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Socio-economic activities and the balance between water resource supply and demand in the Yellow River basin, China

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Abstract The increases of water demand associated with rapid socio-economic development frequently led to river flow stoppage in the Yellow River basin from the early 1970s to the late 1990s. To devise countermeasures for the water shortage, it is important to understand water demand in each region and sector (agricultural, industrial, domestic). The basin covers a vast area, and local industrial structure and natural conditions vary immensely. These societal and natural features lead to seasonal changes in water usage and water resource availability. Firstly, this study characterises the temporal and spatial structure of water supply, and demand for the entire basin are analysed based on the county/city level. Secondly, by emphasizing on the imbalance between water supply and demand, the structure of water supply and demand in the Yellow River basin from 1997 to 2000 is modelled.

Key words water resource management; water supply and demand balance; water shortage; Yellow River basin

INTRODUCTION

The Yellow River basin suffers from severe water shortage. The annual average water resource available was about 580 m^3 per capita, about 6% of the global average, and about 24% of China's average. Meanwhile, the total water demand in the basin has been increasing as a result of population growth, and the expansion of irrigation areas as well as industrialization and urbanization. The annual demand exceeded 30 billion m^3 in recent years. While the basin experienced rapid growth, there have also been water shortages, resulting in severe water shortage in the river in 1997. Thus, it is important to understand the water supply and demand, by region and sector, in order to provide the basis for policy making to control the severe water shortage and enhance the efficient use of water resource.

Much research has been applied to determine the water supply and demand balance or to promote integrated water management over the entire Yellow River basin. Examples of research that analyses the impacts of water supply and demand constraints on the region's society and economy include a report by the World Bank (2001) and another by the Chinese Academy of Engineering (2001). It is, however, generally difficult to obtain the data and literature on which these reports are based. Thus, this study developed a model to describe a spatial diagram of the monthly supply and demand structures of the 305 counties and cities from 1997 to 2000, using statistical reports and announcements released officially in China. Through the analysis, it becomes possible to consider the impact of resource balances between water supply and demand, and to explain the mechanism of water shortage in the river.

METHOD: WATER RESOURCES SUPPLY AND DEMAND MODEL

In order to understand the mechanisms of water resource imbalance, it is essential to analyse the availability of the water supply and the structure of the demand system. In this context, supply and demand is calculated at county and city level as the smallest administrative unit in China. Then, this study focuses on the water supply and demand balance, considering the cascade relationship of water resources upstream to downstream.

Socio-economic framework

Population and GDP were taken from various statistical reports (China Statistics Bureau, 2001a,b; Provincial Statistics Bureau, 1998–2001). The industrial sector's outputs were estimated using a model on the ratio of GDP accounted for in primary, secondary and tertiary industries (Japan Bank for International Cooperation, 2004). In order to assess the monthly values of population and GDP, the yearly data is assumed to be the value of December. Then by calculating the monthly growth rate, the other months values can be achieved:

$$\begin{aligned} &\ln\left(\frac{1}{1-\gamma_1}-1\right) = a_1 \ln y + b_1 \cdots\cdots \text{primary industry} \\ &\ln\left(\frac{1}{\gamma_3}-1\right) = a_2 \ln y + b_2 \cdots\cdots\cdots \text{tertiary industry} \\ &\gamma_2 = 1-\gamma_1-\gamma_3 \cdots\cdots\cdots\cdots\cdots\cdots\cdots \text{sec ond industry} \end{aligned} \tag{1}$$

where y is the per capita gross domestic product (yuan); γ is the ratio of industrial production; and 1..3 denotes industrial structures. Coefficients of a_1, a_2, b_1, b_2 were estimated based on provincial time-series data for the years 1952–2000.

