). Furthermore, the existing water utilization structure and the corresponding industrial structure are unbalanced. This is manifested as follows:

(1) The share of water utilization for production is so large that water for ecosystem and human living cannot be guaranteed. This accelerates the deterioration of eco-environment in the lower reaches. In addition, relationships between the upper, middle and lower reaches are worsening.

(2) Of the water utilization for production, agricultural water utilization occupies the majority so that the industrial water utilization cannot be guaranteed. In addition, the agricultural water utilization is highly inefficient. This restricts the process of industrialization and urbanization, hence the social and economic development.

(3) Of the agricultural water utilization, the majority of water goes to irrigation. Water utilization for forestry, animal husbandry and fishery is relatively underemphasized. This exaggerates the poverty of the rural area.

(4) The current industrial structure is also highly unbalanced. Agriculture is still the primary component of the regional economy, which results in very low cost-benefit for water utilization.

To resolve the above problems, we need to optimize the water resources system. However,

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traditional water resources optimization focuses on water resource system while does not take industrial structure into account (Feiring *et al*., 1998; Watkins and McKinney, 1998). Based on the analysis of the interaction mechanism between water utilization structure and industrial structure in arid inland river basins of Northwest China, we constructed a System Dynamic Model for their mutual optimization. It aims at coordinating the relationships between the water utilization-industrial structure system, the ecology-production-living system, and the upper-middle-lower reaches, so as to achieve a benign circle of eco-environment, a sustainable and efficient production system and a well-off living system for the whole river basin.

2 Materials and methods

2.1 The study area

The arid inland river basins in Northwest China are located in the center of the Eurasian continent, north of 35°N and west of 106°E, occupying almost 25% of China's total land area. Included are the entire Xinjiang Uygur Autonomous Region, the Hexi Corridor in Gansu Province, the Qaidam Basin in Qinghai Province, and the western parts of the Helan Mountains in the Inner Mongolia Autonomous Region (Zhu *et al*., 2004). There are six river basins: the Tarim River Basin, the Urumqi River Basin, the Ertix River Basin, the Shule River Basin, the Heihe River Basin and the Shiyang River Basin.

Of the six rivers, the Heihe River is the second largest. It originated from the glaciers of the Qilian Mountains and vanishes in the Badain Jaran Desert. The middle reaches flow through Zhangye Oasis in the Hexi Corridor. So the Heihe River Basin is a typical meta-ecosystem of mountain, oasis and desert. It

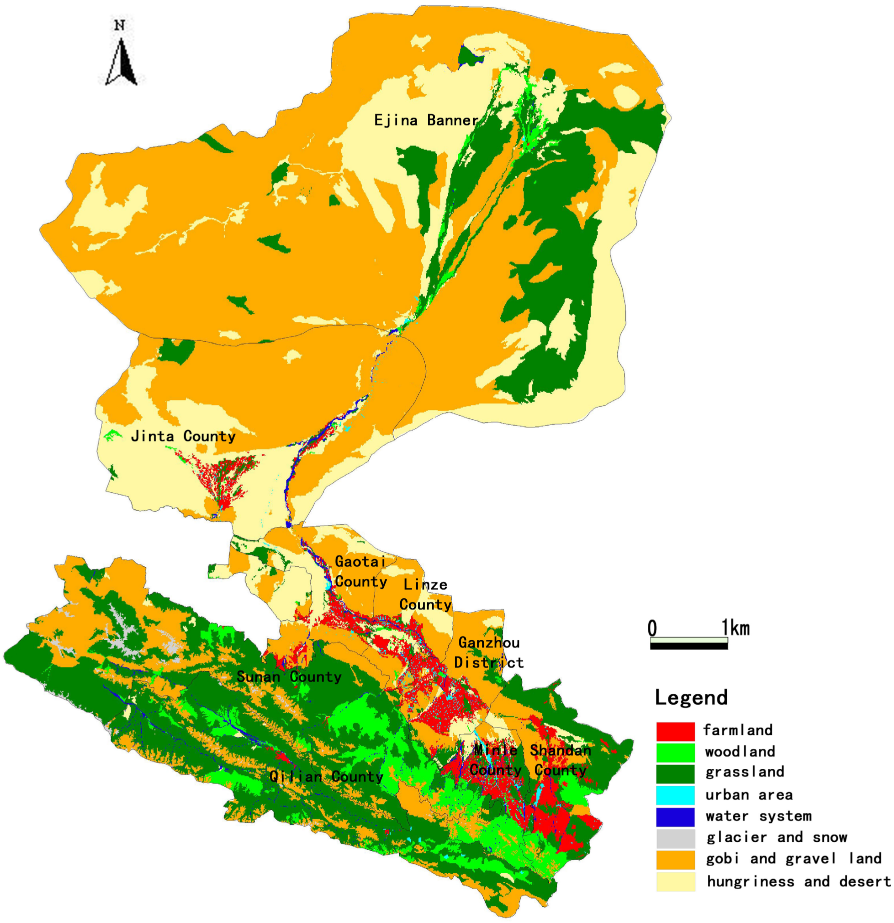

Figure 1 Land cover of the Heihe River Basin in 2000

is also a typical arid inland river basin in Northwest China. For data-gathering convenience, we take Qilian County in Qinghai Province and Sunan County in Gansu Province as the upper reaches. The middle reaches include Shandan County, Minle County, Ganzhou District, Linze County and Gaotai County in Zhangye City of Gansu Province. The lower reaches include Jinta County in Jiuquan City of Gansu Province and Ejina Banner in the Inner Mongolia Autonomous Region. The total area of the Heihe River Basin is about 12.2×10^4 km^2. The farmland area is 0.42×10^4 km^2. The woodland area is 0.52×10^4 km^2. The grassland area is 2.79×10^4 km^2. The urban area is 0.04×10^4 km^2. Most of its land is unavailing. The area of Gobi and gravel land is 5.87×10^4 km^2. The area of hungriness and desert is 2.42×10^4 km^2 (Figure 1). The average annual total water volume is 33.24×10^8 m^3. And the surface water resources are 28.73×10^8 m^3. The unrepeated groundwater resources are 4.91×10^8 m^3. In 2000, GDP is 69.70×10^8 yuan and the three industrial structure is 42.26%:24.92%:32.82%. The total population is about 1.5 million and the urbanization standard is 21.58%.

