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Methodology to determine regional water demand for instream flow and its application in the Yellow River Basin

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Abstract: In order to realistically reflect the difference between regional water demand for instream flow and river ecological water demand as well as to resolve the problem that water demand may be counted repeatedly, a concept of regional water demand for minimum instream flow have been developed. The concept was used in the process of determining river functions and calculating ecological water demand for a river. The Yellow River watershed was used to validate the calculation methodology for regional water demand. Calculation results indicate that there are significant differences in water demands among the different regions. The regional water demand at the downstream of the Yellow River is the largest about 14.893×10^9 m^3/a. The regional water demand of upstream, Lanzhou-Hekou section is the smallest about -5.012×10^9 m^3/a. The total ecological water demand of the Yellow River Basin is 23.06×10^9 m^3/a, about the 39% of surface water resources of the Yellow River Basin. That means the maximum available surface water resources should not exceed 61% in the Yellow River Basin. The regional river ecological water demands at the Lower Section of the Yellow River and Longyangxia-Lanzhou Section exceed the surface water resources produced in its region and need to be supplemented from other regions through the water rational planning of watershed water resources. These results provides technical basis for rational plan of water resources of the Yellow River Basin.

Keywords: regional water demand; instream flow; environmental flow; methodology; the Yellow River Basin

Introduction

Instream flow is a generic and widely used term that refers to the water required to protect the structure and function of aquatic ecosystems at some agreed level. Other terms that are sometimes used include "environmental flow" (Arthington *et al*., 1992), "minimum acceptable flow" (Geoffrey, 1996), "compensation flow" (Sheail, 1984) or "ecology acceptable flow regime" (Orth and Maughan, 1982). Methodologies for prescribing instream flow began at the end of the 1940s, in the western United States of America (Tharme, 2003). During 1960s and 1970s, methodologies were dramatically developed in American in response to the question posed by engineers designing outlet structures for large dams: what is the minimum flow that must be released from the dam for the downstream aquatic ecosystem to survive? In the 1990s and later, methodologies receive extensive concern and become one of the key issues of water resources allocation (Peter, 1998), because reduction of flow in the river channel became important reason to degradation of aquatic ecosystems worldwide.

The majority of methodologies can be grouped into four reasonably distinct categories, namely hydrological, hydraulic, habitat simulation (or rating), and holistic methods (Tharme, 2003; Yang and Zhang, 2003). Hydrological method is used for making environmental flow primarily based on hydrological data, and commonly be a proportion of the mean or median discharge, or an percentile on a flow duration curve, for example Tennant method (Tennant, 1976) and Texas method (Matthews and Bao, 1991). Hydraulic methodologies justify water demand for river by using simple hydraulic variables, such as wetted perimeter or maximum depth, and assume the integrity of the river is related to parameters of river cross-section (e. g. bed area of riffle habitat). Wetted Perimeter (Bartschi, 1976) and Rcrosss method (Mosley, 1982) are typical hydraulic methods. Habitat rating or simulation method is developed on basis of hydraulic model, and attempt to assess or model biological response of a river by combining modeled physical habitat (such as depths, velocities, bottom shear stress), with criteria on what conditions target organisms are suitable to, for example IFIM/PHABSIM method (Bovee, 1982) and CASMIR method (Jode, 2000). Although hydrological and habitat simulation methodologies have been most popular methods used in the world until now, they also have some disadvantage in determining environmental flow. These methods emphasize one aspect of river ecosystem (e. g. one kind of fish or habitat), and are not studied on viewpoint of the entire river ecosystem.

In the 1990s, holistic method was developed in Australian (Arthington *et al*., 1992) and South African (King and Low, 1998), also named as Building Block Method, become one of the chief directions in the field of instream flow. The procedure of holistic methodology is to assess the complete river

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ecosystem, including its various aquatic and riparian biota and components from source to sea, at conserving particular endangered species, or protecting features of scientific, cultural or recreational value. Ecological and hydrological experts analyze synthetically relations of instream flow with aquatic organisms, river channel, water quality and sand in holistic method, and determine the monthly flow that is recommended to meet the requirement of habitat conservation, sediment transportation, pollutant dilution and incursion prevention of seawater at same time. Hydrological method, hydraulic method and habitat simulation method often be used in the procedure of holistic analysis.

