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Healthy Yellow River's essence and indicators

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Abstract: River's healthy life is a description of their living conditions, and it is also a comprehensive assessment of river's functions and relations with the human society. Through analyzing the demands of human being and river ecosystem, the continuous flow, safe river channel for water and sediment transportation, good water quality, sustainable river ecosystem and water supply capacity are regarded as symbols of the healthy Yellow River. Minimum flow, maximum flood discharging capacity, bank-full discharge, transverse slope of floodplain, water quality degree, wetlands area, aquatic ecosystem, and water supply capacity, altogether eight quantitative indicators are set as symbols of healthy Yellow River, and their corresponding standards are determined based on the analysis with historical hydrological data and observed data of 1956–2004.
Key words: Yellow River; life; health; runoff; bank-full discharge; water quality; river ecosystem
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For thousands of years, people have been trying to promote benefit and abolish harm to the Yellow River by means of various activities such as flood control and water abstraction. However, after the last decade of the 20th century, it was noticed that the rigorous flood control and excessive water use had made the river's natural function degraded significantly, which certainly threaten the river's life, and restrict the economic development in the related area, and even threaten the human health. Serious situation forced people to rethink their manners of living along with the Yellow River, and then the new river management concept "Keeping Healthy Life of the Yellow River" has been put forward. This paper aims at expounding the essence, criteria, indicators and methodologies to build a healthy Yellow River, which provides theoretic guidelines to the implementation of the new river management concept.

1 Essence of river's healthy life

1.1 River's life

River's life is a process of hydrologic cycle, which runs under certain direction and path, and represented by continuous flow in the river channels. Continuous flow is the key to maintain river's life, which enables incessant renewal of water resources in land, results in the formation of riverbed and river system, and development of river ecosystem. River's life embodies at least three aspects, namely, river channel, basically complete river system and continuous and appropriate flow.

The river may have different health status; it depends on climate and underlying earth surface. Climate is an important factor influencing the formation and development of a river and hydrological features of a river basin. Underlying surface has an influence on runoff or sediment generation and concentration.

The changes of climate and underlying surface are resulted from the natural movement of the universe and the earth on the one hand, and from human activities on the other. Without interference of human being, the development, prosperity and decay of rivers and relevant ecosystem are natural. The interference from human being may even accelerate a river's dying out.

1.2 River's health

Unfortunately, the natural resources cannot be used directly by human under many situations, and rivers in natural condition frequently bring disaster to human. Under the pressure of survival and development,

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human needs to change the underlying surface and climate, such as clean-up natural vegetation, building reservoirs and dykes, developing industry, etc. Those changes in the past century are so intensive that rivers' status is changed and many rivers' life is in crisis. The crisis of rivers and the pressure and threat brought to the existence and development of human beings urge them to rethink their ways of treating rivers and the ecosystem, and then further put forward new concept of keeping healthy life of rivers.

River health is a description on river life status, which is under the precondition of the existence of river life. In ancient times, without human intervention, every river went through the fluvial processes of formation, development and decline and formed diverse natural landscapes. It is hard to judge which state is healthier. But for most rivers in the world today, rivers are not only natural rivers, but also social rivers. Flood and drought severely affects the survival and development of human, thus the issue of unhealthy river was caused.

Rivers' functions include two main types, i.e. social function and natural function. The social function of rivers reflects the support of rivers to socioeconomic system. It is the original intention and meaning of maintaining the healthy life of rivers. The natural function of rivers is the support capacity to river ecosystem, which will develop or not develop along with the runoff more or less. It is an important index of river life vitality, and will finally affect the sustainable development of society and economy. Possessing both normal social and natural functions at the same time is obviously the basic index of river health.

