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Incorporating Eco-environmental Water Requirements in Integrated Evaluation of Water Quality and Quantity—A Study for the Yellow River

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Abstract River water has dual functions; it can be withdrawn for agricultural, industrial, and domestic uses and provides eco-environmental water (EEW) for riverine systems. A concept of intensity of ecological function of river water (IEFRW) has been put forward, and an integrated water quantity and quality evaluation method in combination with eco-environmental water requirements has been developed for a river. Based on the monthly data of water quality and quantity as well as the withdrawals during 1997 to 1999, an integrated evaluation of water resources has been conducted for the Yellow River. The results indicated that actual IEFRW can directly reflect the health state of riverine ecosystems. The actual increments of water resources availabilities caused by providing EEW for the riverine systems were lower than the eco-environmental water requirements of the riverine ecosystem, leading to the intermittent interruption of river flow and other eco-environmental problems of the Yellow River.

Keywords Water resources · Water quality · Intensity of ecological function of river water · Eco-environmental water requirements · Water resources management

1 Introduction

Water is an essential component of the living world. Water resources availability is of significance to regional socio-economic development, which depends on both quality

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and quantity. Over the past decades, numerous researches have been undertaken to study water resources management (Plate 1993; Suzuki 1998; Xia and Takeuchi 1999; Said 2006; Wang et al. 2008). Many authors emphasized the importance of conjunctly considering both water quantity and quality in water resources management (Luiten and Groot 1992; Vijayan et al. 1999; Azevedo et al. 2000; Paredes and Lund 2006; Croke et al. 2007). For example, Campbell et al. (2001) evaluated alternative water management scenarios for a section of the Klamath River in California by using computer models of water quantity (MODSIM) and quality (HEC-5Q). Dai and Labadie (2001) conducted a research on the methodology for integrating quality and quantity in river basin planning and management, including the conjunctive use of surface- and ground-water. Bhakdisongkhram et al. (2007) developed a water model for water and environmental management at Mae Moh Mine Area in Thailand, manipulating water quantity and quality to reduce environmental impacts. Xia et al. (2004a, b) reported an integrated water quantity and quality management method for the entire Yellow River system where eco-environment has been deteriorating and water quantity is very scarce, and the integration concepts of water resources functional capacity and water resources functional deficit have been put forward, and their characteristics have been analyzed.

In the past decade, several authors have proposed the water resources management should balance ecosystem and human needs (Loomis et al. 2003; Falkenmark 2004; Khan 2004). The concept of eco-environmental water requirements (EEWR) can be divided into two parts: ecological water requirement and environmental water requirement (Yang et al. 2005). The ecological water requirement means the amount of water used by the ecosystem to maintain the water balance of the living beings. The environmental water requirement is the water used to protect and improve the water environment and the environment in which human lives (Yang et al. 2005). Smakhtin et al. (2004) reported a first attempt to estimate the volume of water required for the maintenance of freshwater-dependent ecosystem at the global scale. It is shown that approximately 20 to 50 percent of the mean annual river flow in different basins needs to be allocated to freshwater-dependent ecosystems to maintain them in fair conditions. Sun et al. (2008) developed a method for quantifying the environmental flows in estuaries, while integrating multiple ecological objectives. In addition, as to the riverine ecosystems, EEWR often imply meeting minimum streamflow requirements which supporting the aquatic system of the river. Some terms such as "environmental maintenance flow", "ecological base flow" and "natural flow regime" emerged, which are used to describe the EEWR of riverine ecosystems (Hughes et al. 1997; Koel and Sparks 2002; Shiau and Wu 2004; Suen and Eheart2006).

According to the above-mentioned, river water meets the EEWR of the riverine ecosystem as it flows through the river course before it is withdrawn for human uses. Therefore, the river water has dual functions. One is meeting human needs for domestic, agricultural and industrial uses, and the other is satisfying the EEWR of the river. The dual functions of river water should be considered in integrated water resources management, especially for the rivers with low water resources availability. However, very few researches have been undertaken to incorporate EEWR in integrated management of water quality and quantity.