2.2 Theory and mechanism

2.2.1 Theory for mutual optimization of water utilization structure and industrial structure Mutual optimization of water utilization structure and industrial structure is a systemic and complicated engineering. It mainly concerns the optimization of water resources and the adjustment of industrial structure, and aims at the sustainable development of the arid inland river basins. So we have adopted the theories such as System Theory (Qian, 1985), theories on water resources optimization (Wang *et al.*, 2002), theories on industrial structure evolvement (Li, 1999) and theories on sustainable development (Holdren, 1996).

2.2.2 Interaction mechanism between water utilization structure and industrial structure In arid inland river basins of Northwest China, where total water resources are limited, the spatial structure of water utilization should be optimized according to the spatial distribution of water resources. For example, in the upper reaches, where water resources are relatively abundant, water utilization for production can be increased for economic benefits. However, in the lower reaches, as the eco-environment is getting worsening, water utilization for the eco-system should be increased for ecological benefits. While water utilization of the upper and lower reaches increases，that of the middle reaches will correspondingly decrease. Therefore, to guarantee the sustainable development of economy, the middle reaches should save water and improve the water utilization benefits. After optimizing the spatial structure, water utilization structure should also be optimized. As for the arid inland river basins of Northwest China, restricted by the total water resources, water utilization for the eco-system should be increased until the eco-environment no longer degrades. Water utilization for human living should be increased according to the residential demand. Accordingly, water utilization for production should be decreased. And when it decreases, the water-saving industries should be advocated to guarantee the sustainable development.

The spatial structure of industry should be optimized according to the spatial differentiation of economy. As for arid inland river basins of Northwest China, the population density is the largest in the middle reaches. The middle reaches also have the best production conditions. So the middle reaches should be taken as the key regions to develop economy. Accordingly, GDP will have the greatest growth rate in the middle reaches. After optimizing the spatial structure, industrial structure should also be optimized. As for the arid inland river basins of Northwest China, while GDP increases, the ratio of the secondary industry and the tertiary industry should be increased and that of the primary industry should be decreased. Of the secondary industry, the ratio of water-saving industries such as machinery, electronic and spinning industries should be increased, while the ratio of water-consuming industries such as metallurgic, petroleum & chemical and thermal power generation industries should be limited. Of the primary industry, to guarantee the sustainable development of forestry, animal husbandry and fishery, the increase rate of farming should be limited. As food crops consume more water than economic crops and feedstuff crops, cultivated area of food crops should be decreased.

From the above analysis, we can see that optimization of water utilization structure requires optimization of industrial structure. While industrial structure changes, water utilization structure will correspondingly change. So mutual optimization of water utilization structure and industrial structure is considered. The mechanism of the mutual optimization goes as follows (Figure 2): When water utilization structure is optimized, water utilization for production will decrease, and it will restrict the economic development, so it is required that the industrial structure should become one that is water-efficient. On the other hand, when industrial structure is optimized, water utilization for production will decrease, and some water resources once for production can be used for eco-system and human living. And then the eco-environment and human living will be improved. Anyway, optimization of water utilization structure mainly aims at higher benefits, while optimization of industrial structure mainly aims at saving water.

In arid inland river basins of Northwest China, the key to mutual optimization of water utilization structure and industrial structure is the adjustment of industrial structure and the corresponding water utilization structure for production (Figure 2). And we can divide a river basin into three parts according to their differentiation. As the ratio of water utilization should be decreased while the ratio of GDP should be increased, the middle reaches should be taken as the key regions.

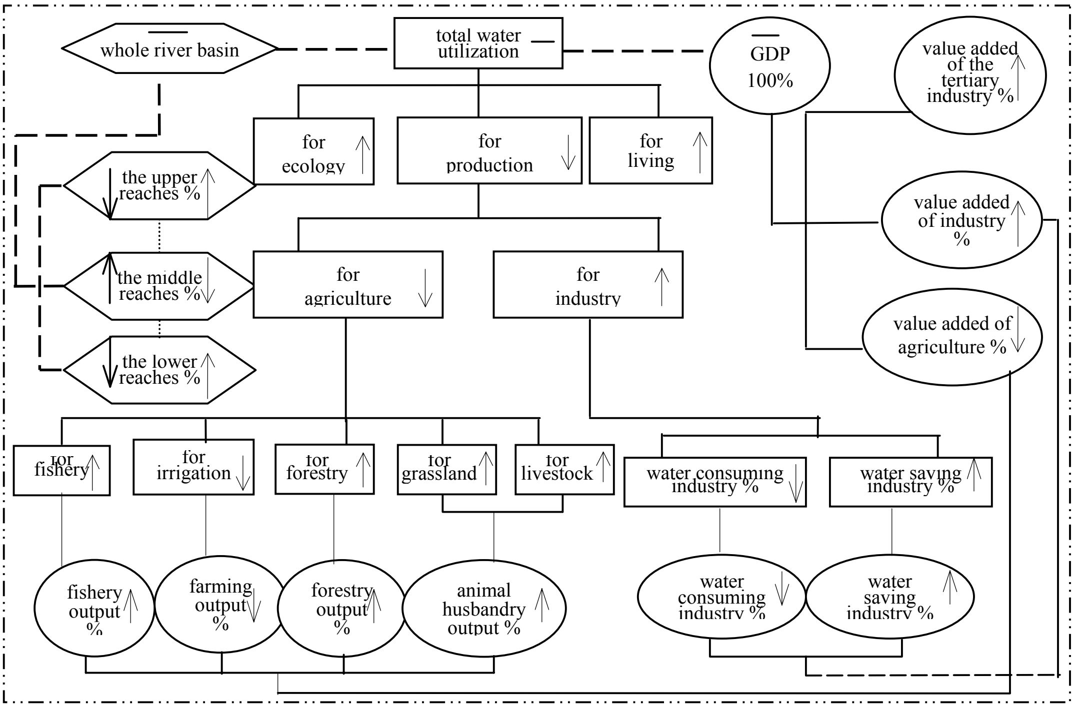

Figure 2 Interaction between mutual optimization of water utilization structure and industrial structure

At the above, we only discussed the interaction mechanism of mutual optimization of water utilization structure and industrial structure. However, if one is optimized while the other is not, or neither of them is optimized, water utilization structure and industrial structure will not fit in with each other, and sustainable development of ecology-production-living system cannot be realized.