WATER DEMAND MODULE

Agriculture water

This study calculates irrigation water demand on a monthly basis:

$$IW_i = \sum_m \left(IWU_{i,m} \times IA_{i,m}\right) \tag{2}$$

where IW_i is the Irrigation Water of each county/city i; $IWU_{i,m}$ is the crop type m of Irrigation Water Unit of each county/city i; $IA_{i,m}$ is the crop type m of Irrigation Area of each county/city i. The crop type m includes eight different crop types. Among the irrigation constants, in sections indicating the amount of water used per unit of area on irrigated land, data are available in the Chinese Academy of Engineering (2001), Ministry of Water Resources (1997–2000), and Sun *et al.* (2001). Consumption patterns by crop and by month are referred from Xu *et al.* (2004) and research by Yang *et al.* (2004). The effective irrigation area data is obtained from the China Statistics Bureau (2001a,b). Furthermore, crop irrigation area data are not published for county or city level, and the sown area of crops is only available at provincial level (China Statistics Bureau, 1998–2001). Thus, the irrigation area in each county or city is calculated according to the same provincial proportion.

Industrial water

The amount of water for industrial use is calculated by multiplying the water usage per unit of industrial production (cubic meters per 10 000 yuan) (hereinafter the industrial water standard unit). The estimates of industrial production for each county and city are calculated by the following formula, using the values for the secondary industry ratio which is obtained from equation (1):

Cities: $Y_i = 3.0986 \times GDP_i \times \gamma_{2,i}$ (3)

Counties (region minus cities): $Y_i = 3.6751 \times GDP_i \times \gamma_{2,i}$ (4)

where Y_i is the gross industrial production of each county/city i; GDP_i is the gross domestic product of each county/city i:

$$WI_i = \sum_k \left(Y_{i,k} \times w_{i,k} \times f_{i,k}\right), \quad Y_{i,k} = Y_i \times r_{i,k} \tag{5}$$

where WI_i is the amount of Water for Industrial use in county/city i; $Y_{i,k}$ is the amount of industrial production of industry k in county/city i; w_{ik} is the water usage per unit of industry k in county/city i; f_{ik} is the water recovery ratio of industry k in county/city i; r_{ik} is the industrial ratio of industry k in county/city i. Industry k includes 20 different industrial sectors. Here, for the calculation methodology for each industry $w_{i,k}$ and $f_{i,k}$, we refer to methodologies used by the Japan Bank for International Cooperation (2004).

Domestic water

The projection of domestic water use of each county/city i, DW_i comprises two parts. This study makes separate estimates for the amounts of urban domestic water uses *Piped_DW*$_i$ (amount of water provided by municipal water supply systems), and rural domestic water uses *NonPiped_DW*$_i$. The urban domestic water uses *Piped_DW*$_i$ is calculated by urban non-agricultural population Pop_i, diffusion rate of urban water supply systems S_i, and the unit domestic water use $Piped\_dw_i$ (litres/person/day). The rural domestic water usage $NonPiped\_DW_i$ is calculated by the same method, urban agricultural population and rural agricultural population Pop_i', diffusion rate of water supply systems S_i', and unit water use $NonPiped\_dw_i$ (litres/person/day).

$$DW_i = Piped\_DW_i + NonPiped\_DW_i \tag{6}$$

$$Piped\_DW_i = Piped\_dw_i \times Piped\_Pop_i\,,\ Piped\_Pop_i = Pop_i \times S_i \tag{7}$$

$$NonPiped\_DW_i = NonPiped\_dw_i \times NonPiped\_Pop_i\,,\ NonPiped\_Pop_i = Pop_i' \times S_i' \tag{8}$$

Because the values for Pop_i and Pop_i' are annual amounts (China Statistics Bureau, 2001a,b), by calculating the monthly growth rate, the other months' value can be assessed.

WATER RESOURCE MODULE

Information regarding the amount of water resources at provincial level or at the overall river basin level can be obtained from the Ministry of Water Resources (1997–2000), Yellow River Conservancy Commission (1997–2000). Documentation from China uses the term "water resource" to indicate the amount of water that humans can actually use in terms of surface water and groundwater. However, it is difficult to obtain the county or city level's water resource amount from published literature. Thus, we allocated the amount of water resources for the entire river basin according to the proportion of precipitation in each county or city, and used the results as the amount of water resources for each county or city.

Water resource cascade

The catchment area is defined, composed of the main channel and tributaries, from the Digital Elevation Model (DEM). Firstly, combining the water catchment boundaries so defined with county/city administrative boundaries, we assign the counties/cities with the largest areas to the respective water catchment areas. Next, the county/city sequence is determined in accordance with the flow from upstream to downstream of each catchment area. As this study's aim is a general analysis of the entire river basin, we consider the eight tributaries separately from the main course of the river (Fig. 1).