Because of change of human knowledge on rivers and different social, economic and environmental backgrounds, river function expected certainly has different characteristics in various periods. In the forepart of human history, flood is the main problem of river health. Along with the rapid development of society and economy, water shortage becomes the important embodiment of an unhealthy river. After having enough food and clothes, people began to pay attention to living quality, then river pollution and its ecosystem shrinkage becomes the focus of attention. The concept of river health came into being in the Western developed countries where their main challenge is ecological protection (Scrimgeour, 1996). For instance, the river Rhine can be regarded as healthy if salmon back to the upper reaches (International Commission of Rhine Protection, 1994), and Danube River takes biodiversity and the scale of species as the indexes of river health (Nijland, 2000). The pH value and conductivity of water are regarded as indicators of river's health and insects are indicative species in America (Gurtz, 1994). The river healthy plan of South Africa selected invertebrate, fish, and plant along banks, river ecological state, water quality, hydrology and morphology of a river as indicators for appraising river's health (Kleynhans, 1999; Department of Water Affairs and Forestry, 2004). To recover rivers into a state similar to that in the 1980s was set as the objective of river management in Japan (Nakamura, 2004; Katsuhide, 2004). But, along with the development and deepening of this concept, people are paying more attention to the integrated requirements of society, economy and nature. For example, Australia puts forward the concept of *Living Murray* (Murray Darling Basin Commission, 2004) and its purpose is to provide a standard, which can be identified by society, for compromising between river ecosystem protection and water resources utilization. In a word, in different times and different areas, the essence of river health reflects the contradiction between economic development and natural environmental protection, reflects the values of people under corresponding background. The standard of river health is the balance or compromise of human's benefit and other biology's benefit in corresponding times and river reaches. River health can only be a relative health. The standard of river health under different backgrounds is actually a choice of society and its judging indexes should be dynamic and changeable.

Healthy rivers mean that benefits of human beings and other living things can be harmonized in corresponding times and river reaches, or the social and ecological functions can be or balanced, under the precondition of the existence of river's life. If social function of rivers is emphasized unreasonably, ecosystem will be destroyed and finally the living environment of human being will be influenced; and if ecological function or the completely original state is paid too much attention, human being will be unable to live and develop once extreme flood or drought occurs, therefore ecosystem will be destroyed also.

1.3 Criteria of the healthy Yellow River

To determine standards of the healthy life of the Yellow River (YR) at present, it needs to firstly analyze the demands from human being and other living things on the river. The people's demands on the YR include safe channel for water and sediment transportation, favorable water quality and water-supply capacity. The YR flood disaster has been called as China's sorrow, so it is the first expectation of people that the river should possess enough discharging ability to avoid flooding. Water quality is the key factor that influences people's life and health. Water is the basic condition for human survival and development. Economic development often relies on the available water quantity. But the available water resources of the YR are limited and people cannot expect to satisfy their unlimited requirements only with it. The serving function of the river also includes maintaining the fertility in floodplain and estuarine delta, salinity in the offing near the estuary, and the important scenes such as Hukou waterfall.

Maintaining the ecological function of rivers has become a common understanding of the river basin managers in the world. The purpose is to maintain the normal succession of biological community and the normal circulation of the food chain. The required services from the YR include water quality and water quantity. The requirements of species on water quality are consistent with that of human, but in normal or dry years, the water demand from river species often conflicts sharply with human water demand.

Continuous flow is obviously the common requirement of rivers, people and ecosystem; a safe channel could meet demand of river's life on water and sediment transportation; acceptable water quality and enough water are the common requirement of human and ecosystem. So, the health criteria of the YR can be summarized as follows: continuous flow; favorable riverbed for water and sediment transportation, favorable water quality which can meet healthy demand of biological community; and enough water for sustainable development of society and river ecosystem.

2 Health indicators of the Yellow River

In order to make indicators of the healthy YR more feasible and cognitive, this paper selected some parameters as the indicators of the healthy YR. The selection of these indicators and their values are expounded below.

2.1 Flow continuity

Continuous flow is the key to maintain river's life. The continuous flow demands certain amount of discharge to be ensured not only from river source to the sea, but also in those main branches of the YR.

In theory, only if discharge in mainstream and branches is not zero, can the YR meet the demand of minimum flow for maintaining its life. However, too small discharge could not support its ecosystem, the river is actually in a functional drying-up state. Therefore, the minimum flow for maintaining healthy life of the YR should consider demand of water circulation and river system, domestic demand of human being, as well as the basic demands of ecological function, self-purification and sediment transportation. Water demand of self-purification is greatly influenced by economic development and sewage treating capability; water demand of sediment transportation depends on sediment amount to be transported and acceptable siltation on riverbed. The minimum value is hard to be determined. Therefore, the minimum runoff mainly takes into account basic demand of human living and river ecology.

Based on measurement and calculation, during 2030–2050, domestic water demand in the area supported by the YR water will reach 5 billion m^3, and water consumption will be about 2.5 billion m^3. In this paper, water consumption being 2.5 billion m^3 is adopted to estimate minimum discharge in cross sections of the mainstream and branches deduced from human water demand.