2.3 System Dynamic Model for mutual optimization

2.3.1 Basic hypothesis for mutual optimization According to the characteristic of water utilization and industrial structures in the river basins under study, we suppose that:

(1) The average annual total water resources will remain constant. Although global climate fluctuation will affect the average annual total water resources, the effect would be marginal here (Lan *et al*., 2003). Within the limits of the carrying capacity of water resources, we can increase water supply at a certain rate. And the total water utilization should be limited according to water availability.

(2) The total land resources available will remain constant. We can take measures to protect farmland from being converted to other uses and prevent land resources available from desertification. Restricted by the total quantity, land resources available should be optimized so as to adjust the industrial structure and water utilization structure. For example, cultivated area of economic crops and feedstuff crops should be increased while that of food crops should be decreased. Besides, grassland area and woodland area should also be increased.

(3) Water utilization for ecosystem will increase at a fixed rate. And it is decided by the demand of eco-environment. While the water utilization for ecosystem increases, water utilization structure for production and human living is optimized to achieve systemic optimization.

(4) Progress in science and technology will improve water use efficiency for agriculture, industry

and living. All kinds of water utilization ration will continuously change.

(5) Economy will increase at a certain rate. This rate is decided by many factors, such as the restriction of corresponding total water utilization, the past and present status, the future national and international development environment, and so on.

2.3.2 Basic thoughts for mutual optimization Based on the basic hypothesis, the basic thoughts of constructing the System Dynamic Model for mutual optimization go as follows (Figure 3):

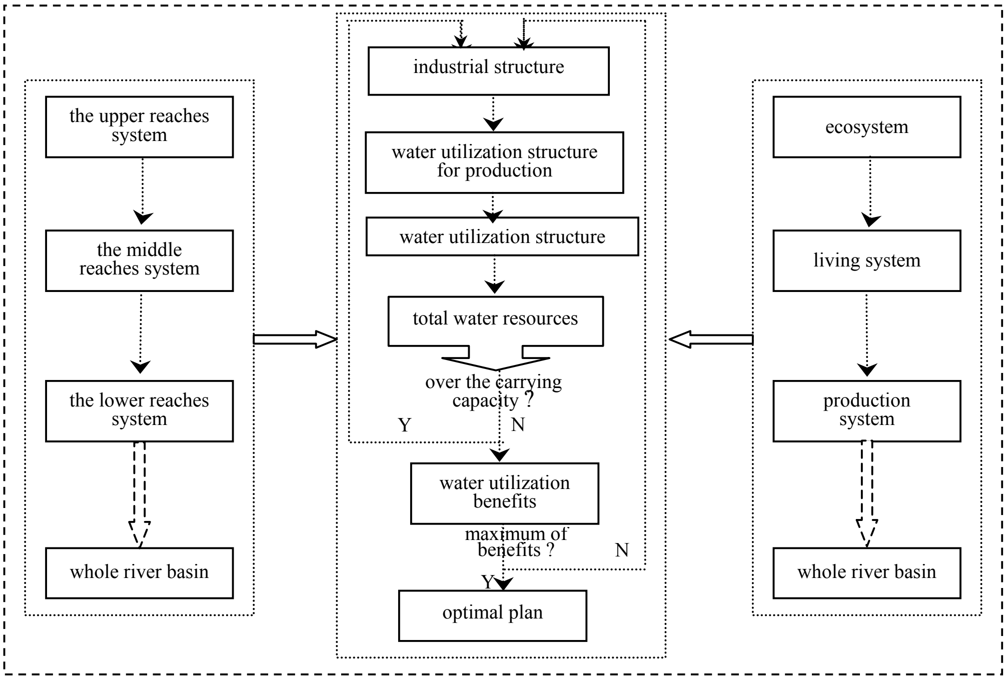

Figure 3 Basic thoughts of constructing the System Dynamic Model for mutual optimization

(1) We take total water resources as the valve to control the mutual optimization. To begin with, industrial structure is adjusted. Then water utilization structure for production will be optimized. So will water utilization structure. After optimization of water utilization structure, the total water utilization should not exceed the carrying capacity of water resources. If it does, the industrial structure should be adjusted until it does not.

(2) We take maximum of the water utilization benefits as the supreme target. To begin with, water utilization for ecosystem and human living is top-priority. And then, water-saving industrial structure system is constructed so as to optimize the water utilization structure for production. If the total water utilization does not exceed the carrying capacity of water resources, and water utilization benefits still can be increased, the industrial structure should be adjusted until the water utilization benefits cannot.

(3) We take the whole basin as the principal axis. According to the total water resources in the upper, middle and lower reaches, we forecast their scales of economy and population respectively. Based on the mutual optimization of water utilization structure and industrial structure in the upper, middle and lower reaches, the optimal plan of the whole basin is finally obtained.

2.3.3 Flow chart of the System Dynamic Model for mutual optimization According to the basic thoughts for mutual optimization, the ecology-production-living system is divided into five subsystems, including the population subsystem, the total water resources subsystem, the water utilization structure subsystem, the industrial structure subsystem and the total economic output subsystem. Based on the interaction mechanisms between mutual optimization of water utilization structure and industrial structure, the flow chart of the System Dynamic Model for mutual optimization is drawn (Figure 4). According to the results, we can summarize the results of the whole river basin. Therefore, if any parameter of the upper, middle or lower reaches changes, the results of the whole river basin will also change. On the other hand, if results for the whole river basin are irrational by analysis, some parameters should be adjusted.