Methodologies of instream flow is the key basis for a sound water resources management and allocation. However, calculation methods still have some unsolved problems, which hinder the application of environemtal flow method in water resources allocation. For example, the same water quantity of ecological demand for the minimum stream flow may be repeatedly used in the calculation for up stream and for down stream (Yang *et al.*, 2003). In different regions of a watershed, the hydrological conditions and river functions are different, so the water demands for the minimum streamflow in different regions are also different (Arthington *et al.*, 1992; King and Low, 1998). Therefore water demands for different sections of a large river should be calculated on the basis of divided regions. Because the water in the river is a continuous flow, the water demand of the upper section has to become a part of that of the lower section. This causes repeated calculation of the same amount of ecological water demand for instream flow between upper section and lower section. The repeated amount must be eliminated in water resources allocation planning, in order to reserve adequate amount water for ecological water demand and to meet industrial, agricultural and domestic water uses in all regions at the same time (Wang *et al.*, 2003). Therefore, the regional water demand for the upper stream and the down stream should be calculated separately with a scientific calculation method.

According above analysis on methodologies and its problems, this paper takes the entire Yellow River Basin, which is in northern China, as an example to studied the water demand for instream flow by holistic analysis. For solving the repeated calculation problem, the concept and the calculation methods of regional water demand for instream flow is brought forward and applied in the entire Yellow River Basin. The results of this study will provide technical support for the application of the ecological water demand for instream flow and scientific basis for the water regulation and allocation in the Yellow River Basin.

1 Basic conception

Water demand for instream flow refers to the instream flow needed to maintain health of a river ecosystem, the balance of water and sediment, the balance of salinity, and the ecological functions of the estuary (Wang *et al.*, 2002; Sheail, 1984). The geological conditions, water quantity and ecological functions vary along river's longitude, so the water demand for each section may be different. Generally, a river is divided into several reaches; each drainage basin is a studied unit and its water demand is calculated separately. The water quantity of certain river reach consists of the water from upper stream and the water produced in its reach (Luo, 1992). So the water demand for instream flow in a reach is the sum of the water from the upper stream (or tributary) and the water produced in the region of the reach. To solve the problem of repeated calculation of water demand between upper section and lower section, and that between the main stream and tributary, this paper introduces the concept of regional water demand for instream flow. The term of regional water demand for instream flow in this paper is defined as water quantity required from local region to maintain the ecological function of certain river reach excluding the water from upper stream (or tributary).

To a certain river reach, water demand for instream flow is not a single value, but a range with two thresholds, minimum and the maximum (Yang *et al.*, 2003). If the flow is below the minimum water demand or above the maximum water demand, the ecological functions of the river are adversely affected. Considering the fact that instream flow of most rivers in northern China are decreasing as economy developing which is competing the same water resource, to determine the minimum streamflow becomes more critical in practice point of view (Liu, 1999). That is why the paper only addresses the minimum water demand. In the rest of the paper, the water demand for instream flow and the regional water demand for instream flow all refer to the minimum water demand.

2 Calculation methods and procedures

The calculation procedures of regional water demand for instream flow are as the following: (1) to delineate the regional watershed; (2) to designate the ecological functions of each segment of river and to calculate its corresponding water demand for instream flow; (3) to comprehensively analyze and designate the water demands for instream flow of each segment; (4) to calculate the regional water demand for the minimum instream flow.

2.1 Delineating regions of a watershed

To delineate regions several principles should be followed: (1) the natural conditions, such as geology, geotopography, hydrology and climate, and the functions of the river system must be similar within a region, and the river functions in a region are primarily the same; (2) the delineation should be coordinated with the spatial units of water regulation and management. So that the calculation results not only represented the spatial distribution of regional water demand of instream flow, but also provides technology basis for the implementation of the water allocation in a basin; (3) it requires steady and reliable hydrological data in the region.

2.2 Designation of ecological functions of the river and the calculation method

River ecosystem has various ecological functions, such as for sustaining the habitats of the aquatic lifes, holding capability of pollutants dilution, maintaining the sediment carrying capacity of river and sustaining the ecological health of estuary (Li and Zheng, 2000). According to these functions, water demands for instream flow mainly includes water demand for sustaining river habitats, water demand for receiving pollutants, water demand for transporting sediment, and water demand for entering sea. The ecological functions vary for different reaches of a river because of the difference of ecological features of the river and the impacts of human activities (Jansson *et al.*, 1999). It should designate the major functions of each reach before the calculation of water demand to maintain corresponding ecological functions. The following methods to determine water demand were used according to these functions designated.

