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Water Resources Allocation Considering the Water Use Flexible Limit to Water Shortage—A Case Study in the Yellow River Basin of China

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Abstract Water resources allocation in a river basin is customarily determined based on long-term mean water availability. However, inter-annual variability of water resources caused by climate fluctuation should also be considered in order to keep an effective and flexible allocation policy. This paper analyzes the historical evolution of the water resources allocation system in the Yellow River basin of China. Based on the concept of water use flexible limit to water shortage and actual water use data from 1988–2006, a set of flexible limits to water shortage adapted to the Yellow River basin has been proposed. This includes total water use flexible limit to water shortage for all provinces, which is approximately 70%; and the different water use flexible limits to water shortage for each social sector, which are approximately 90% for agriculture, 85% for domestic use, and 50% for other industries. It offers a simple, yet effective, method for future water resources allocation in the Yellow River basin to achieve the optimal use of water resources. It likewise provides a beneficial reference for water resources management in the water deficient regions of China.

Keywords Flexible limit · Water shortage · Water resources allocation · Yellow river

1 Introduction

Water resources planning and allocation in the river basin scale is among the most widely discussed issues in water resources management. Various programming

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methods were developed in the recent years, such as linear programming (Devi et al. 2005), dynamic programming (Shangguan et al. 2002), stochastic process (Maqsood et al. 2005), priority-based maximal multi-period network flow (Wang et al. 2007a), and decision support systems for water supply risk management (Xu et al. 1996, 1998). Some of these methods have been utilized by the Yellow River water resources management (Feng et al. 2007; Xu et al. 2003). However, most of these are either aimed at developing a water resources allocation plan based on water availability at the average level or optimizing the water resources allocation according to variations of the water storage volumes. Therefore, what they determined was the water resources allocation for the average climate level. However, climate change has significant consequences on water resources in a watershed scale (Wood et al. 1997; Giacomelli et al. 2008). The planning and allocation decisions in watershed management require strict review, especially in the arid or semi-arid regions with different dryness levels, because water resources are becoming scarcer and increasingly susceptible to variation.

A water allocation policy should integrate equity, efficiency, and environmental consciousness (Jouravlev 2005). A stable water rights system should be strengthened in multiple dimensions, focusing on security and flexibility, to be an effective incentive for the development and conservation of water resources (Solanes and Jouravlev 2006). Under scarce water conditions, the difficulty level of allocation increases due to the conflict of interests among users. Therefore, an effective method of water resources allocation should consider different water resources reliability to seek harmony with the resources base under the climate change (Garrote et al. 2007). Taking the Yellow River as a case study, this paper aims to analyze the water shortage experiences of the provinces and social sectors along the river, and design a water resources reallocation plan that can serve as a model for the water deficient regions of China.

1.1 Study Area

Yellow River, the second largest river in China, originates from the Tibetan plateau, wanders through the northern semi-arid region, crosses the loess plateau, passes through the eastern plain, and finally discharges into the Bohai Gulf (Fig. 1). The river mainly flows through nine provinces (municipalities), namely Qinghai, Sichuan, Gansu, Ningxia, Shaanxi, Shanxi, Henan, Shandong province, and Inner-Mongolia municipality. The main course of the river flows about 5,500 km in distance and accumulates 753,000 km^2 of drainage area. Approximately 100 million people live within the basin, which consists of 1200 million ha of farmland, nearly half of which is irrigated by the Yellow River. The long-term mean annual natural runoff of the Yellow river is about 58,000 million cubic meters, accounting for 2.0% of the total river runoff in China. However, an evident inter-annual variation of the natural runoff exists for Yellow River. The annual natural runoff frequently changes at different years due to climate fluctuations (Table 1). In the 1990s, the Yellow River basin experienced a continuous dry spell (Yang et al. 2004). This led to the dry-up of the lower reach, thereby causing numerous eco-environmental problems. For this reason, an effective and flexible water resources allocation policy must consider the annual and inter-annual variability of water resources, aside from the long-term mean of the water availability. It is only logical to set up a water allocation policy