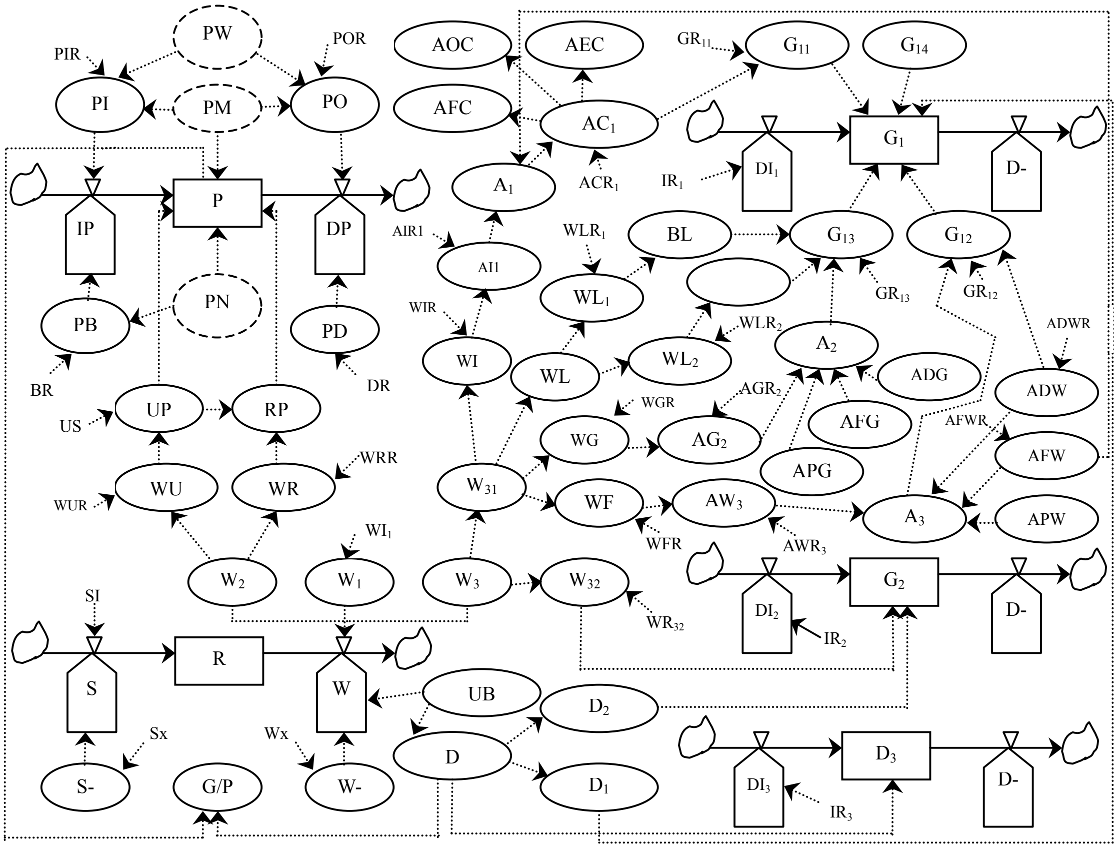

Figure 4 Flow chart of the System Dynamic Model for mutual optimization

P: total population; IP: increased population; DP: decreased population; PI: immigration; PO: migration; PIR: immigration rate; POR: migration rate; PW: water resources impact on floating population; PM: policy impact on floating population; PB: birth population; PD: death population; BR: birth rate; DR: death rate; PN: policy impact on birth population; UP: urban population; US: urban standard; RP: rural population; R: total water resources; S: water supply; SI: increase rate of water supply; S-: water supply consuming; Sx: consuming rate of water supply; W: water utilization; W-: water utilization consuming; Wx: consuming rate of water utilization; W_1: water utilization for ecology; WI_1: increase rate of water utilization for ecology; W_2: water utilization for living; WU: water utilization for urban living; WUR: ration of water utilization for urban living; WR: water utilization for rural living; WUR: ration of water utilization for rural living; W_3: water utilization for production; W_{31}: water utilization for agriculture; WI: water utilization for irrigation; WIR: ration of water utilization for irrigation; WL: water utilization for livestock; WL_1: water utilization for big livestock; WLR_1: ration of water utilization for big livestock; WL_2: water utilization for small livestock; WLR_2: ration of water utilization for small livestock; WG: water utilization for grassland; WGR: ration of water utilization for grassland; WF: water utilization for forestry; WFR: ration of water utilization for forestry; W_{32}: water utilization for industry; WR_{32}: ration of water utilization for industry; D: GDP; D_1: value added of the primary industry; D_2: value added of the secondary industry; D_3: value added of the tertiary industry; D-: decrease of a certain industry; G_1: total output value of the primary industry; DI_1: increase of the primary industry; IR_1: increase rate of the primary industry; G_{11}: output value of farming; GR_{11}: increase rate of output value of farming; G_{12}: output value of forestry; GR_{12}: increase rate of output value of forestry; G_{13}: output value of animal husbandry; GR_{13}: increase rate of output value of animal husbandry; G_{13}: output value of animal fishery; G_2: total output value of the secondary industry; DI_2: increase of the secondary industry; IR_2: increase rate of the secondary industry; DI_3: increase of the tertiary industry; IR_3: increase rate of the tertiary industry; G/P: per capital GDP; A_1: farmland area; AI_1: virtual irrigation area of farmland; AIR_1: virtual irrigation coefficient of farmland; AC_1: cultivated area of crops; ACR_1: multiple cropping index; AFC: cultivated area of food crops; AEC: cultivated area of economic crops; AOC: planting area of other crops; A_2: grassland area; AG_2: virtual irrigation area of grassland; AGR_2: virtual irrigation coefficient of grassland; APG: planting area of grassland; AFG: grassland area from farmland; ADG: area of degraded grassland; A_3: woodland area; AW_3: virtual irrigation area of woodland; AWR_3: virtual irrigation coefficient of woodland; APW: planting area of woodland; AFW: woodland area from farmland; AFWR: coefficient of woodland area from farmland; ADW: disafforestation area; ADWR: coefficient of disafforestation area; BL: big livestock; SL: small livestock.