This research is an extension of the previous efforts (Xia et al. 2004a, b), emphasizing on developing an integrated approach for incorporating EEWR in dealing with twined water quality and quantity management in the Yellow River Basin with a high population pressure, low water resources availability, and serious ecological deterioration. A concept of intensity of ecological function of river water (IEFRW) will be put forward. Based on the monthly data of water quality and quantity as well as the withdrawals and water quality demand of the EEWR in 1997, 1998 and 1999, the temporal and spatial variations of IEFRW of river water will be highlighted; an integrated evaluation of water quantity and quality in combination with EEWR will be conducted for the Yellow River.

2 Methodology

2.1 Integrated Evaluation of Water Resources

River water has three ways to go. Firstly, some water can be withdrawn from the river course for agricultural, industrial, and domestic uses. Secondly, some can flow out of the basin into a sea. Thirdly, some water can be stored in the river course such as reservoirs and lakes. Therefore, total natural runoff of a river includes these three parts. In addition, as mentioned before, river water has dual functions. That is to say, if river water quality meets the quality demand of both EEWR and human uses; one unit -volume river water has the functions of two unit volume water. In this case, the water resources availability amounts to two unit volumes; one unit volume is for human uses, and the other is the increment of water resources availability caused by providing eco-environmental water for riverine ecosystems. Therefore, the dual functions of river water result in the increase of water resources availability.

Therefore, the total water resources availability of a river can be calculated with the following formula:

$$W_{\mathrm{T}} = W_{\mathrm{ur}} + W_{\mathrm{er}} \tag{1}$$

where W_{T} is the total water resources availability of a river, m^3; W_{ur} is the total water resources availability withdrawn for domestic, industrial and agricultural uses, m^3; W_{er} is the total increment of water resources availability caused by the ecological function of river water, m^3. The river water flowing out of the basin into a sea belongs to the W_{er} because it only provides eco-environmental water for the riverine systems. The river water stored in the river course such as reservoirs and lakes was caused by the human activities or the self-adjustment of the river course; the river water belongs to the W_{ur} for the former case and belongs to the W_{er} for the latter case.

Water resources availability depends on both quality and quantity. In fact, only that water of which quality satisfies the requirement of water body function can be called as water resources; it is qualified for the desired function which is here named as "water resources function". Therefore, if the water system is below the standard, water resources availability is not equal to the water quantity. For the area where water resources is very scarce, even if river water can not satisfy the water quality demand of domestic, industrial and agricultural uses, people will try to use this kind of river water and make the river water provide water resources for human activities where water is desired. In this case, water resources availability can not be regarded as zero. Meanwhile, it will depend on both water quantity and quality. For example, if chemical oxygen demand (COD) mainly caused by oxygen-consuming organics, is the major pollutant of a water body, and the measured COD concentration is 10 mg/l while the desired (regulated) concentration is 5 mg/l. Therefore, the water must be pretreated before use. For example, one of the pretreatment methods is taking out half unit volume of the water and diluting the other half unit volume at a 1:1 ratio with other water with COD concentration of zero; then the total water quantity is still one unit volume. That is to say, the water resources availability of one unit volume water with COD concentration of 10 mg/l amounts to half unit volume. Based on the above analysis, if river water can not satisfy the water quality demand of human uses, water resources availability can be calculated with the following equation:

$$W_{\mathrm{r}} = \frac{C_{\mathrm{d}}}{C_{\mathrm{m}}} \times Q \tag{2}$$

where W_{r} is the water resources availability, m^3; C_{d} is desired (regulated) concentration of the major pollutant, mg/l; C_{m} is measured concentration of the major pollutant, mg/l; Q is the water quantity, m^3. If river water satisfies the water quality demand of human uses, the water resources availability is equal to the water quantity. Therefore, no matter what the river water quality is, the water resources availability withdrawn for domestic, industrial and agricultural uses can be calculated with the following equation:

$$W_{\mathrm{r}} = \min\left(1, \frac{C_{\mathrm{d}}}{C_{\mathrm{m}}}\right) \times Q \tag{3}$$

This equation reflects the integrated effect of water quantity and quality on the water resources availability.