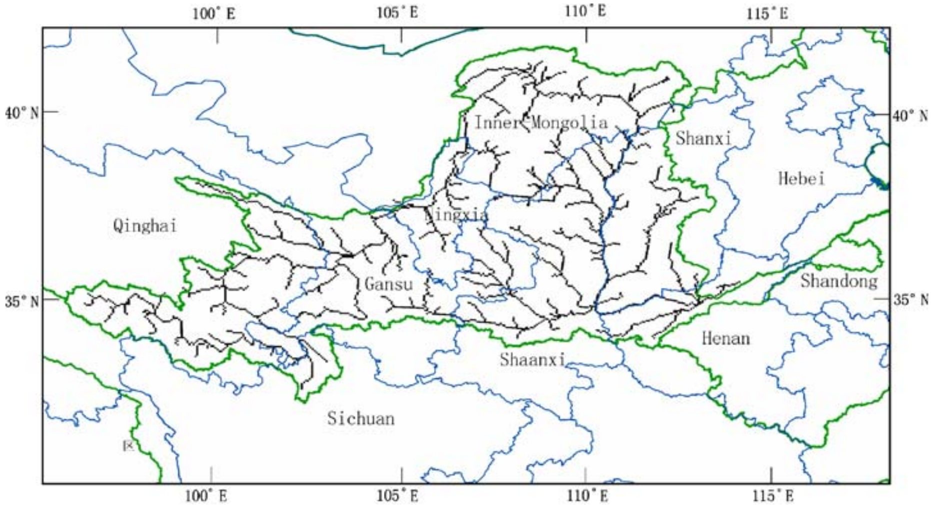


Fig. 1 The Yellow River basin, its river networks and the provinces (municipalities) along the Yellow River

considering various situations of water shortage for the water resources management in the Yellow River basin.

1.2 Historical Evolution of the Water Resources Allocation System in the Yellow River Basin

Three main water resources allocation systems have been employed in the Yellow River basin since the 1950s (Table 2). In the early years, water resources management in the basin mainly focused on flood control, agricultural irrigation, and hydro-power exploitation. The water allocation policy followed the concept of "free water for all." The expansion of agricultural irrigation along the river gradually caused an insufficiency in water resources. As a result, the lower reach of the river began drying-up in 1972. In 1987, the "Water Resources Allocation Plan of the Yellow River" was promulgated by the central government as a regulation, which stipulated the annual water quotas that can be withdrawn from the main trunk of the Yellow River by each province or municipality based on long-term average annual runoff in the basin (Table 3). According to this plan, 21,000 million cubic meters of water are left for the river eco-environment. Meanwhile, the social sectors allocated 37,000 million cubic meters of water among the provinces (municipalities) along the river based on their actual average water consumption in the past, the development

Table 1 The natural runoff of the Yellow River in recent years (unit: 10^8 m^3)

Year	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006
Annual runoff	378.17	447.97	452.18	349.87	323.33	300.30	575.42	396.70	555.47	400.41

Data Source: the Yellow River Conservancy Commission

Table 2 Historical evolution of the water resources allocation system in the Yellow River basin

Periods	Water resources allocation system	Notes
1950~1987	Free water for all	Riparian areas take water from the Yellow River freely. Agricultural irrigation is free of payment for the water withdrawn
1988~1998	Upstream priority	Upstream areas have the priority of taking water from the Yellow River and using the water without constraint
1999~ the present	Integrated regulation	The Yellow River Conservancy Commission (YRCC) is authorized to regulate water resources in the Yellow River

of their agriculture, and the increment of industry and domestic water use (Peng and Hu 2006a). The allocation plan, however, merely stipulated the macro water resources allocation quota for long-term mean conditions, and failed to delineate the water resources allocation under different drought situations. Furthermore, it fell short in assigning the inner annual allocation. Consequently, the allocation plan was unsuccessful. In practice, water diversion projects were intended to divert water from the Yellow River (Peng and Hu 2006b), and water use was in guided by the principle of “upstream priority,” because the upstream has natural priority in utilizing the water. On the other hand, the downstream suffered from water insufficiency and the lower reach of the river began drying up. In 1997, the lower reach experienced the most serious period of drying up, wherein the main river close to the sea dried up for 226 days and the no-flow distance reached 704 km from the river’s mouth.