2.3.4 Program composition and parameters affirmance According to the flow chart of the System Dynamic Model for mutual optimization in the upper, middle and lower reaches, relationships between the variables of the five subsystems are expressed by mathematic equations. These mathematic equations are mainly classified as the level equation, the assistant equation, the rate equation, the initial value equation, the table equation, and so on (Wang, 1995). Most equations can be obtained directly by the relationships between the variables. However, some equations should be obtained by Input-Output Model, Multiple Targets Decision Model, Grey System Model, and Multiple Regression Analysis Method according to historic data. All these equations constitute the program of the System Dynamic Model for mutual optimization. In the program, the feasibility and rationality of the parameters are important to the final results. So an Expert Decision Support System (Vacik and Lexer, 2001) should be constructed to affirm the parameters.

2.3.5 Program control and checkout By Professional Dynamo Plus 1.5, a certain software of the System Dynamic Model, the mutual optimization of water utilization structure and industrial structure in the upper, middle and lower reaches is respectively simulated. Then the results of the whole basin are summarized. Finally, we can contrast the optimal results with the real conditions. If we make the best use of the total water resources and the total water utilization does not exceed the carrying capacity of water resources, and if the water utilization structure and industrial structure are more rational than before, and if the benefits of per stere water utilization are highly improved, we can consider the mutual optimization is completed. Otherwise, we should adjust the parameters and simulate the System Dynamic Model until we obtain the optimal results.

2.4 Data acquisition

We take investigation data and statistical data as the main data sources, and choose the eco-environmental, social and economic data of each county in 2000 as the basic data. Statistical yearbooks of each county from 1980 to 2000 are taken as the historical data. In the System Dynamic Model, the basic data in 2000 are used as the initial values. And then, by systemic simulation, values of each variable from 2001 to 2030 are forecasted.

3 Results

As the ecology-production-living system is complicated, values of many variables are obtained in the results. To be brief, we mainly discuss the mutual optimal results of water utilization structure and industrial structure in the whole Heihe River Basin.

3.1 Optimization of water utilization structure in the Heihe River Basin

In the Heihe River Basin, the total water utilization is projected to increase to 33.89×10^8 m^3 in 2030 compared to 32.83×10^8 m^3 in 2000. However, from 2000 to 2030, the total water consumption will be limited. And it is 32.8×10^8 m^3 or so (Table 1). This is within the limits of the carrying capacity of water resources (Qu and Fan, 2000; Su *et al.*, 2002).

Table 1 Optimization of water utilization structure in the Heihe River Basin (10^8 m^3, %)

TIME	2000		2005		2010		2015		2020		2025		2030	
water utilization	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio
Sum up	32.83	100.00	32.61	100.00	32.89	100.00	32.82	100.00	32.84	100.00	32.92	100.00	33.89	100.00
for ecology	8.15	24.84	8.46	25.95	8.78	26.71	9.12	27.78	9.46	28.81	9.82	29.84	10.20	30.08
for production	24.30	74.01	23.71	72.72	23.61	71.79	23.15	70.52	22.76	69.30	22.42	68.11	22.96	67.75
for living	0.38	1.15	0.43	1.33	0.49	1.50	0.56	1.71	0.62	1.89	0.68	2.05	0.73	2.17
for industry	0.85	3.51	1.25	5.25	1.84	7.77	2.80	12.11	3.79	16.65	4.81	21.47	6.74	29.36
for agriculture	23.44	96.49	22.47	94.75	21.78	92.23	20.34	87.89	18.97	83.35	17.61	78.53	16.22	70.64
for irrigation	20.60	87.89	19.64	87.43	18.97	87.13	17.56	86.34	16.22	85.51	14.89	84.59	13.55	83.53
for livestock	0.26	1.10	0.27	1.18	0.27	1.26	0.28	1.38	0.29	1.53	0.30	1.70	0.31	1.90
for grassland	2.16	9.21	2.12	9.44	2.08	9.56	2.04	10.01	1.99	10.48	1.94	11.01	1.88	11.60
for forestry	0.42	1.80	0.44	1.95	0.45	2.06	0.46	2.26	0.47	2.47	0.48	2.71	0.48	2.97

Based on the mutual optimization in the Heihe River Basin, the water utilization structure will be more rational. First, the ratio of water utilization for ecosystem, production and human living will change into 30.08%:67.75%:2.17% in 2030 instead of 24.84%:74.01%:1.15% in 2000. The ratio of water utilization for ecosystem and human living will increase while that for production will decrease. Secondly, the ratio of water utilization for agriculture and industry will change into 70.64%:29.36% in 2030 instead of 96.49%:3.51% in 2000. The ratio of water utilization for industry will increase while that for agriculture decrease. Finally, the ratio of water utilization for irrigation, livestock, grassland and forestry will change into 83.53%:1.90%:11.60%:2.97% in 2030 instead of 87.89%:1.10%:9.21%:1.80% in 2000. The ratio of water utilization for livestock, grassland and forestry will all increase while that for irrigation is decreased (Table 1). Furthermore, the spatial structure of total water utilization in the upper, middle and lower reaches will change into 3.13%:65.02%:31.85% in 2030 instead of 2.26%:70.25%:27.49% in 2000. The amount of water consumption in the upper and lower reaches all increases while that in the middle reaches decreases. All the above results match the interaction mechanism between mutual optimization of water utilization structure and industrial structure (Figure 2).