2.2.1 Water demand for sustaining river habitat

Hydrological methodologies are considered to be the most appropriate at the planning level of water resource management, or in situations where relation of habitat quality with flow is not distinct or hydraulic data is not enough to sustian hydraulic methods (Tharme, 2003). Tennant approach (Tennant, 1976) is the most commonly applied hydrological methodology worldwide. It proposed a linking of different percentages of average or mean annual flow to different level of river condition on different season, and used the percentage of the average annual natural in-stream flow as the recommendatory flow of the river and regards 10% of the average or mean annual natural flow as the criteria of the minimum flow, 30% as for a satisfactory healthy ecosystem. While the monthly guarantee rate approach (Wang *et al.*, 2003), is a method targeted rivers of northern China. It determines the recommended flow according to the percentage of monthly natural flow at a guarantee rate (e.g. Q75 or Q50). In this paper, 10% of monthly natural flow at 50% guarantee rate is considered as the minimum monthly flow for survival of aquatic lifes. Finnaly, the recommended minimum flows were determined by using both above approaches comprehensively.

2.2.2 Water demand for receiving pollutants

The water demand for receiving pollutants refers to the flow needed to sustain the ability of the river to dilute and clean up the pollutants. In overseas, the 7Q10 method is initially used to determine water demand based on on average occurs for 7 consecutive days once every 10 years. China revised 7Q10 into driest monthly flow method so that the method is more suitable to actual condition. It was estimated by using average of monthly minimum flow of last ten years. This approach has been used to determine the hydrological conditions for water pollutant discharge permission in China as well (Wang *et al.*, 2002).

2.2.3 Water demand for sediment transportation

Considering the practical situation of the lower-section of the Yellow River, this study used total sediment amount, sediment amount permitting to sedimentation and water consumption for per unit sediment transportation to calculate the water demand for sediment transportation.

$$q_s = s \times (I - D) \tag{1}$$

Where q_s is the total water demand for sediment transportation (m^3); s is the water consumption for per unit sediment transportation (m^3/t); I is the total sediment (t); D is the sediment amount permitting to sedimentation (t).

The water consumption for per unit sediment transportation (s) can be was determined by the sediment amount in the river (Qi and Li, 1994; Zhao *et al.*, 1990). When the sediment concentration is greater than 60 kg/m^3, the water consumption for per unit sediment transportation decreases as the sediment concentration increases. When the sediment concentration is less than 30 kg/m^3, water consumption for per unit sediment transportation increases distinctly as sediment concentration decreases (Chang *et al.*, 1998). That is, once the sediment amount is greater than 60 kg/m^3, the water demand for sediment transportation does not decrease significantly as the sediment concentration increases. In this situation, the river channel would be heavily filled up with sediment. On contrast, once the sediment concentration is lower than 30 kg/m^3, the water consumption is mainly in sediment flushing. Therefore, when the sediment amount of the river is between 30 and 60 kg/m^3 during the flood season, the water consumption for per unit sediment transported is most efficient (Shi *et al.*, 2003). Therefore 60 kg/m^3 is considered to be the proper sediment amount of the minimum water required for the sediment transportation. According to the relationship between the water amount for per unit sediment transportation and sediment concentration, the water amount for per unit sediment transported is

16 m^3/t on 60 kg/m^3 sediment concentration condition (Qi and Li, 1994).

2.2.4 Water demand for entering sea

Although some researches about water demand for entering sea to sustain the balanced functions of estuary ecosystem have been conducted, all of them were qualitative analysis and no accurate calculation method has been established (Ni *et al.*, 2002). Based on the former studies, this paper has researched the actual conditions and historical data. Through analyzing the relationship between the ecological status of the estuary, the balance of flushing and settling of sediment and the flow entering sea in different years. The minimum water demand entering sea was estimated based on the minimum requirement for protection of estuary ecosystem.

2.3 Final determination of the minimum water demand for streamflow

If several functions of the river must be met at the same time, the water demand for the river streamflow should be determined by the principle of the muximum (Yang *et al.*, 2003). That is, to take the maximum water demand among that of different functions in each month as the minimum monthly water demand for the instream flow. The sum of the monthly minimum water demand is the annual minimum water demand for the river (Equation (2)). If only one function is designated, the minimum ecological water demand of the reach is the calculation result of this function.

$$q = \sum_{i=1}^{12} (\max (q_{b,i}, q_{p,i}, q_{s,i}, q_{c,i})) \quad (2)$$

Where q is annual minimum water demand for instream flow (m^3/a); $q_{b,i}$ is the water demand for instream flow in the ith month (m^3/month); $q_{p,i}$ is the water demand for purifying pollutants in the ith month (m^3/month); $q_{s,i}$ is the water demand for transferring sand in the ith month (m^3/month); $q_{c,i}$ is the water demand to enter sea in the ith month (m^3/month); i is the ith month.