To relieve the conflict between water demand and supply in the Yellow River basin, an annual operation plan for allocating available water in the main stream and an operational regulation were promulgated and implemented in 1998. The Yellow River Conservancy Commission (YRCC) was appointed as the authority agency for the Yellow River water resources management. The operational plan in 1998 was based on the allocation plan issued in 1987 and considered the actual water consumption conditions from 1988~1996; it likewise stipulated the inner annual water resources allocation (water consumption quotas of every month) for the provinces (Wang et al. 2007b; Zhao et al. 2005). Owing to the unified management and regulation, the drying up situation has been alleviated since 1998. Even though the Yellow River basin experienced a serious drought in 2000, the lower reach

Table 3 Water resources allocation plan of the Yellow River issued in 1987 (unit: 10^8 m^3)

Province or municipality	Annual amount of water withdrawn	Percentage of the total basin (%)
Qinghai	14.1	3.81
Sichuan	0.4	0.11
Gansu	30.4	8.22
Ningxia	40.0	10.81
Inner-Mongolia	58.6	15.84
Shaanxi	38.0	10.27
Shanxi	43.1	11.65
Henan	55.4	14.97
Shandong	70.0	18.92
Tianjin	20.0	5.41

maintained its water flow and supplied sufficient water for agriculture and non-agriculture industries along the downstream.

However, the operational plan issued in 1998 suffered from several shortcomings. The regulation stipulated the same increment and reduction proportions of water supply to all provinces or municipalities in a wet or dry year. The same increment proportion of water supply in a wet year may be reasonable, whereas the same reduction proportion of water supply during a dry year remains unresolved, because different social sectors within different provinces possess varying tolerance capacities to water shortage.

2 Methodology

First, a preliminary design of the water entitlements allocation system for the water deficient regions of China is proposed. Next, we define the water use flexible limit to water shortage, which represents the reduction possibility of water consumption among different areas or social sectors. This would be the potential method for instructing the allocation of water supply in the event of future droughts according to the user's water shortage experience and bearing capacity.

2.1 Design of the Water Resources Allocation System for the Water Deficient Regions

The general principle of water resources allocation in the dry areas should ensure basic domestic water demand and food security. Water allocation should be aimed at optimizing water utilization in accordance with the principles of sustainable development. Based on the water resources assessment, water resources can be allocated on the basis of long-term mean water availability for the normal year. Following the general principles, water resources should be allocated to different areas and sectors according to their respective water deficient degrees. During the wet year, there is no water supply stress among the regions, and water resources can be reallocated based on the same increment proportion of water supply for all social sectors. However, during a dry year, reducing the water resources among the areas and sectors at the same proportion is not reasonable because they have varying water shortage-bearing capacities. Flexible ranges and limits to water shortage must first be determined to ensure the minimum requirements for different areas and sectors, and subsequently, adjust the water allocation based on the limits to water shortage. In extreme-dry situations, the water shortage exceeds the flexible limits and water crisis managing measures are necessary, such as an urgent water supply by lorry or urgent water transmission through tap water pipes. In case the water crisis cannot be effectively solved locally, diversion or immigration will be required. Figure 2 shows the preliminary design of water entitlements allocation flowchart for water deficient regions of China.

2.2 Concept of the Water Use Flexible Limit to Water Shortage

Water resources in a river basin are generally allocated among different sectors, such as industry, agriculture, and domestic use, after excluding the eco-environmental

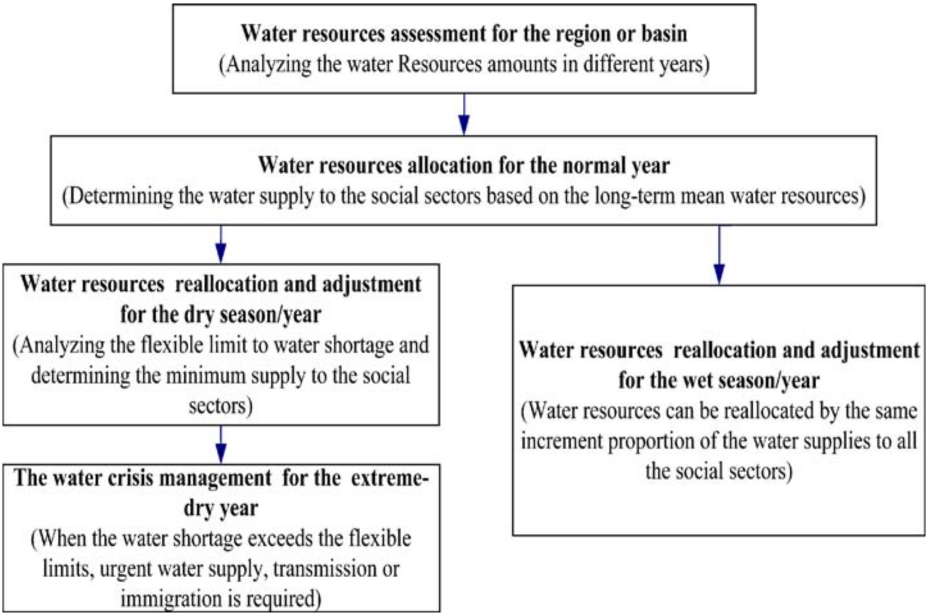
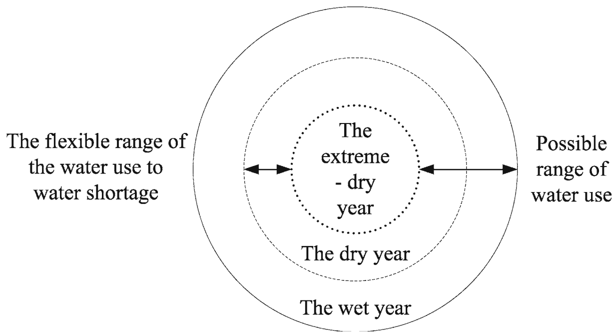