To see more clearly, we contrast the changes of the major kinds of water utilization before and after the mutual optimization (Figure 5). In 1980, the ratio of water utilization for ecology, production and human living is 32.63%:66.63%:0.75%. In 2030, it is 30.08%:67.75%:2.17%. The water utilization structure changes little. However, the water utilization system changes materially. Before 1995, the water utilization system was not optimized. The water utilization for production continued to rise (from 22.35×10^8 m^3 in 1980 to 24.41×10^8 m^3 in 1995). So the water utilization for ecology had to be decreased (from 10.94×10^8 m^3 in 1980 to 8.05×10^8 m^3 in 1995). From 1995 to 2000, as the eco-environment deteriorated, the government started to pay more attention to it, and the water allocation plan deiced by the State Council in 1997 was carried out. Then water utilization for ecology was increased (from 8.05×10^8 m^3 in 1995 to 8.15×10^8 m^3 in 2000). After 2000, we plan to increase the water utilization for ecology step by step. And it will reach up to 10.20×10^8 m^3 in 2030, which approximates that of the mid-1980s. The water utilization for agriculture will be cut down and the water utilization for industry will be highly increased. Then higher economic benefits can be obtained. Therefore, though the water utilization structure in 2030 in the Heihe River Basin will approximate that in 1980, yet they are quite different from each other. The former is a more sustainable and high-efficient system.

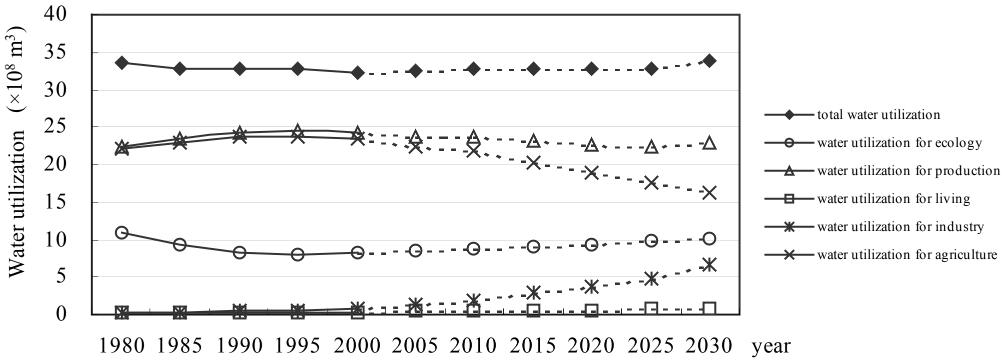

Figure 5 Changes of the major kinds of water utilization before and after mutual optimization

3.2 Optimization of industrial structure in the Heihe River Basin

In the Heihe River Basin, GDP will continuously increase and the industrial structure will also be more rational after the mutual optimization. First, GDP of the whole river basin will change into 1201.16×10^8 yuan in 2030 instead of 69.70×10^8 yuan in 2000. The average annual growth rate will be 10.00%, which equals to that of China at present. Secondly, the three industrial structure will change into 12.28%:44.98%: 42.74% in 2030 instead of 42.26%:24.92%:32.82% in 2000. The ratio of the secondary and tertiary industries will increase while the ratio of the primary industry will decrease. Thirdly, the agricultural structure will change into 53.04%:6.77%:36.07%:4.12% in 2030 instead of 75.12%:3.08%:21.53%:0.27% in 2000. The ratios of forestry, animal husbandry and fishery will increase while the ratio of farming will decrease (Table 2). Finally, the structure of the secondary and tertiary industries will also be rational and it will save more water resources and produce higher benefits.

Besides, the spatial structure of GDP in the upper, middle and lower reaches will change into 6.55%:81.40%:12.05% in 2030 instead of 7.11%:80.40%:12.49% in 2000. The ratio of GDP in the middle reaches will increase while those of the upper and lower reaches will both decrease. So higher water utilization benefits in the middle reaches will be required. All the above results match the interaction mechanism between mutual optimization of water utilization structure and industrial structure (Figure 2).

Table 2 Optimization of industrial structure in the Heihe River Basin (10^8 yuan, %)

TIME	2000		2005		2010		2015		2020		2025		2030	
value added	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio	total	ratio
Sum up	69.70	100.00	107.98	100.00	170.28	100.00	273.84	100.00	443.10	100.00	724.62	100.00	1201.16	100.00
primary industry	29.46	42.26	38.99	36.11	51.54	30.27	68.08	24.86	88.27	19.92	114.31	15.77	147.46	12.28
secondary industry	17.36	24.91	32.14	29.77	59.40	34.89	110.20	40.24	187.48	42.31	317.25	43.78	540.28	44.98
tertiary industry	22.88	32.82	36.85	34.12	59.33	34.84	95.56	34.90	167.35	37.77	293.06	40.44	513.42	42.74
farming	34.32	75.13	43.68	71.75	55.59	68.53	65.86	60.93	81.85	58.19	101.73	55.56	126.41	53.04
forestry	1.41	3.08	2.16	3.54	3.32	4.10	4.73	4.37	7.11	5.05	10.70	5.84	16.14	6.77
animal husbandry	9.84	21.53	14.64	24.05	21.87	26.96	28.78	26.62	41.36	29.40	59.57	32.53	85.96	36.07
fishery	0.12	0.27	0.40	0.65	0.33	0.41	8.73	8.08	10.35	7.36	11.11	6.07	9.82	4.12

To see more clearly, we illustrate the industrial structure in the whole river basin before and after the mutual optimization (Figure 6). In 1980, the three industrial structures were 58.92%:22.96%: 18.12%. As the middle reaches of the Heihe River Basin was taken as one of the important commercial food bases in Gansu Province in the 1980s, agriculture developed rapidly and industry was neglected. The ratio of the primary industry increased from 58.92% in 1980 to 61.90% in 1990, and the secondary industry decreased from 22.96% in 1980 to 16.34% in 1990. As agriculture developed rapidly, the water utilization increased much and shortage of water resources brought many social and eco-environmental problems. After 1990, the government began to realize it and started to adjust the industrial structure. Then the ratio of the primary industry continued to decrease, dropping to 42.26% in 2000. However, the ratio is still too big. During the process of industrialization and urbanization, the industrial structure and the corresponding water utilization structure should be adjusted. In our mutual optimization plan, the ratio of the primary industry will decrease to about 10% in 2030, and the ratio of both the secondary and the tertiary industries will be increased to more than 40%.