Water consumption rate

It is necessary to estimate how much of the water used is returned to the river. This study uses water consumption rate from Sun *et al.* (2001) and the Yellow River Conservancy Commission (1997–2000). To summarize the above points, the water demand in each sector is represented by the water intake, and the amount of water consumption is this amount multiplied by the water consumption rate. To compile the above methods, *Outflow* of county/city *i* is shown as follows:

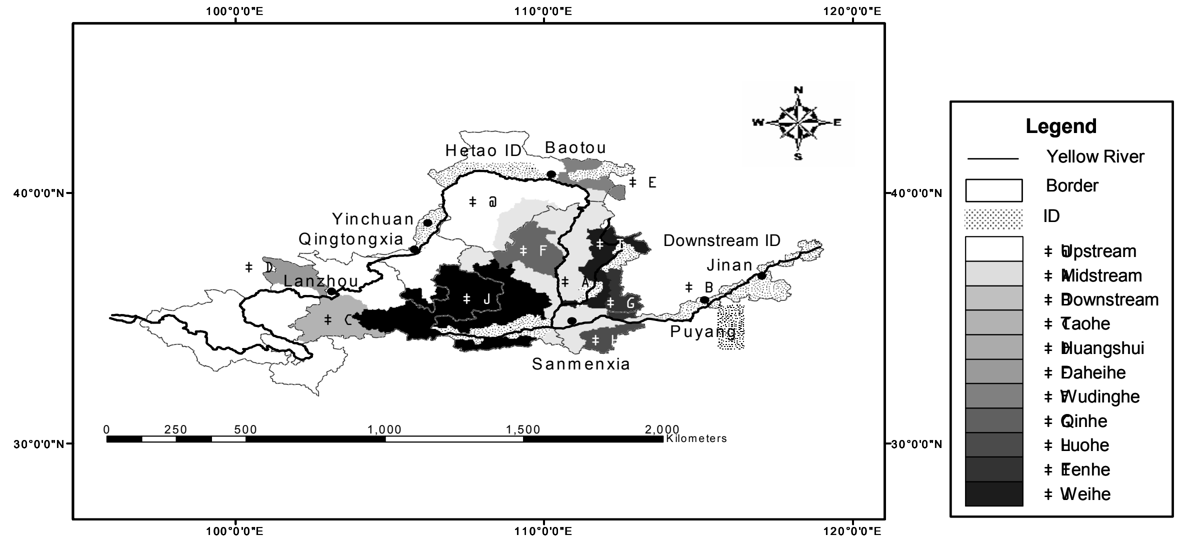

Fig. 1 Main channel and tributaries of the Yellow River basin: Upstream, Midstream, Downstream belong to the main channel of the Yellow River; ID, Irrigation District.

$$\underbrace{\underbrace{Outflow_i = Outflow_{i-1} + WR_i}_{\textit{Natural river flow}} - IWC_i - WIC_i - DWC_i}_{\textit{Actual river flow}} \tag{9}$$

where WR_i is the amount of water resource; IWC_i, WIC_i, DWC_i is the water consumption of each sector.

RESULTS: WATER SUPPLY AND DEMAND STRUCTURE

The results are summarized in Table 1. The following points can be noted: (1) most of water resources comes from upstream region, (2) in all basins in Yellow River, the amount of water resources was lower in 1997 compared with those in other years, (3) the amount of water consumption is large in the upstream and downstream regions, (4) the amount of water consumption in the downstream region exceeds the amount of available water resources from 1997 to 2000, (5) Industrial and domestic water consumption gradually increase. Figure 2 shows the temporal and spatial distribution of water resources and consumption, along the main channel of the Yellow River, from upstream to downstream (tributaries are omitted due to space limitations). The results of water supply and demand imbalances are shown by county/city. The following points can be noted: (1) large amounts of water resources are supplied from areas upstream of Lanzhou, and the amounts supplied during summer are largest, (2) in downstream region with large irrigated areas, the amount of water consumption chronically exceeds the amount of water resources, (3) the amount of water consumption exceeds water resources in the Hetao irrigation district from April through August. As a result of imbalances in these counties/cities, downstream along the main course of the Yellow River, the actual river flow volume became zero from January through June (dashed borders in Fig. 2).