2.2 Concept of Intensity of Ecological Function of River Water

Assuming there are two kinds of river water, both of them are one unit-volume and satisfy the quality demand of EEWR. One flows through the river course for 1,000 m before it is withdrawn for human uses while the other flows through the river course for 100 m before its withdrawal. Obviously, the action of these two kinds of river water on riverine ecosystems is different; the former is ten times of the latter. Here, we refer to the concept of "work" in physics. The action of river water on riverine ecosystems, named as intensity of ecological function of river water (IEFRW), is not only related to the water quantity but also correlated with the flow distance of water through the river course. If water quantity does not exceed the upper limit of EEWR of the river ecosystems and water quality satisfies the quality demand of EEWR, accordingly, IEFRW can be calculated with the following equation:

$$I = Q \times L \tag{4}$$

Where I is the IEFRW, m^4; Q is the water quantity, m^3; L is the flow distance of water through the river course, m.

For the area where water resources is scarce, even if the river water quality does not meets the quality demand of EEWR for riverine ecosystems, it is still useful to the riverine ecosystems where water is desired. In this case, the IEFRW can not be regarded as zero. In order to keep the calculation of IEFRW consistent with that of the water resources availability of the withdrawn river water, the following equation is used to calculate the IEFRW:

$$I = \frac{C_{\mathrm{d}}}{C_{\mathrm{m}}} \times Q \times L \tag{5}$$

Where I is the IEFRW, m^4; C_{d} is desired (regulated) concentration of the major pollutant, mg/l; C_{m} is measured concentration of the major pollutant, mg/l; Q is the water quantity, m^3; L is the flow distance of water through the river course, m. Therefore, if water quantity does not exceed the upper limit of EEWR of the riverine ecosystems, the IEFRW can be calculated as the following equation regardless of the water quality:

$$I = \min\left(1, \frac{C_{\mathrm{d}}}{C_{\mathrm{m}}}\right) \times Q \times L \tag{6}$$

2.3 Application of Intensity of Ecological Function of River Water to Water Resources Management

A river can be divided into many sections such that the hydrological flow within each section is uniform throughout the reach. For one section, assuming the river water quality satisfies the quality demand of the EEWR, the IEFRW of the section is called as theoretical IEFRW; it can be calculated with Eq. 4. The total theoretical IEFRW of a river is the sum of all the river sections, and it can be calculated with the following equation:

$$I_{\mathrm{T}} = \sum_{i=1}^{n} I_i \tag{7}$$

where I_{T} is the total theoretical IEFRW of a river, m^4; I_i is the theoretical IEFRW of river section i, m^4; n is the number of river sections. The total actual IEFRW of a river can be calculated with the following equation:

$$I_{\mathrm{ta}} = \sum_{i=1}^{n} I_{\mathrm{a}i} \tag{8}$$

where I_{ta} is the total actual IEFRW of a river, m^4; I_{ai} is the actual IEFRW of river section i, m^4, which can be calculated with Eq. 6; n is the number of river sections.