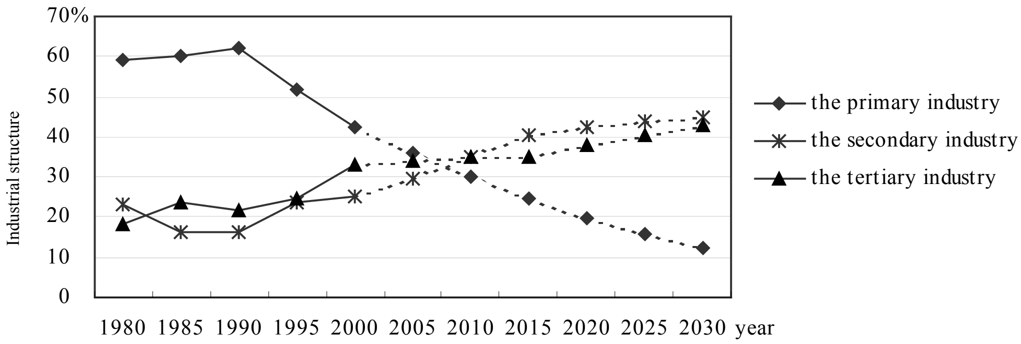

Figure 6 Changes of the industrial structure before and after mutual optimization

4 Discussion and conclusions

4.1 Integrated benefits of the mutual optimization in the Heihe River Basin

Based on the mutual optimization of water utilization structure and industrial structure in the Heihe River Basin, water utilization for ecology will change into 10.2×10^8 m^3 in 2030, which almost equates to that in the mid-1980s (Figure 5). The woodland area will increase to 0.60×10^4 km^2 from 0.52×10^4 km^2. The grassland area will increase to 2.87×10^4 km^2 from 2.79×10^4 km^2. The farmland area will remain about 0.42×10^4 km^2. Under these conditions, the eco-environment will no longer degrade. Furthermore, it will be restored to the standard in the mid-1980s. This is just our eco-environmental target and we finally obtained high ecological benefits.

As the spatial structures of the water utilization and GDP are both optimized in our plan, balance and efficiency of the upper, middle and lower reaches are concerned. The relationships between the upper, middle and lower reaches can be harmonized. Prosperity and stabilization of the whole river basin can be guaranteed. And high social benefits can be obtained.

Moreover, high economic benefits can also be obtained in the upper, middle, and lower reaches. On the one hand, the total economic outputs are continuously increased (Table 2) and the industrial structure is more rational (Figure 6). On the other hand, the input-output benefits of water resources (GDP/water utilization for production) are continuously improved (Figure 7). In 1980, the benefits of per stere water utilization in the upper, middle, lower reaches and the whole river basin were 1.06 yuan/m^3, 0.19 yuan/m^3, 0.35 yuan/m^3 and 0.21 yuan/m^3 respectively. In 2000, they increased to 8.71 yuan/m^3, 2.62 yuan/m^3, 3.77 yuan/m^3 and 2.87 yuan/m^3. The annual growth rates are 11.11%, 14.02%, 12.62% and 13.97%. After the mutual optimization, they will increase to 92.95 yuan/m^3, 49.21 yuan/m^3, 64.38 yuan/m^3 and 52.30 yuan/m^3 in 2030. The annual growth rates will be 8.21%, 10.27%, 9.92% and 10.16% respectively. These growth rates are almost the same with the growth rates of economy. And we considered that these growth rates are all moderate. It can give attention to the harmonious development of economy and eco-environment.

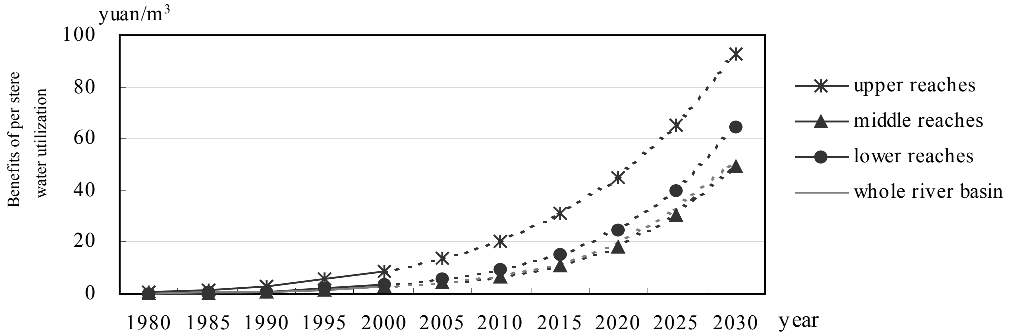

Figure 7 Increasing trend on the benefits of per stere water utilization

From the above discussion, water resources are adequately utilized within the limits of the carrying capacity in the Heihe River Basin. And the highest integrated benefits are obtained by the mutual optimization. A benign circle of eco-environment, a sustainable and efficient production system and a well-off living system of the whole river basin can be achieved. Therefore, we can consider that the mutual optimization of water utilization structure and industrial structure for the Heihe River Basin is successfully completed.

4.2 Comparing the mutual optimization results with other regions in China and abroad

In recent years, especially in developing countries, social and economic water utilization have deprived of much water utilization for ecology. Then the eco-environment in many regions has become deteriorated. People have to pay more attention to the water utilization for ecology during the water resources planning and management. However, water utilization for ecology has not been uniformly defined, and the calculating methods are different (Yang, 2003). So people usually discuss the social and economic water utilization and we can only cursorily compare the water utilization for ecology in different regions. According to Liu's study, water utilization for ecology should take up 30%-50% of the total water resources in Northwest China (Liu, 2004). Our results accord with it. But taking the rapid growth of social and economic water demand into account, we increased the water utilization for ecology in 2030 only to the standard in 1985. This result accords with the real conditions in the Heihe River Basin.