Table 1 Annual water supply and demand structure by regions from 1997 to 2000.

	Upstream					Midstream					Downstream				
	IWC (10^8m^3)	*WIC* (10^8m^3)	*DWC* (10^8m^3)	*TWC* (10^8m^3)	*WR* (10^8m^3)	*IWC* (10^8m^3)	*WIC* (10^8m^3)	*DWC* (10^8m^3)	*TWC* (10^8m^3)	*WR* (10^8m^3)	*IWC* (10^8m^3)	*WIC* (10^8m^3)	*DWC* (10^8m^3)	*TWC* (10^8m^3)	*WR* (10^8m^3)
1997	63.39	9.22	2.91	75.52	207.89	18.83	4.50	2.95	26.29	56.91	116.56	7.55	5.19	129.29	24.42
1998	62.87	10.01	3.04	75.91	276.45	18.82	4.70	3.01	26.52	82.33	115.90	8.03	5.32	129.25	35.32
1999	71.47	11.81	3.54	86.82	259.59	20.42	5.37	3.16	28.96	78.12	114.06	9.12	5.53	128.72	31.59
2000	67.27	12.08	4.01	83.36	230.36	19.79	5.42	3.23	28.44	77.18	92.14	9.69	5.74	107.57	35.79
	Taohe basin					Huangshui basin					Daheihe basin				
1997	2.56	0.77	0.56	3.89	16.15	5.07	0.96	0.67	6.70	40.26	18.46	1.12	0.57	20.15	7.43
1998	2.54	0.83	0.56	3.93	25.25	5.02	1.06	0.59	6.67	47.86	18.15	1.19	0.58	19.92	9.11
1999	2.71	0.96	0.67	4.34	25.84	5.47	1.13	0.67	7.27	51.51	20.30	1.30	0.60	22.20	8.25
2000	3.31	0.90	0.71	4.92	25.49	6.22	1.19	1.35	8.76	35.30	18.58	1.46	0.79	20.84	8.12
	Wudinghe basin					Qinhe basin					Luohe basin				
1997	0.98	0.33	0.45	1.76	10.64	2.90	3.33	0.68	6.90	6.86	5.66	2.03	1.44	9.13	7.65
1998	0.98	0.36	0.46	1.80	16.08	2.83	3.18	0.63	6.64	10.01	5.49	2.14	1.47	9.10	12.01
1999	1.01	0.40	0.51	1.92	13.71	3.33	3.30	0.62	7.26	9.88	6.70	2.52	1.59	10.81	10.38
2000	1.10	0.39	0.59	2.07	18.15	3.08	2.94	0.58	6.60	9.60	6.08	2.64	1.54	10.25	11.90
	Fenhe basin					Weihe basin					Entire basin				
1997	11.24	4.75	2.14	18.13	18.24	28.35	12.68	6.16	47.20	72.59	274.01	47.25	23.70	344.96	469.04
1998	11.09	4.80	2.21	18.10	27.07	28.07	13.61	6.38	48.05	109.37	271.76	49.91	24.25	345.91	650.88
1999	10.45	5.27	2.31	18.02	23.70	29.10	15.47	7.40	51.97	108.24	285.03	56.65	26.60	368.28	620.81
2000	10.81	4.91	2.25	17.97	22.82	31.53	15.07	8.37	54.96	104.86	259.91	56.70	29.14	345.76	579.57

Notes: *TWC*, Total Water Consumption (*TWC=IWC+WIC+DWC*).

CONCLUSIONS

This study presents a model helping examine the mechanism of water supply and demand imbalance in Yellow River basin during the period of 1997 and 2000. The water shortage was caused not only by the lack of water resources, but also by the excessive consumption by the agricultural sector, especially in the irrigation areas of upstream and downstream regions during spring. In addition, the industrial and domestic water demand exhibits a tendency of increasing in the context of rapid socio-economic development. Therefore, it is crucial to control the water demand efficiently in order to achieve the sustainable development. For this purpose, the model presented in this study can provide a basis for the integrated water resource management of a watershed, especially in the Yellow River basin.