For a river, if no river water is withdrawn for human use, and river water quality satisfies the quality demand of EEWR, then the total natural runoff is used as eco-environmental water for the riverine systems, and the water resources availability possessing the ecological function is equal to the total natural runoff. As it is easy to get monthly data of water quantity and quality, based on the above analysis, the following formula can be used to calculate the increment of water resources availability caused by the ecological function of river water in month m:

$$W_{\mathrm{erm}} = \frac{I_{\mathrm{tam}}}{L} \tag{9}$$

where W_{erm} is the increment of water resources availability caused by the ecological function of river water in month m, m^3; I_{tam} is the actual IEFRW of a river in month m, m^4; L is the length of the river, m. Therefore, the total increment of water resources availability caused by the ecological function of river water is the sum of 12 months, which can be calculated with the following equation:

$$W_{\mathrm{er}} = \sum_{m=1}^{12} \frac{I_{\mathrm{tam}}}{L} \tag{10}$$

where W_{er} is the total increment of water resources availability caused by the ecological function of river water in 1 year, m^3; m is month, 12 months for every year.

2.4 Data Sources of the Yellow River

The overview of the Yellow river has been described in the previous study (Xia et al. 2004b). Monthly-average water quality and quantity data of 1997 to 1999 as well as precipitation data in 1997 and 1998 were obtained from the Yellow River Conservancy Commission (YRCC 1997–1999). The water quantity and quality data were comprehensive in these three years. In addition, the Xiao Lang Di Dam was built in the end of 1997; selection of these three years is helpful to understand the influence of Xiao Lang Di Dam on the water resources of the Yellow River. Water quality data include dissolved oxygen (DO), chemical oxygen demand, biochemical oxygen demand (BOD_5), ammonium nitrogen (NH_4^+–N), nitrite nitrogen (NO_2^-–N), nitrate nitrogen (NO_3^-–N), total phosphate, heavy metals, volatile phenol, petroleum contaminants, surfactants, and fecal coliform. This investigation was a part of a basin-wide water-quality-monitoring program (YRCC 1985). Water samples were collected from over 445 stations. They were analyzed in eight provincial laboratories under the National Environmental Monitoring Network Program (Ministry of

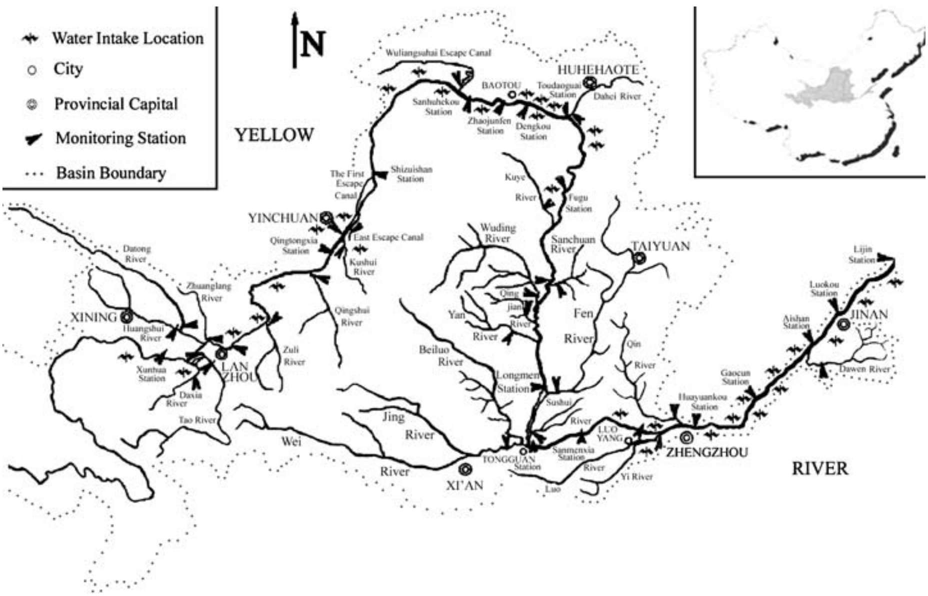


Fig. 1 The Yellow River basin

Water Resources 1980, 1985). The water quantity data include river runoff at each hydrological station and water withdrawal at each intake point. Locations of the hydrological stations and intake points are shown in Fig. 1. According to the national standard of surface water, which has been described in the previous study (Xia et al. 2004b), water quality should be better than or equal to grades V, IV and III for agricultural, industrial and domestic withdrawals, respectively. For water stored in the river course or used as eco-environmental water for riverine ecosystems, the quality should be better than or equal to grade III.