2.4 Calculation method of regional water demand for instream flow

According to water balance principle of the river, the regional water demand of regional j can be estimated by water demand of the upper section (controlling cross-section j-1) minus that of the Lower Section (controlling cross-section j), which is named as the upper-Lower Section control method in this paper (Fig.1).

Taking region 2 as an example to demonstrate calculation of regional water demand for instream flow. The regional water demand for regional 2 is calculated as water demand of controlling section 2 minus that of controlling section 1, $Q_2 = q_2 - q_1$. The result may be in one of three situations:

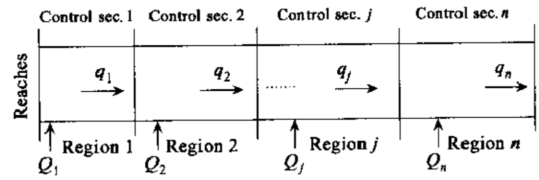

Fig.1 Upper-Lower Sections control method
Region j is the jth region of watershed, j=1, 2 …… n; n is the number of divided regions of watershed; q_j is the water demand for streamflow of region j; Q_j is the regional water demand for streamflow of region j

(1) $q_2 - q_1 > 0$, refers that the water demand of reach 1 is less than that of reach 2. In this situation, the regional water demand of region 2 is positive. It equals to $q_2 - q_1$.

(2) $q_2 - q_1 = 0$, refers that the water demand of reach 1 equals to that of reach 2. In this situation, the regional water demand of region 2 is zero.

(3) $q_2 - q_1 < 0$, refers that the water demand of reach 1 is larger than that of reach 2. The regional water demand of region 2 is negative. In this situation, the water from reach 1 to reach 2 can meet the water demand of region 2. Region 2 needn't to offer water to reach 1, and can make use of the water from reach 1, too.

For a closed watershed system, the surface water of each water resource region enters corresponding river channel separately and form river runoff, and finally discharge from the watershed as runoff. Therefore, the water demand for the river channel of the lowest reach equals to the sum of the regional wa ter demands of each region. That is

$$\sum_{i=1}^{n} Q = (q_1 - 0) + (q_2 - q_1) \cdots\cdots + (q_n - q_{n-1}) \quad (3)$$

3 Calculation of regional water demand in the Yellow River Basin and discuss

3.1 Delineation of regions

The Yellow River flows from west to east through nine provinces and autonomous regions to reach the Bohai Sea at Kenli County, Shandong province of China (Fig.2). The watershed is located between 96° – 119°E, 32° – 42°N, with an east-west extent of about 1900 km and a north-south width of 1100 km. The Yellow River is 5464 km long with a basin area of 794712 km^2. The main tributries include Huangshui River, Taohe River, Beiluohe River, Jinghe River, Weihe River, Fenhe River, Yiluohe River and Qinhe River. The annual runoff is about 58.5×10^9 m^3, and concentrates from July to September. Inter-annual variation at runoff is high and the ratio of the maximum annual natural runoff to the minimum is about 3.47 between 1920 and 2000. The Yellow River is exploited highly by human being, and the surface water utilization ratio reached 72.6% in 2002. The excessive utilization of surface water resources in the Yellow River Basin, has brought a series of problems to watershed ecosystems such as, reduction of the streamflow, increase of concentration of pollutants, drying up of the river channel, extinction of aquatic species, sediment deposition, decrease of wetland area, and degradation of estuarine delta. From 1972 to 2000, there were nineteen years that the river channel dried up in the lower reach of Yellow River. In 1997 the length of dried river channel was about 708 km, which was about ninety percent of lower reach, and the dried period was 227 d. In order to recover and preserve the environmental conditions in the basin, and to realize social, economic and ecological coordinated development of watershed, ecological water demand has been become one of the key issues of water resources management.