The minimum eco-water demand of the YR is the minimum water amount to realize the ecological protection objectives. Therefore the relation between ecological protection objectives and freshwater supply from the YR should be analyzed first. Because of the lack of systematical data, Tennant method is adopted to estimate the minimum eco-water demand. The minimum ecological flow is set as 10% of the observed discharge of base series.

With the boundary condition of domestic water demand, minimum eco-water demand, continuity of flow in the whole river and integrity of river system, fully taking into account natural infiltration, evaporation and runoff supply in different reaches, to deduce from the downstream to the upstream gradually, the minimum flow of mainstream's different sections in different periods can be deduced out (Table 1). Based on the minimum flow of mainstream, and checked with observed monthly discharge series of the period 1956–1985, minimum flow of each main branch at cross section entering the YR can be deduced out (Table 1).

Since 1986, due to the explosive increase of human water demand and decrease of natural precipitation, in the middle and lower mainstream of the Yellow River, the period with discharge smaller than the minimum discharge accounts for 3%–8%, that in Lijin is 25%–60%. Those in the Fenhe and Weihe rivers are often smaller than the minimum discharge. The construction of water-saving society and fine regulation of the YR water mainly relies on the guarantee of the continuity of mainstream and branches.

Table 1 Monthly minimum flow requirement at the key cross-sections (m^3/s)

Section	River	1	2	3	4	5	6	7	8	9	10	11	12
Lanzhou	Yellow River	60	70	100	140	140	140	180	180	210	170	90	60
Hekouzhen	Yellow River	50	50	60	60	50	50	110	150	160	140	60	50
Longmen	Yellow River	60	80	120	120	100	90	160	220	190	190	100	70
Tongguan	Yellow River	60	70	90	100	80	70	180	240	250	210	120	60
Xiaolangdi	Yellow River	110	110	160	160	180	160	190	290	280	310	200	150
Huayuankou	Yellow River	120	130	160	170	170	160	220	310	320	330	220	150
Lijin	Yellow River	50	50	70	70	70	60	170	260	260	240	140	70
Minhe	Huangshui River	5	6	6	7	9	10	19	25	25	18	9	7
Xiangtang	Datong River	5	5	6	13	22	28	48	46	41	22	10	6
Hongqi	Taohe River	13	13	15	23	38	41	59	72	83	62	31	18
Hejin	Fenhe River	4	4	3	3	3	4	10	14	13	8	6	4
Huaxian	Weihe River	12	12	15	30	40	30	65	60	95	75	36	15
Heishiguan	Yiluohe River	16	15	16	23	28	23	75	67	65	60	34	21

2.2 Channel configuration for water and sediment transportation

The YR water and sediment transportation in the lower reach and Ningxia-Inner Mongolia reach is a focus concerned. Channel for water and sediment transportation can be at least expressed as the following three aspects: larger flood releasing ability of the watercourse to meet demand from extreme flood; main channel should possess certain water and sediment discharging ability to meet normal water and sediment transportation demand; and acceptable transverse gradient of floodplain to reduce the risk of secondary suspended river.

2.2.1 Flood discharging capacity of river course Flood of the lower YR is characterized with high peak discharge, short duration, high sediment content, and rapid rise and fall. So there should be enough space for corresponding flood to ensure the safety of flood control.

Since 1919, the maximum flood peak discharge 22,300 m^3/s was observed in 1958 at Huayuankou (HYK) station. The flood volume of 12 days amounts to 8.885 billion m^3. In addition, it is estimated from the historical records that the maximum peak discharge at Huayuankou station was 33,000 m^3/s which occurred in 1843, and the flood volume of 12 days was 13.6 billion m^3. Dyke system in the lower YR has been fortified to prevent dyke breaching with standard of flood of 22,000 m^3/s at Huayuankou station, and it had been heightened and strengthened 4 times since 1949, which can basically meet the demands. During recent 30 years, the occurrence frequency of ordinary flood in the middle YR has reduced because of water conservation project and medium and small reservoirs. But the occurrence frequency of large floods and extreme floods have not changed. Therefore, taking into account the flood regime in the future, the importance of ensuring the safety of flood control to social safety and economic development, and the demands of prompting China into an affluent society in the 21st century, the standard of flood control of the lower YR afore-mentioned should be maintained.