3 Results and Discussion

3.1 Intensity of Ecological Function of River Water of the Yellow River

Based on the water quantity data, the theoretical IEFRW were calculated for the river. Based on the water quantity and water quality data of DO, COD, BOD_5, NH_4^+–N, NO_2^-–N, NO_3^-–N, total phosphate, heavy metals, volatile phenol, petroleum contaminants, surfactants, and fecal coliform from 1997 to 1999, the actual IEFRW of the river were calculated. As shown in Fig. 2, the intra-annual distribution of monthly actual IEFRW of the river was uneven; the actual IEFRW in high-water season was higher than those in low-water season. For example, the highest of monthly actual IEFRW was $9.50 \times 10^{15} m^4$ occurring in May while the lowest was $3.16 \times 10^{15} m^4$ occurring in February of 1997; the former was about three times of the latter. The intra-annual variation trend of actual IEFRW was generally consistent with both of the river runoff and the precipitation in the basin. The correlation coefficients between the IEFRW and the precipitation were 0.72 and 0.84 in 1997 and 1998, respectively, and those between the IEFRW and the river runoff were 0.69, 0.73 and 0.83 in 1997, 1998 and 1999, respectively. In some periods, however, the temporal variations of the actual IEFRW did not agree with those of the river runoff and the precipitation; this was probably due to the temporal and spatial variations of water quality as well as the spatial variations of water quantity caused by the variations of agricultural, industrial, and domestic withdrawals from the river.

The annual precipitation increased from 331 mm in 1997 to 484 mm in 1998, leading to the increase of theoretical IEFRW of the Yellow River. As shown in Fig. 3, the actual and theoretical IEFRW of the Yellow River manifested an increasing trend during 1997 to 1999. For example, the actual IEFRW of the upper reach of the river increased from 14.87×10^{15} m^4 in 1997 to 19.16×10^{15} m^4 in 1998 and 30.18×10^{15} m^4 in 1999, and those of the lower reach increased from 3.47×10^{15} m^4 in 1997 to 7.12×10^{15} m^4 in 1998 and 7.39×10^{15} m^4 in 1999. The intermittent interruption of river flow occurred for 226, 142 and 42 days at the Lijin Station located at the river mouth in 1997, 1998 and 1999, respectively; the number of interruption days were negatively correlated with the actual IEFRW of the lower reach. This suggested that the actual IEFRW directly reflected the health state of riverine ecosystems.

As shown in Fig. 3, the actual and theoretical IEFRW manifested a decreasing trend from the upper (from the headwater to the Toudaoguai Station) to the middle (from the Toudaoguai Station to the Huayuankou Station) and lower (from the Huayuankou Station to the river mouth) reaches. For example, the inter-annual