This study divided the Yellow River Basin into

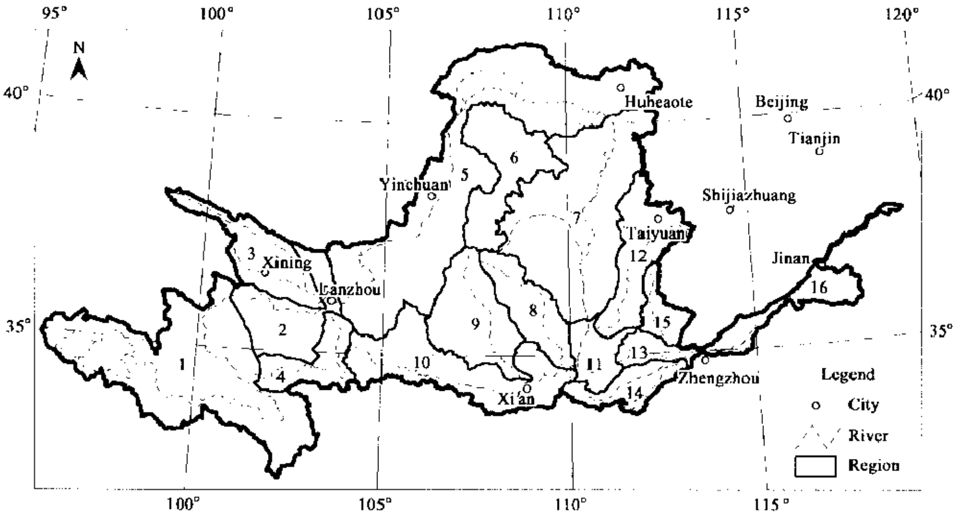

Fig.2 Region's map of the Yellow River Basin

1.Upper section of Longyangxia; 2. Longlan main channel section; 3. Huangshui Basin; 4. Taohe Basin; 5. Lanhe main channel section; 6. interior section; 7. Helong main channel section; 8. Beiluohe Basin; 9. Jinghe Basin; 10. Weihe Basin; 11. Longsan main channel section; 12. Fenhe Basin; 13. Sanhua main channel section; 14. Yiluohe Basin; 15. Qinhe Basin; 16. Lower section of the Yellow River

16 regions according to the principle discussed (Fig.2, Table 1), including 7 main channel regions, 8 tributary regions and 1 inner region. They were used to calculate the water demand for the river channel and the regional water demand. The inner region is relatively independent and the hydrological data is insufficient, so it was not studied in this paper.

3.2 Designation of the ecological functions of the river

The Yellow River flows through the Qinghai-Tibet Plateau, the Loess Plateau and the Northern China Plain from the upper stream to the down stream. In this basin, the climate changes from humid through semi-arid to arid from southeast to northeast. The annual precipitation decreased from above 800 mm to less than 200 mm from southeast to northwest. There are remarkable differences in geography, climate and vegetation conditions among the regions. The impacts of human activities to the river are different, as well. Therefore, the ecological functions of the river vary in different regions. Above the upper river of Longyangxia Section where human activities are less, the major river function to be sustained is the habitat of aquatic life and main water demand for instream flow is to sustaining integrity of biological habitat. Between the Longyangxia Section and the Lower Section of the Huayuankou Section, where human activities are getting intensified. The river receives increasingly amount of waste water and pollutants. The ecological function of rivers to be sustained is the habitat of the aquatic biota as well as to dilute and carry away the pollutants. At the Lower Section of the Yellow River, water contains a large quanity of sediment, and the river channel is filled up heavily with sediment. So the function of sediment transportation becomes prominent. Meanwhile, the river should also sustain the ecological function of Estuary Delta Wetland of the Yellow River. Based on the analyses above, when the water demand of the upper section of Longyangxia is calculated, only the habitat function has been considered. All the four functions of ecology, pollution receiving, sediment transportation and entering sea have been considered comprehensively in the Lower Section of the Yellow River. The two functions of ecology and pollution receiving are determined in rest regions (Table 2).

3.3 Calculation results of the water demand for different river functions

Water demand for sustaining river habitat is calculated by monthly natural flow data from 1950 to 1998, and water demand for receiving pollutants is estimated by monthly actual flow from 1991 to 2000