The flood control standard in the Ningxia-Inner Mongolia reach is to prevent a 20–50 year flood, corresponding flood peak of which ranges between 5600 and 5900 m^3/s. This discharge can be regarded as the necessary flood discharging and detention capacity in the section.

2.2.2 Water and sediment transportation capacity of the main channel The main channel which has small resistance and large flow velocity, is the main body for water and sediment transportation. Its flood discharging capacity accounts for 60%–80% of that of the whole cross section, while sediment discharging capacity nearly completely relied on it. It is significant to maintain certain water and sediment discharging capacity of the main channel to ensure the water and sediment transportation of the whole river.

Cross section is the key factor influencing main-channel's water and sediment transportation capacity, and bank-full discharge or flood discharging capacity of the main channel is a comprehensive parameter reflecting the configuration of main-channel cross section. Therefore bank-full discharge is adopted to express the water and sediment transportation capacity of the main channel in this paper. In the 1950s–1960s, bank-full discharge of the downstream is about 5000–8000 m^3/s. In the recent 50 years,

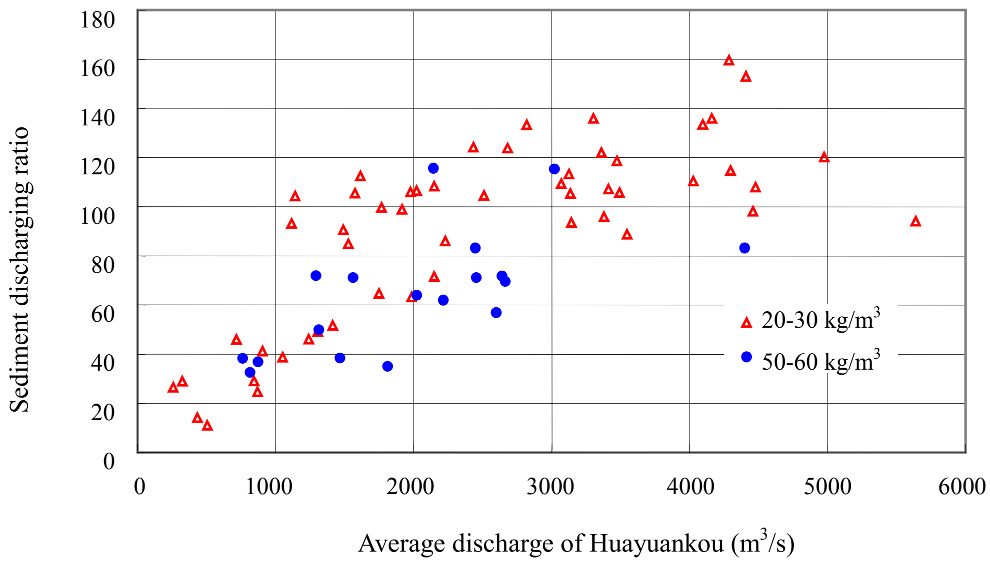

Figure 1 The relationship between flood discharge and sediment discharging ratio (1986–2004)