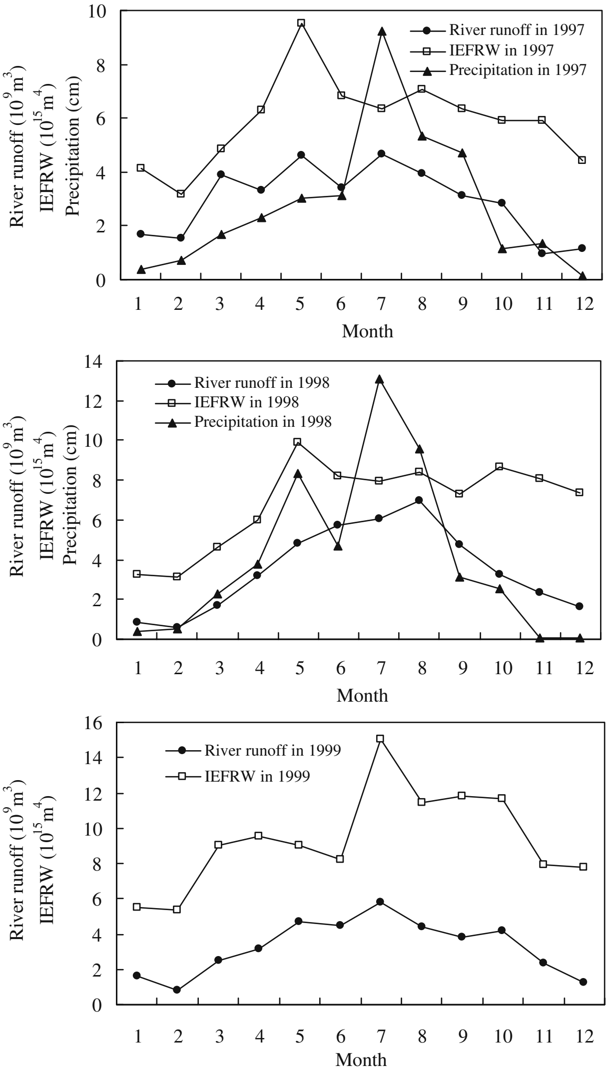


Fig. 2 Intra-annual distributions of river runoff and IEFRW in 1997, 1998 and 1999

averages of actual IEFRW during 1997 to 1999 decreased from 21.41×10^{15} m^4 in the upper reach to 12.38×10^{15} m^4 in the middle and 5.99×10^{15} m^4 in the lower reach. Although the decreasing trend of river length from the upper to the middle and lower reaches is one of the reasons for the decreasing trend of IEFRW, the ratios of actual IEFRW to the river length also showed a decreasing trend. According to the previous research (Xia et al. 2004b), there was a decreasing trend for river flow and a deterioration trend for water quality from the upper to the middle and lower reaches. Therefore, the decreasing trend of the actual IEFRW was caused by the decreasing trend of river flow and the deterioration trend of water quality. In addition, the ratios of the inter-annual averages of actual IEFRW to that of the theoretical IEFRW were 0.76, 0.68 and 0.65 in the upper, middle and lower reaches, respectively. The

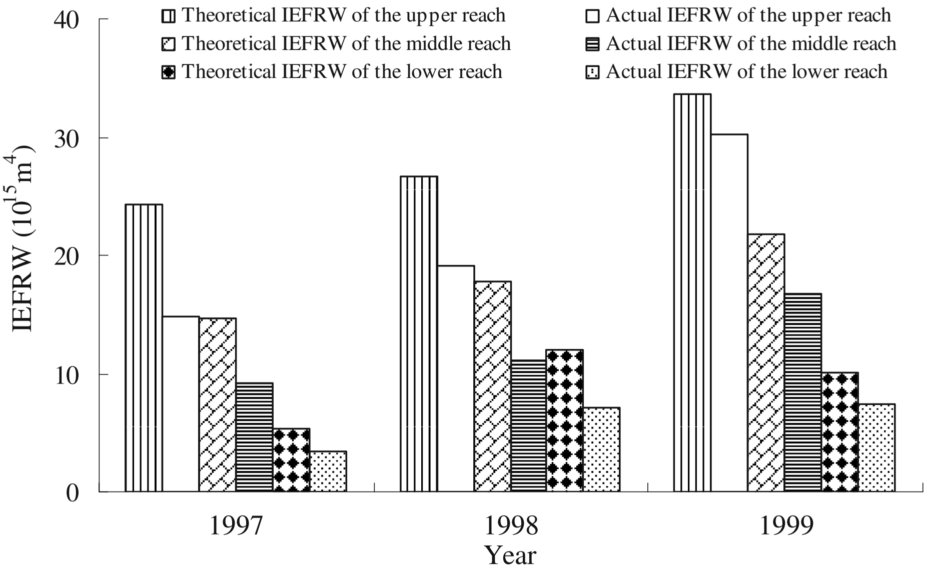
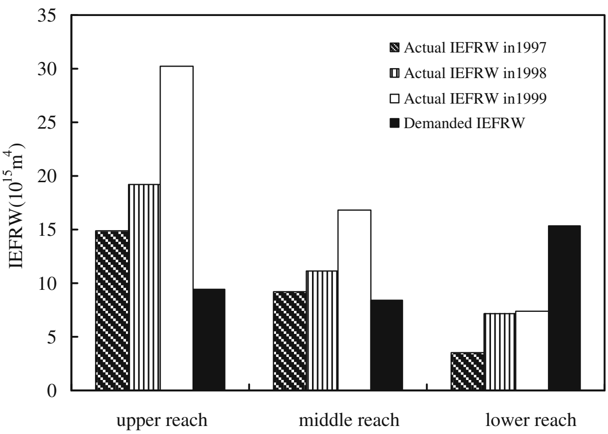