Table 1 Area and controlling sections for every region of the Yellow River Basin

No.	Reach of river	River type	Controlling sections		Area, km^2	Total area of the basin, %
			Upper section	Lower section		
1	Upper section of Longyangxia	Main channel		Guide	131405	16.5
2	Longlan main channel section	Main channel	Guide	Lanzhou	32756	4.1
3	Huangshui Basin	Tributary		Xiantang	32863	4.1
4	Taohe Basin	Tributary		Hongqi	25527	3.2
5	Lanhe main channel	Main channel	Lanzhou	Toudaogua	163415	20.5
6	Interior section				42269	5.3
7	Helong main section	Main channel	Toudaoguai	Longmen	111595	14.0
8	Beiluohe Basin	Tributary		Zhuangtou	26905	3.4
9	Jinghe Basin	Tributary		Taoyuan	45421	5.7
10	Weihe Basin	Tributary		Huaxian	62440	7.9
11	Longsan main channel section	Main channel	Longmen	Sanmenxia	16623	2.1
12	Fenhe Basin	Tributary		Hejin	39471	5.0
13	Sanhua main channel section	Main channel	Sanmenxia	Huayuankou	9202	1.2
14	Yiluohe Basin	Tributary		Heishitou	18881	2.4
15	Qinhe Basin	Tributary		Wuzhi	13532	1.7
16	Lower Section of the Yellow River	Main channel	Huayuankou	Lijin	22407	2.8

in this paper. The water demand for sediment transportation was calculated with equation 1 in Section 2.2. Now the actual sediment amount of the Lower Section of the Yellow River is 13×10^8 t, and most sediment enter the river during the flood season (Chang Binyan *et al.*, 1998). The allowable filling-up amount of the Lower Section of the Yellow River is below 2×10^8 t (Chang Binyan *et al.*, 1998).

Analysis of the hydrological data of the Lijin station from 1916 to 1999 shows that the water amount entering sea from Lijin station has declined since 1920s, and even worse in 1990s (Fig.3). The qualitative research indicated that the ecology and environment status of the estuary of the Yellow River have been seriously deteriorated since 1990s. Therefore, in this study the conditions of the estuary in 1990s are considered to be the ecological protection baseline, the average runoff entering sea in 1990s is set to be the minimum runoff entering sea. In this way, the required runoff of the Yellow River entering sea has been determined.

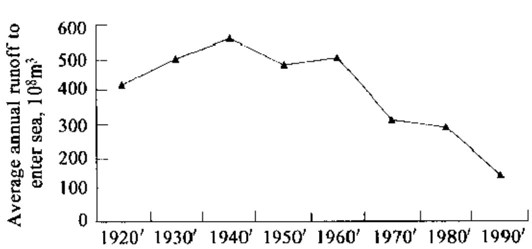

Fig.3 Runoff to enter sea in Lijin Station from 1920′--1990′

3.4 Calculation results of water demand and regional water demand for instream flow

According to calculation methods mentioned in Section 2.3 and Section 2.4 and the calculation results of water demand for instream flow for various functions in Section 3.3, the water demand for instream flow and corresponding regional water demand in each region of the Yellow River Basin were calculated and the results are listed in Table 2 too.

3.5 Discussion of the calculation results

In Table 2, water demand for sustaining river habitat is between 2.453×10^9 m^3/a and 6.568×10^9 m^3/a in the main channel of the Yellow River, and the monthly water demand are not evenly distributed (Fig. 4). There are great differences of water demand for receiving pollutants among sixteen regions. The three regions with greatest water demand are Longlan Section, Longsan Section and Sanhua Section. The water demand for sediment transportation in the Lower Section of the Yellow River is about 176×10^8 m^3/a, the most in the flooded season. The runoff for entering sea is 140×10^8 m^3/a, and 54.6×10^8 m^3/a in non-flood season.

Water demand for river instream flow is sum of twelve monthly maximum water demand for different functions (Table 2). The result indicates that the minimum water demand for instream flow in the main channel of the Yellow River Basin (including the upper section of Longyangxia, Longlan Section, Lanhe Section, Helong Section, Longsan Section, Sanhua Section and the Lower Section of the Yellow River) is between 24.53×10^8 and 230.6×10^8 m^3/a. The Lower Section of the Yellow River is the maximum. The tributary consists of Huangshui Basin, Taohe Basin, Beiluohe Basin, Jinghe Basin, Weihe Basin, Fenhe Basin, Yiluohe Basin and Qinhe Basin. The water demand of Weihe Basin is the largest, 9.96×10^8 m^3/a,

Table 2 Water demand for instream flow and its regional water demand in every region of the Yellow River Basin