From the experience of China and other countries, among the social and economic water utilization, agriculture consumed the majority of the total water utilization. In 1900, worldwide agriculture accounted for 87.5% of the total. In 1940, it accounted for 80.3%. In 1975, it accounted for 69.9%. In 1990, it accounted for 60.2% (Wu, 1995). As the ratio of water utilization for agriculture decreased, the ratio of water utilization for industry and living continued to rise. Recent estimates show that a given amount of water used in industry generates more than 60 times the value of the same water used in agriculture (Saghir, 2000). So the ratio of water utilization for industry is an important indicator of the industrialization standard for a country or a district. In developing countries, water utilization for agriculture accounts for about 90%. While in developed countries, water utilization for industry accounts for more than 50% (Xu, 2002). For example, in 1987, in China, India and Mexico, water utilization for agriculture accounted for 87%, 93% and 86%, and water utilization for industry accounted for 7%, 4% and 8%. While in Canada, Russia and USA, water utilization for agriculture accounted for 12%, 23% and 42%, and water utilization for industry accounted for 70%, 60% and 45%. Therefore, decreasing the ratio of water utilization for agriculture is a major measure to optimize water resources throughout the world (Esther, 2005). Our results also accord with this thought. In 2000, in the Heihe River Basin, water utilization for agriculture accounted for 95.1% of the social and economic water utilization. Water utilization for industry accounted for 3.46% and water utilization for living accounted for 1.53%. Its social and economic water utilization structure is close to that in arid inland river basins of Northwest China (93.85:2.84:3.31). In 2025, its social and economic water utilization structure will be 76.23:20.84: 2.93. The ratio of water utilization for industry is close to that in China in 2000 (20.72%). In 2030, in the Heihe River Basin, the ratio of water utilization for agriculture will continue to decrease, and the social and economic water utilization structure will be 68.46:28.45:3.10. The ratio of water utilization for agriculture is close to that in China in 2000 (68.82%).

From the analysis of water utilization benefits for each industry, it is found that they vary greatly from country to country, and from region to region within the same country. The variations depend upon the technology chosen, the climate, the water availability and many other factors (Bindra and Muntasser, 2003). For example, water utilization of per ten thousand yuan GDP was 120 m^3 in USA in 1990. It was 40 m^3 in Japan in 1989 (Xu, 2002). While in China and inland river basins of Northwest China in 2000, it was 610 m^3 and 2941 m^3 respectively (Chen, 2004). In the Heihe River Basin, per ten thousand yuan GDP needs more water. In 2000, it was 3540 m^3, 83% of that in inland river basins of Northwest China, 17% of that in China, 3% of that in USA in 1990 and 1% of that in Japan in 1989. Industrial structure should be adjusted and water-saving measures should be adopted to improve the water utilization benefits in the Heihe River Basin. According to our mutual optimization model, water utilization of per ten thousand yuan GDP will decrease to 528 m^3 in 2020, less than that in China in 2000. It will continue to decrease to 197 m^3 in 2030, 61% of that in USA in 1990 and 20% of that in Japan in 1989.

4.3 Certain measures on the mutual optimization

4.3.1 Changes of our concept In arid inland river, restricted by the total water resources, water utilization structure and the corresponding industrial structure are unbalanced. Therefore, we cannot optimize water resources system by traditional concepts. We should analyze the interaction mechanism between water utilization structure and industrial structure, and realize their mutual optimization. That's to say, we should increase water supply within the limits of the carrying capacity of water resources and limit water utilization for production according to it, so that water utilization for ecology and living can be guaranteed. Restricted by water utilization for production, the scale and the increase rate of economy are decided. Under this condition, industrial structure is adjusted. Based on this concept, we put forward the basic thoughts for mutual optimization (Figure 3). Basically we take a bottom-up measure, i.e. adjust industrial structure at first and realize the mutual optimization in the end.

4.3.2 Measures on the basic hypothesis We put forward five basic hypotheses to predigest the construction of the System Dynamic Model. So we should take measures to make these five hypotheses come into existence. First, under the conditions of little change of total water resources, irrigation works should be rationally located so that the total water supply can steadily increase. Second, if the optimal plan is implemented, land utilization structure can be optimized, farmland and eco-environment can be protected, and the total land resources available will hardly change. So the implementation of the optimal plan is important. Third, eco-environmental protection engineering should be carried out to increase the water utilization for ecology. And certain water transfer from the upper and middle reaches to the lower reaches should be guaranteed so as to increase the water utilization for ecology in the lower reaches. Fourth, the economic and social system which saves water and has high efficiency should be constructed. It is required that advanced water-saving technologies should be introduced into the river basin and be popularized in time. Finally, growth rate of economy in the System Dynamic Model is a well-balanced one after considering the restriction of total water resources and other factors. Therefore, measures should be taken to avoid the abnormity of those factors. In case those factors become abnormal, the increase rate of economy in the System Dynamic Model should be properly adjusted.

4.3.3 Measures on the parameters affirmance Because of the complexity of the ecology-production-living system in the upper, middle and lower reaches, a lot of equations, variables and parameters exist in the System Dynamic Model. Moreover, uncertain factors will affect the variables and parameters. So the parameters affirmance is very difficult. However, the feasibility and rationality of the parameters are important to the final results. So the Expert Decision Support System should be constructed. To begin with, we should find the present and historical values of each parameter in the river basin and other similar regions. From those values, we can forecast their future values. And then, we should invite enough experts to consult with the feasibility and rationality of those values. At last, by those values of the parameters, we obtain an optimal plan. And we should check out the feasibility and rationality by the Expert Decision Support System. If it is irrational or impossible, we should adjust those values of the parameters until the satisfying results are obtained.

4.3.4 Measures on the popularization of the System Dynamic Model System Dynamic Model for mutual optimization of water utilization structure and industrial structure can realize the sustainable development of the ecology-production-living system in the Heihe River Basin. As the geographical and economic conditions of the other five river basins in Northwest China are similar to those of the Heihe River Basin, the System Dynamic Model can be applied to them. Therefore, further studies should be carried out to express the quantitative relationships between the variables of the other five river basins. In other words, we can obtain the mutual optimization results of the other five river basins only by adjusting the parameters of the System Dynamic Model in the Heihe River Basin. Besides, for the arid inland river basins in other parts of the world, this study also gives a new insight and method for the sustainable utilization of water resources.

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