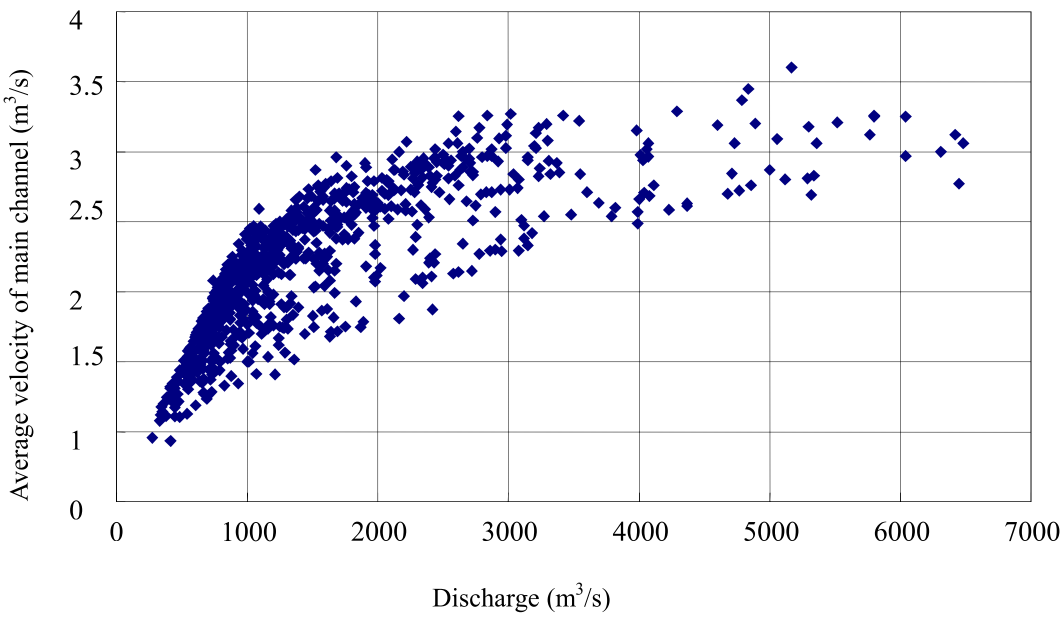

Figure 2 The relationship between discharge and velocity in the lower Yellow River (Gaocun, 1956–2004)

with the change of coming water and sediment, bank-full discharge has a decreasing trend. Before the flood season of 2002, bank-full discharge in most sections is less than 3000 m^3/s; in some sections, it is even less than 2000 m^3/s. The situation is serious. The expected restoration objective of bank-full discharge of the main channel depends mainly on the demands of efficient sediment transportation and river channel formation, the demand of extreme flood prevention and the demand of people's living in floodplain, as well as consideration of possible water and sediment condition in the lower river.

Based on the observed data series of 168 floods from 1974 to 1990, it was proposed that the most suitable discharge and sediment content is 3500 m^3/s and 75 kg/m^3 respectively for sediment transportation effectively (Yue, 1996). More work has been done recently according to the observed data since 1986. From the relationship between discharge and the sediment transportation efficiency (Figure 1), it can be found that the sediment transportation ratio increases with the discharge increasing. But after the discharge exceeds 3000 m^3/s, the increase of sediment transportation ratio gets slow or keeps stable basically. This result is agreed with the velocity-changing rule at different discharges in the main channel (Figure 2). Similarly, after the discharge exceeds 3000 m^3/s, the increase of velocity slows down, so the sediment transportation capacity will increase slowly. The relationship between the discharge and scouring of per cubic meter of water in the lower YR is analyzed (Figure 3) and it is found that: with the increase of discharge, the scouring increases and the scouring of per cubic meter of water almost reaches the maximum value of about 3500 m^3/s. After the discharge exceeds 3500 m^3/s the scouring of per cubic meter of water does not increase obviously. From the above analysis, when the main-channel discharge capacity is larger than 3500 m^3/s, the flow with a discharge of near bank-full discharge would possess favorable high sediment transportation efficiency and scouring efficiency. The efficiencies do not increase obviously when the discharge increases further. The discharge with the maximum sediment transportation efficiency does not mean the corresponding sediment load is the largest. The sediment load of flood is proportional with the discharge and flood duration. The larger the discharge is and the longer the duration is, the more the sediment load carried by flood is. But because water shortage in the YR is very serious at present, and the future possible bank-full discharge is possibly close to the above mentioned discharge, hence it is better to select the discharge as the minimum objective of the expected bank-full discharge.