Ecological region	q_h, 10^8 m^3/a	q_p, 10^8 m^3/a	q_s, 10^8 m^3/a	q_e, 10^8 m^3/a	q, 10^8 m^3/a	Q, 10^8 m^3/a
Upper section of Longyangxia	24.53	-	-	-	24.53	24.53
Huangshui Basin	5.89	6.6	-	-	7.45	7.45
Taohe Basin	5.56	9.96	-	-	9.96	9.96
Longlan main channel section	38.22	91.08	-	-	91.08	49.14
Lanhe main channel	38.64	29.04	-	-	40.96	-50.12
Helong main section	44.68	54.84	-	-	59.75	18.79
Fenhe Basin	2.50	0.24	-	-	2.5	2.5
Beiluohe Basin	0.99	0.6	-	-	0.99	0.99
Jinghe Basin	2.25	0.48	-	-	2.37	2.37
Weihe Basin	9.96	5.04	-	-	9.96	6.6
Longsan main channel section	58.00	68.64	-	-	75.43	3.22
Qinhe Basin	1.36	0	-	-	1.36	1.36
Yiluohe Basin	3.54	2.04	-	-	3.54	3.54
Sanhua main channel section	64.43	72.84	-	-	81.67	1.34
The lower section of the Yellolw River	65.68	14.28	176	140	230.6	148.93

Notes: q_h. water demand for sustaining river habitat; q_p. water demand for receiving pollutants; q_s. water demand for sediment transporation; q_e. water demand for entering sea; q. water demand for instream flow; Q. regional water demand for instream flow; - means the function has not been considered

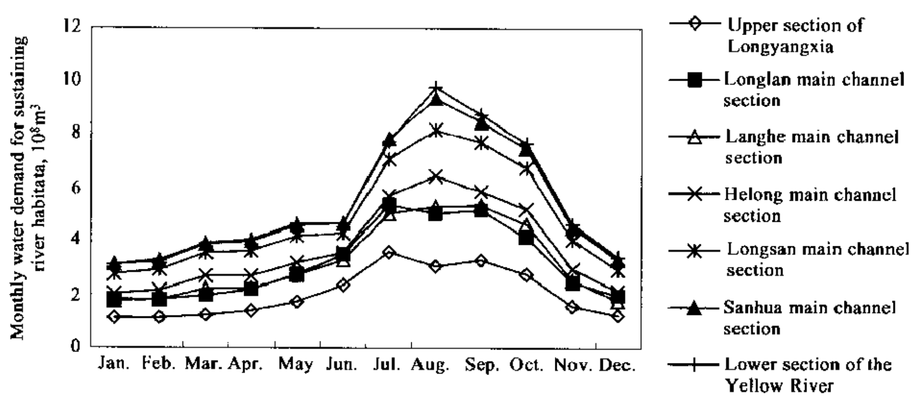

Fig.4 Monthly water demand for sustaining river habitata in the main channals of the Yellow River

and that of Beiluohe Basin is the smallest, 0.99×10^8 m^3/a.

Regional water demands of tributary sections and the upper section of the main channel of Longyangxia equal to their water demand for instream flow, because these regions have not any repeated calculation problem in the regional water demand with other sections. But the 6 main channel sections have the problem between them and with other regions. Therefore the regional water demand for 6 main channel sections does not equal to water demand for instream flow of that sections. The total regional water demand in the Yellow River Basin is 230.6×10^8 m^3/a. The 89.2% of total, 192.47×10^8 m^3/a, is the regional water demand for main channels of the Yellow River, and the 10.8% of total, 38.13×10^8 m^3/a, is the regional water demand for the tributaries.

4 Spatial-temporal distribution and allocation of regional water demand in the Yellow River Basin

4.1 Spatial-temporal distribution of regional water demand for instream flow

Water demands for instream flow in main channels increase gradually from the upper river to the lower river except for Longlan Section. But the regional water demand for instream flow does not follow this trend. The water demand for instream flow and the regional water demand in the Lower Section of the Yellow River is the maximum among all regions because of the huge amount of water demand for sediment transportation. The regional water demand for the main channel of Lanhe reach is negative. This implies that the water demand for instream flow of the upper reaches (Longlan main channel, 91.08×10^8 m^3/a) is larger than that of Lanhe main channel (40.96×10^8 m^3/a). So Lanhe main channel does not need extra water for this reach, and there is still surplus water after the ecological function of the river has been met by water demand of the upper reaches. About 50.12 $\times 10^8$ m^3/a extra water from the upper river can be used.

Furthermore, the regional water demands for each region are not constant in one year. There are great differences between flood season and non-flood season. In Fig.5, the regional water demands for instream flow in different regions have the same pattern during the year. All of them are large in the flood season and relatively small in the non-flood season. Taking the Lower Section of the Yellow River as an example, the regional water demand is about 142.89 $\times 10^8$ m^3/a in the flood season and only 6.04 $\times 10^8$ m^3/a in the non-flood season.