Fig. 2 A preliminary design of water entitlements allocation flowchart in water deficient regions

water use. Social sectors are postulated to have stable water supplies in a normal year equaling their long-term mean water use, which is considered as their normal water requirements. With the climate fluctuating, actual water resources availability frequently varies among the different seasons and years. In dry years, water supply to the social sectors decrease due to the insufficiency of natural water resources. However, random or unrestricted reduction of water supply may put the socioeconomic system under stress (Wood et al. 1997). The variation range of the individual sectors' water supply in a dry year is defined as the flexible range of water use to water shortage, while the lower limit of the reduction is defined as the flexible limit to water shortage, indicating the lowest water requirement of the sector during periods of droughts. The flexible limit can also be described as a minimum proportion of water supply in a dry year to the normal water requirement of a sector. This paper analyzes the flexible ranges and flexible limits to water shortage of the water uses among different social sectors in the Yellow River basin.

In the abridged general view (Fig. 3), the concentric circles represent the social sector's water consumption variation from extreme-dry to wet years. The inner annulus represents the general dry years, and the range of water consumption variation in this annulus represents the flexible range of water use to water shortage. The smallest circle represents the extreme-dry years. In extreme-dry situations, the water shortage exceeds the flexible limits, thus a water crisis occurs. The outer annulus represents the wet years, wherein water consumptions are not restricted by the natural resources as compared to a normal year. The water consumption variation range from the general dry year to the wet year is the whole possible water use range. Outside the biggest circle means the flood year.

Fig. 3 Abridged general view of the range of water use and its flexible limit to water shortage



3 Analysis of the Water Shortage Experience in the Yellow River Basin

Based on the data provided by "Bulletin of Yellow River Water Resources" (Yellow River Conservancy Commission 1998–2006) and "China Water Resources Bulletin" (The Ministry of Water Resources of China 1988–2006), the actual water consumptions from 1988 to 2006 of the provinces or municipalities along the Yellow River were analyzed. A set of empirical flexible limits to the water shortage adapted to the Yellow River basin was proposed.

3.1 Analysis on the Flexible Limit of Water Consumption to Water Shortage for the Provinces (Municipalities)

Table 4 shows the variations of actual annual water consumptions in different provinces/municipalities from 1988–2006 since the "Water Resources Allocation Plan" was issued in 1987. The actual mean annual surface water consumptions of Shaanxi and Shanxi provinces have been lower than the 1987 quota. This is because their surface runoff in the Fenhe and Weihe Rivers (two main tributaries of the Yellow River) was deficient and they could not take water from the Yellow River easily. In the meantime, groundwater was pumped extensively in these areas. Table 4 also indicates that the actual mean annual water consumptions of Qinghai, Gansu, Ningxia, and Henan were a little less than the 1987 quotas, while the actual mean annual water consumptions of Inner-Mongolia and Shandong were much higher than the 1987 quotas. With the exception of Shaanxi and Shanxi, the variance of the actual mean annual water consumptions of other provinces and municipalities ranged from 47∼193%. According to the definition of water use flexible limit to water shortage, and considering the 1987 quotas are the normal annual water requirements for the provinces, the flexible limit of water consumption for Henan province is about 50%, about 60% for Gansun province, about 70% for Qinghai and Shandong provinces, about 80% for Ningxia province, and about 90% for Inner-Mongolia municipality. This preliminary result indicates that the mean flexile limit to the water shortage is approximately 70% of the normal year for all provinces (municipalities) along the Yellow River. The implication of which is that water supply for the provinces must guarantee 70% of the normal year level; otherwise, disasters may happen.