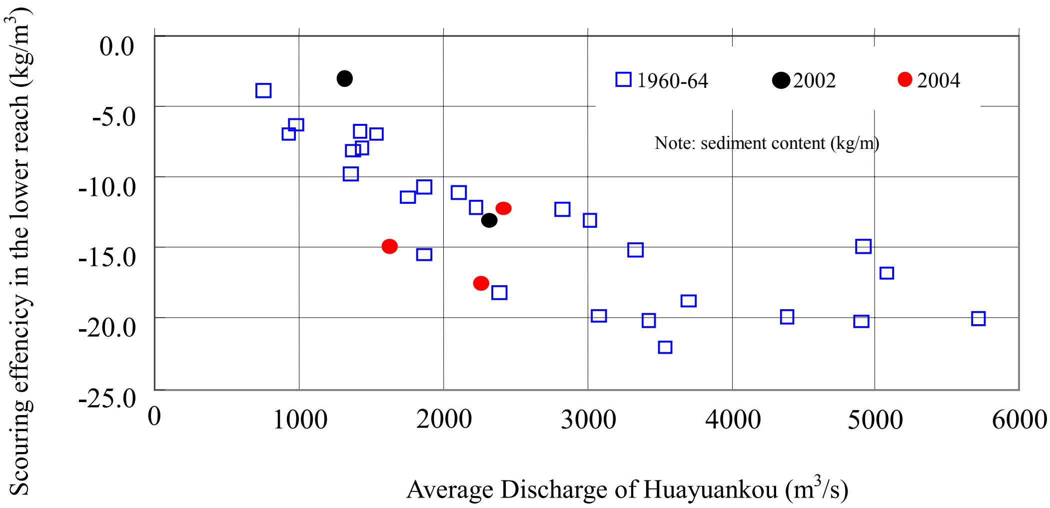

Figure 3 Flood scouring efficiency in the lower Yellow River

The discharging capacity of the main channel is closely related with the 1.81million people who live on the floodplain. After embankment breaching at Tongwaxiang in 1855, many people have been forced to live in the YR floodplains. The floodplains play a remarkable role in flood and sediment detention especially during big flood period, with the flood peak reduction reaching 50% and siltation ratio about 70%. If the floodplains cannot realize the function of sediment and flood detention, the lower YR will face much bigger pressure of dealing with flood and sediment. For many years the peak discharges greater than 4000 m^3/s at Huayuankou station have been regarded as the registered floods. So the objective of bank-full discharge should be above 4000 m^3/s. The bank-full discharge certainly influences the discharge capacity of the whole river channel. But because the area of river cross-section is much larger than that of the main channel, the difference of water level is only 21 cm when the bank-full discharge increases from 4000 m^3/s to 6000 m^3/s, and it has little effect on the lower embankment which is 2.5 m higher in most parts.

The main hydrodynamic force for channel formation is from impact of flood and resistance from riverbed. In case flood is smaller than bank-full discharge, the resistance from riverbed does not change much and channel-forming force mainly comes from kinetic energy of flood. The force is a function of discharge and flood volume: when discharge is small and duration is short, the force will be smaller than the resistance from riverbed and siltation will occur in the main channel; on the contrary, scouring will occur in the main stream. With the observed data since 1952, except those typical floods with high sediment content, for Gaocun station, the corresponding relationship between the main-channel area and hydrodynamic force ($W^{0.32}Q^{0.37}$) is analyzed (Figure 4). According to this relationship, if no extra water joins into the YR, the coming water in the lower YR is about 13 billion m^3, then water, which can be used for channel formation, is about 8–10 billion m^3 by the effective regulation of Xiaolangdi reservoir. The main channel with a section area of 1800–2000 m^2 could be formed, which corresponds to the bank-full discharge of 4000–5000 m^3/s. If there is no regulation of reservoirs (maintaining a natural runoff), according to the relationship between the flood volume and bank-full discharge, runoffs for flow discharge greater than 2000 m^3/s in flood season and bank-full discharge, the bank-full discharge in the lower YR could be maintained at 3500–3700 m^3/s basically. It must be pointed out that the annual sediment deposition is more than 0.15 billion t in the lower YR during the period above mentioned. In the future, the frequency of flood causing floodplain flooding will reduce and most deposition will take place in the main channel. If maintaining the main channel from depositing, sediment must be treated suitably. Before the sediment storage capacity of Xiaolangdi reservoir runs out completely, the sediment load entering the lower YR could be under 0.5–0.6 billion t. Through water and sediment diversion, sediment deposition in floodplain and in areas along the embankment, about 0.2 billion t sediment can be disposed. Sediment transportation of flow will be about 0.4 billion t. Therefore, as the sediment-trapping function of Xiaolangdi reservoir is available, flood-discharging ability of the lower main channel is able to be maintained at 4000 m^3/s; after that, if Guxian reservoir and west route of the Water Transfer from South to North can put into effect in time, the main channel can be maintained from shrinking.

Based on the aforementioned analysis, the bank-full discharge of and above 4000 m^3/s is regarded as the restoration objective of discharging capacity for lower main channel.

Similarly, that of Inner Mongolia should be no less than 2000 m^3/s.

Reducing or even avoiding flood is the main concept of traditional flood control. However, from the relationship between flood power and channel formation (Figure 4), the YR should not have no flood. To improve the situation of the main-channel shrinkage in the lower YR and Inner Mongolia, the key is to ensure necessary channel-forming dynamics (Liu, 2006).