Fig. 3 Spatial and inter-annual distribution of theoretical and actual IEFRW of the Yellow River

decreasing trend of the ratio inferred that the water quality of the upper reach was much better than that of the middle and lower reaches.

According to the previous research (Yang et al. 2006), based on the Tennant method, the minimum streamflow requirements for supporting the aquatic ecosystem for one year are 9.10 billion m^3 at the Lanzhou Station, 4.01 billion m^3 at the Toudaoguai Station, 5.98 billion m^3 at the Longmen Station, 7.54 billion m^3 at the Sanmenxia Station, 8.17 billion m^3 at the Huayuankou Station and 23.06 billion m^3 at the Lijin Station. Based on the minimum streamflow requirements of the river, the demanded IEFRW of the upper, middle and lower reaches were 9.42×10^{15}m^4, 8.40×10^{15}m^4 and 15.31×10^{15}m^4, respectively. As shown in Fig. 4, the actual

Fig. 4 Comparison of demanded and actual IEFRW of the Yellow River



IEFRW of the upper reach was much higher than the demanded IEFRW; the inter-annual average of actual IEFRW in the three years was more than two times of the demanded. The inter-annual average of actual IEFRW of the middle reach was about 1.5 times of the demanded. In contrast, the actual IEFRW of the lower reach was much lower than the demanded; the inter-annual average of the former was about one third of the latter. Among the three reaches, the demanded IEFRW of the lower reach was the highest; in contrast, the actual IEFRW of the lower reach was the lowest, this was caused by the intermittent interruption of river flow in the lower reach. Therefore, the spatial variations of demanded IEFRW should be considered for the integrated management of water resources of the Yellow River.

3.2 Water Resources Availability of the Yellow River

The natural runoff of the Yellow River was 31.82, 43.93 and 43.36 billion m^3 in 1997, 1998 and 1999, respectively (Xia et al. 2004b). The water quantity withdrawn from the upper and middle reaches for human uses was 27.66, 27.17 and 27.72 billion m^3 in 1997, 1998 and 1999, respectively; according to Eq. 3, the corresponding water resources availabilities were 22.64, 21.65 and 21.21 billion m^3, respectively. The water quantity withdrawn from the lower reach for human uses was 10.05, 9.63 and 10.25 billion m^3, and the corresponding water resources availabilities were 7.93, 7.87 and 8.45 billion m^3 in 1997, 1998 and 1999, respectively. Therefore, the total water resources availabilities withdrawn from the mainstream and tributaries were 30.57, 29.52 and 29.67 billion m^3 in the three years, respectively. As shown in Table 1, the total water resources availabilities consumed by human activities from the mainstream and tributaries of the Yellow River basin were 24.17, 26.28 and 29.12 billion m^3 in 1997, 1998 and 1999, respectively, which were lower than the withdrawn water resources availabilities because a small part of the withdrawn water would come back to the river course.