Table 4 Actual water consumption of provinces/municipalities along the Yellow River (10^8 m^3)

Province/municipality	Qinghai	Gansu	Ningxia	Inner-Mongolia	Shaanxi	Shanxi	Henan	Shandong
Allocation quota in 1987	14.1	30.4	40.0	58.6	38.0	43.1	55.4	70.0
Maximum water consumption from 1988–2006	15.90	30.05	42.5	71.55	26.84	14.4	50.82	134.8
Minimum water consumption from 1988–2006	9.83	17.56	30.37	50.46	17.30	9.04	26.07	49.57
Mean of actual water consumptions from 1988–2006	12.01	25.90	36.88	62.22	21.84	11.24	33.98	77.45
Variation of the actual water consumption from 1988–2006 compared to the quota in 1987 (%)	69.7~112.8	57.8~98.8	75.9~106.3	86.1~122.1	45.5~70.6	21.0~33.4	47.1~91.7	70.8~192.6

Variation of the actual water consumption from 1988–2006 compared to the quota in 1987: the lower limit is calculated using the minimum water consumption from 1988–2006 compared by the allocation quota in 1987, while the higher limit is the maximum water consumption from 1988–2006 compared by the quota in 1987. Sichuan province and Tianjin City are not included in the analysis because the water use of Sichuan is much less than the other provinces, while the water consumptions of Tianjin do not have data for some years.

Table 5 Statistics of annual agricultural water use for the eight provinces (municipalities) along the Yellow River from 1998~2006 (unit: m^3/year per mu)

Province/municipality	Annual maximum	Annual minimum	Annual mean	Variation (%)
Qinghai	647	616	628.0	98.1~103.0
Gansu	628	542	589.3	92.0~106.6
Ningxia	1352	848	1092.3	77.6~123.8
Inner-Mongolia	455	353	408.6	86.4~111.4
Shaanxi	318	280	298.1	93.9~106.7
Shanxi	217	201	209.3	96.0~103.7
Henna	234	170	203.1	83.7~115.2
Shandong	275	232	251.8	92.1~109.2

3.2 Analysis on the Water Consumptions and Flexible Limits to Water Shortage for Different Sectors

Based on the data from "China Water Resources Bulletin," an analysis has been carried out on the agricultural, industrial, and domestic water consumptions in the Yellow River basin from 1998 to 2006. Tables 5, 6, 7, and 8 indicate the actual maximum, minimum, and mean amount of water consumption, and variation ranges from the minimum to the mean are identified as the flexible ranges of water use to water shortage.

These four tables indicate that from 1999–2006, the variations of the agricultural, industrial, urban domestic and rural domestic water use for all provinces were about 77.6~123.8%, 32.6~190.9%, 61.5~129.4%, and 37.9~164.0%, respectively. The mean flexible limits to water shortage of agricultural, industrial, urban domestic and rural domestic users were approximately 90%, 50%, 85% and 75% respectively. It can be observed that the industrial water user had the largest flexible range to water shortage, while the agricultural and urban domestic water users had the least flexible range to water shortage. This may be because the industry can enhance water recycling techniques and improve production technologies to largely reduce the proportion of water use when a water shortage happens. When droughts occur, the agricultural water supply should be guaranteed at least 90% of the normal level, especially during the critical growing period for the crops. However, during the non-critical growing period, irrigation water for the plants can be reduced accordingly. Here, rural domestic water consumption in the Yellow River basin has a larger

Table 6 Statistics of annual industrial water use for the eight provinces (municipalities) along the Yellow River from 1998~2006 (unit: m^3 per 10,000 RMB value added of industry)

Province/municipality	Annual maximum	Annual minimum	Annual mean	Variation (%)
Qinghai	476	264	365.3	72.3~130.3
Gansu	540	182	355.9	51.1~151.7
Ningxia	514	120	278.9	43.0~184.3
Inner-Mongolia	185	84	136.4	61.6~135.6
Shaanxi	230	63	148.1	42.5~155.3
Shanxi	187	62	120.4	51.5~155.3
Henan	201	80	135.3	59.1~148.6
Shandong	117	20	61.3	32.6~190.9

Table 7 Statistics of the annual urban domestic water use for the eight provinces (municipalities) along the Yellow River from 1998~2006 (unit: liter/day per capital)