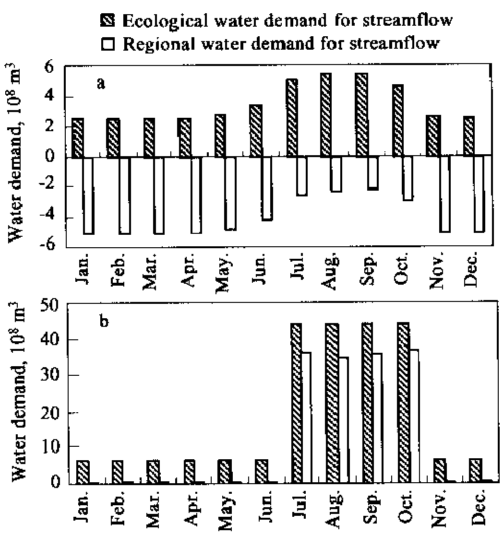

Fig.5 Monthly variation of regional water demand for insteam flow
a. Lanhe main channel section; b. the lower section of the Yellow River

4.2 Allocation of the regional water demand for instream flow

Comparing the regional water demand for instream flow with surface runoff produced in its region of the Yellow River Basin, it has revealed that how much regional water demand for instream flow can be met in itself region. The satisfaction degree of the regional water demand and the surplus surface water in the region of the Yellow River Basin are listed in Table 3. In Table 3 the surface runoff produced in the region of the Longlan main channel and the Lower Section of the Yellow River can not meet the regional water demand for instream flow, and the deficits were 28.39 $\times 10^8$ and 138.51 $\times 10^8$ m^3/a, respectively. This means that in these two regions, water supplies from other regions would be needed in order to meet their water demand.

According to the calculation results, the minimum water demand for instream flow is about 39% of surface runoff in the Yellow River Basin, and the surplus surface runoff is about 354.23 $\times 10^8$ m^3/a. It means that the maximum utilization ration of surface water resources should be below 61% in the Yellow River Basin. But the recent utilization ration which is about 72.6% has already exceeded it, and the ecological functions of the river could not be sustained.

Table 3 Comparison between regional water demand of instream flow and surface runoff produced in its region of the Yellow River Basin

Water resource region	Surface runoff produced in its section, $\times 10^8$ m^3/a	Regional water demand for instream flow, $\times 10^8$ m^3/a	Regional water demand in surface runoff produced in its section, %	Surplus surface runoff, $\times 10^8$ m^3/a
Upper section of Longyangxia	214.4	24.53	11	189.87
Huangshui Basin	51.61	7.45	14	44.16
Taohe Basin	49.42	9.96	20	39.46
Longlan main channel section	20.75	49.14	237	-28.39
Lanhe main channel	2.91	-50.12	-1722	53.03
Helong main section	56.34	18.79	33	37.55
Fenhe Basin	25.63	2.5	10	23.13
Beiluohe Basin	8.97	0.99	11	7.98
Jinghe Basin	19.52	2.37	12	17.15
Weihe Basin	61.05	6.6	11	54.45
Longsan main channel section	7.39	3.22	44	4.17
Qinhe Basin	11.86	1.36	11	10.5
Yiluohe Basin	31.53	3.54	11	27.99
Sanhua main channel section	13.04	1.34	10	11.7
The lower section of the Yellow Basin	10.42	148.93	1429	-138.51
Yellow River Basin	584.83	230.6	39	354.23

Notes: Surface runoff produced in its section is calculated according to the hydrological data of the Yellow River from 1950 to 1998

5 Conclusions

The problem of repeated calculation of water demand between the upstream and the down stream of river, also between the main channel and the tributary can be solved by using the conception of regional water demands for the minimum instream flow in divided regions of the basin. It reveals the allocation pattern of water demand for river basin.

There are remarkable differences in regional water demands in the regions of the Yellow River Basin. The largest is the Lower Section of the Yellow River, which is about 148.93×10^8 m^3/a, and the smallest is the Lanhe main channel, which is -50.12×10^8 m^3/a. The negative water demand means that water from upstream can meet water demand for the instream flow of this reach, and extra water can be available for economy development.

The regional water demand for river instream flow of the Lower Section of the Yellow River and Longlan reach can not be met by the surface water resources produced in its own region and need water supply from other regions. The results can provide technology basis for rational planning of water resources of this basin

The total regional water demands in the Yellow River Basin are 354.23×10^8 m^3/a, which is about 39% of its surface water resources. This implies that the maximum available of surface water resources should be restricted below 61% in the Yellow River Basin.

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