The increments of water resources availabilities caused by providing eco-environmental water (EEW) for the riverine systems were 12.95, 15.15 and 20.59 billion m^3 in the three years, respectively. As shown in Table 2, the total water resources availabilities of the river were 37.12, 41.43 and 49.71 billion m^3 in 1997, 1998 and 1999, respectively. Except for 1998, the total water resources availabilities were higher than the total natural runoff of the river; this was due to the dual functions of the river water. The percentages of the increment of water resources availability caused by providing EEW to the total water resources availability were only 35%, 36% and 41% in 1997, 1998 and 1999, respectively. Therefore, the water resources used as EEW only occupied a small part of the total water resources availability. According to the previous research (Yang et al. 2006), the EEWR of

Table 1 Water resources availability consumed by human uses (billion m^3)

Year	Withdrawn from the mainstream	Withdrawn from the tributaries	Consumed from the mainstream	Consumed from the tributaries	Stored in the river course	Total water resources availability consumed by human uses
1997	21.90	8.67	16.76	7.41	0.00	24.17
1998	22.05	7.47	16.38	6.33	3.57	26.28
1999	22.16	7.51	17.15	6.42	5.55	29.12

Table 2 Water resources availability of the Yellow River (billion m^3)

Year	Water resources availability consumed by human activities	Increment of water resources availability caused by providing EEW	Total natural river runoff	Total water resources availability
1997	24.17	12.95	31.82	37.12
1998	26.28	15.15	43.93	41.43
1999	29.12	20.59	43.36	49.71

riverine ecosystems of the Yellow River is about 23.06 billion m^3. Therefore, the actual increments of water resources availabilities caused by providing EEW for the riverine systems during 1997 to 1999 were lower than the EEWR, leading to the intermittent interruption of river flow and other eco-environmental problems of the Yellow River. According to the above analyses, the actual increments of water resources availabilities caused by providing EEW for the riverine systems directly reflected the water resources used as EEW. Since it is very difficult to calculate the water resources used as EEW, the actual increments of water resources availabilities caused by providing EEW for the riverine systems can be used to express it.

4 Conclusion

River water functions have been analyzed in the present research. A concept of intensity of ecological function of river water (IEFRW) has been put forward, and an integrated water quantity and quality evaluation method in combination with eco-environmental water requirements has been developed for a river. IEFRW is an indicator of ecological function of river water. The actual increments of water resources availabilities caused by providing eco-environmental water requirements (EEW) for the riverine systems can be used to express water resources used as EEW for a river; it can also reflect and affect the health state of riverine ecosystems. The "environmental flow methodologies" mentioned in many references can be used to determine the EEW, while the method put forward in this research can be used to estimate how much water resources have been used as EEW. Therefore, the combination of these two methods can become a powerful tool for the integrated water quantity and quality management of water resources.

Based on the monthly data of water quality and quantity as well as the withdrawals and water quality demand of the EEWR in 1997, 1998 and 1999, an integrated evaluation of water resources has been conducted for the Yellow River. The results indicate that the temporal and spatial variations of IEFRW were related to that of the water quantity and quality. The actual IEFRW can directly reflect the health state of riverine ecosystems. The water resources availabilities consumed by human activities from the mainstream and tributaries were 24.17, 26.28 and 29.12 billion m^3 in 1997, 1998 and 1999, respectively. The actual increments of water resources availabilities caused by providing EEW for the riverine systems, which can be used to express the water resources used as EEW, were 12.95, 15.15 and 20.59 billion m^3 in the 3 years, respectively. They were lower than the eco-environmental water requirements in 1997, 1998 and 1999, leading to the intermittent interruption of river flow and other eco-environmental problems of the Yellow River.

River water has dual functions, which can be withdrawn from the river course for agricultural, industrial, and domestic uses and provides eco-environmental water for riverine system. Therefore, it is necessary to consider these two functions of river water in water resources management.

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