Province/municipality	Annual maximum	Annual minimum	Annual mean	Variation (%)
Qinghai	217	195	201.8	96.6~107.5
Gansu	194	190	191.6	99.2~101.3
Ningxia	192	115	157.6	73.0~121.8
Inner-Mongolia	134	71	115.4	61.5~116.1
Shaanxi	192	147	171.0	86.0~112.3
Shanxi	148	99	114.4	86.5~129.4
Henan	186	159	171.4	92.8~108.5
Shandong	145	119	132.6	89.7~109.4

extent than urban domestic water consumption, primarily because in rural areas some crude projects are effective, such as ponds for collecting precipitation and wells for pumping groundwater, whereas these water resources are not included in the statistics. In fact, domestic water use can not be reduced too much due to social security; 85% of the normal level may be the limit.

4 Discussion

This paper proposes a potential methodology for water resources reallocation and adjustment in dry years/periods based on the regional water resources assessment and water shortage experiences analysis. Referring to recent literature, some researchers have proposed similar ideas of considering climate change in relation to water resources planning.

Giacomelli et al. (2008) pointed out that "the significance of water rights is to establish a maximum limit of water consumption allowed for each user; in fact, it cannot exceed the respective water rights limit and it can be far lower," which implicitly reflects the concept of the water use flexible range to water shortage we proposed. The disciplinary perspective of drought was discussed and the competition among water users along the Adda River was analyzed in their paper. They focused on the inner-annual (monthly) water resources demand and supply analysis and produced a preliminary picture of the water right volumes. Wheida and Verhoeven (2007) argued an alternative solution for the water shortage problem in Libya, including water supply management, water demand management, and water allocation

Table 8 Statistics of the annual rural domestic water use for the eight provinces (municipalities) along the Yellow River from 1998~2006 (unit: per capital l/day)

Province/municipality	Annual maximum	Annual minimum	Annual mean	Variation%
Qinghai	124	39	79.6	49.0~155.8
Gansu	57	41	49.5	82.8~115.2
Ningxia	44	25	34.0	73.5~129.4
Inner-Mongolia	121	28	73.8	37.9~164.0
Shaanxi	57	42	50.1	83.8~113.8
Shanxi	48	35	40.1	87.3~119.7
Henan	70	44	55.5	79.3~126.1
Shandong	67	49	56.3	87.0~119.0

management. In water demand management, they mentioned that the reduction of agricultural water consumption could be achieved by several means, such as a national policy on water resources, agricultural planning, irrigation technique, and production efficiency. For the water allocation management aspect, they mentioned how Libya needs legislation for actual water consumption. Their paper presented a similar idea through controlling the water supply when droughts happen, but they focused on water-saving techniques and legislation improvement. The “Urban Water Management Plan” for the City of Santa Cruz (City of Santa Cruz Water Department 2005) analyzed the city’s water shortage contingency plan. It divided the water shortage condition into four stages and decided water consumption reduction methods for social activities based on these four stages (minimal, moderate, serious, and severe). For example, there are voluntary restrictions of water consumptions for the minimal stage and mandatory restrictions of water consumptions for the moderate shortage. This plan provided a detailed description of water supply reliability and water shortage countermeasures, which would be a good reference for our further study.

In contrast with the operational plan issued in 1998 for the Yellow River, which stipulated the same reduction proportion of water supply to all provinces or municipalities in a dry year, the method proposed in our research appears to be more reasonable because it considered the varying water shortage-bearing capacities of the provinces. Furthermore, it can also instruct water reallocation among different social sectors. However, as a preliminary design of water entitlements, this research calls for further study, such as more detailed water shortage classifications, impact of populations increment on water reallocation policy, and a more operable program for water reallocation in non-humid regions especially at the inner-annual scale.

5 Conclusion

Taking the Yellow River basin as a case study, this paper discussed a method for designing a future water resources allocation plan especially during water shortages. It indicates that if the Yellow River basin once again experiences a dry year in the future, based on the water use flexible limits to water shortage of the provinces along the river, water supplies for the provinces must guarantee 70% of the normal year level; otherwise, disasters maybe happen. Meanwhile, for the social sectors of all the provinces, agricultural water supply for the critical growing period must guarantee 90% of the normal year level, industrial water use about 50% of the normal year level, and domestic water use about 85% of the normal year level. This would be a simple and pragmatic method for prior allocation and would be utilized in determining future allocation based on the water resources assessment and the flexible limits analysis. This method is expected to provide a useful reference for water resources management in the water deficient regions of China.

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