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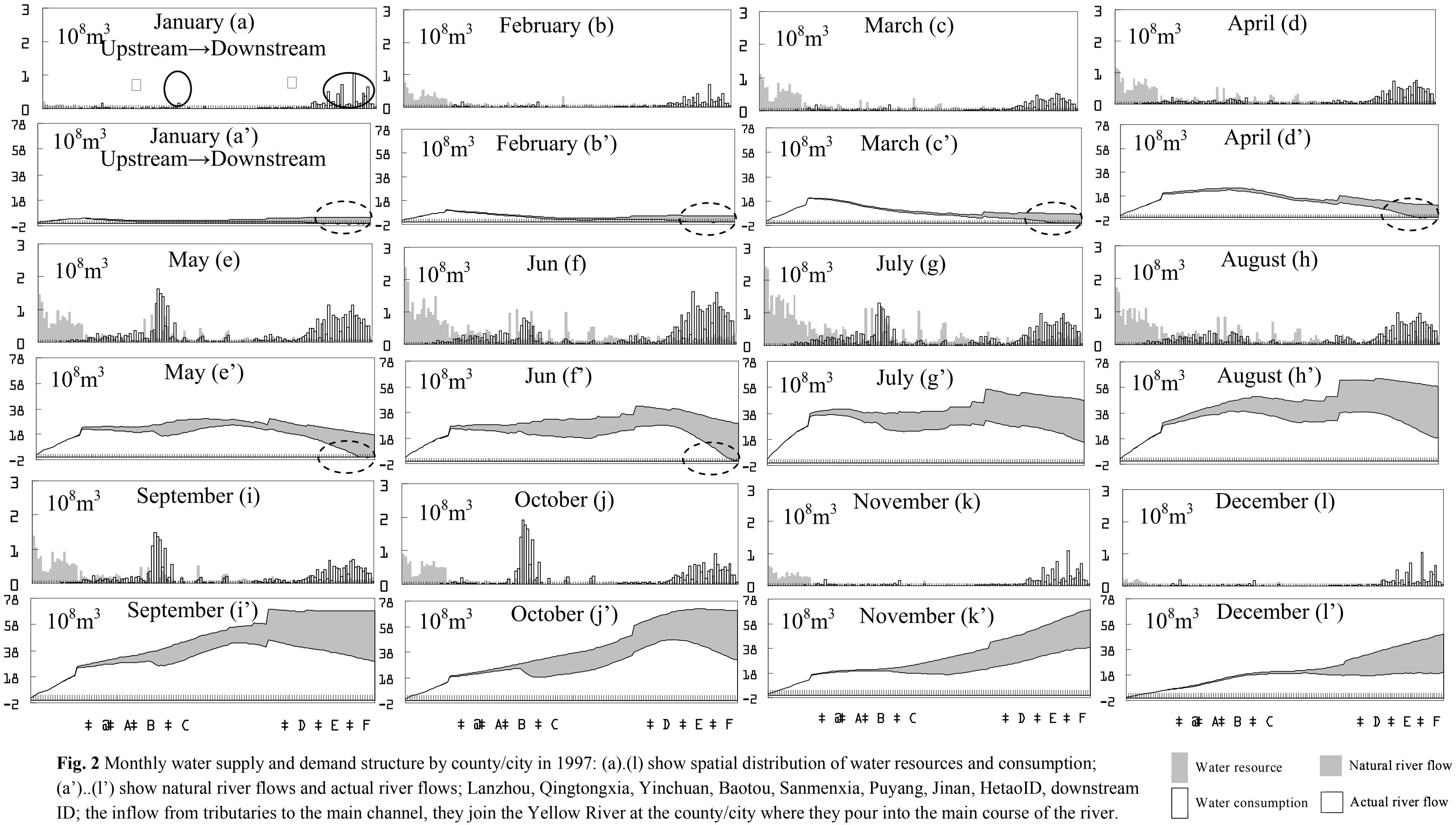

Fig. 2 Monthly water supply and demand structure by county/city in 1997: (a).(l) show spatial distribution of water resources and consumption; (a')..(l') show natural river flows and actual river flows; Lanzhou, Qingtongxia, Yinchuan, Baotou, Sanmenxia, Puyang, Jinan, HetaoID, downstream ID; the inflow from tributaries to the main channel, they join the Yellow River at the county/city where they pour into the main course of the river.

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