3.2.3 Transverse Slope To maintain river channel with certain transverse gradient, the risk of secondary suspended river can be reduced. The deposition in the main channel is inevitable due to the incompatible water and sediment flow of the YR. The sediment silts up firstly along the natural levee of floodplain. So the transverse slope of the floodplain is also difficult to be avoided even without dyke system. The transverse slope of the floodplain was not remarkable because the main flow often shifted

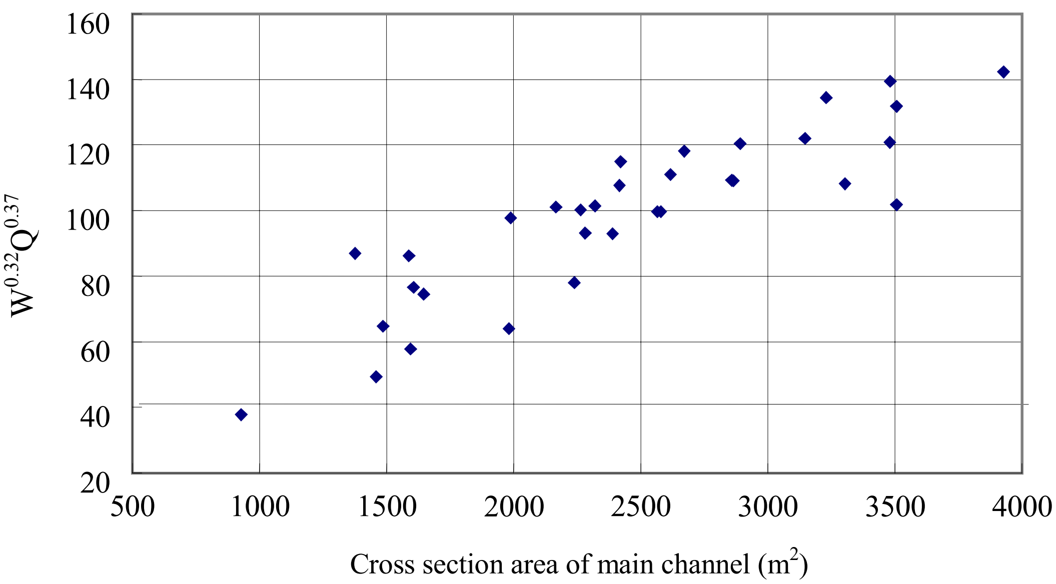

Figure 4 The relationship between cross-section area and hydrodynamics (1952–2004)

and overflowing flood occurred frequently. In recent 30 years, sediment deposition in the main channel and near the lips of the floodplain have increased because the frequency of overflowing flood occurrence decreased, sediment concentration increased, the scope of the main flow shifting reduced and the flow resistance increased. Thus the transverse slope has increased. Taking into account the safety of livelihood and production in the floodplains, the transverse slope to a certain extent has to be accepted. On the other hand, when embankments have been heightened and strengthened, if bank-full discharge can be recovered and maintained at 4000 m^3/s, the transverse gradient to a certain extent in the floodplain of the lower YR is acceptable. The acceptable gradient j relates to the anti-scouring capacity of the embankment system and floodplain roughness. The roughness ranges from 0.012 to 0.016 in the mainstream of the YR and from 0.03 to 0.035 in floodplain (fresh floodplain is not included). During recent 20 years, the floodplain roughness has increased with the economic development. According to Chezy formula of $V = R^{2/3}j^{1/2}/n$, the floodplain transverse gradient can reach 6–9 times that of the longitudinal gradient. But it is the transversal gully that usually caused danger, and its roughness is much less than the average of the floodplain and is generally 2 times less than that of the mainstream, so the critical floodplain transversal slope is within 4 times that of the longitudinal slope. Thus the transverse slope should be controlled less than 4 times of the longitudinal slope to safeguard against floods.

At present the transverse slope of the floodplain is 4–10 times the longitudinal slope in floodplain of the Dongbatou-Taochengpu section (Table 2). Whether or not the transverse slope of the floodplain can be reduced to a scope within 4 times of the longitudinal slope depends on warping intensity in the floodplain in the future. Recently the transverse slope can be controlled by avoiding small overflowing flood and silting up the waterway along the dykes. With the improvement of the warping technology and the standard of flood defense in the floodplains, and the implementation of the inundation compensation policy, the transverse slope of the floodplain can be reduced gradually.

Table 2 Floodplain characteristic value of the lower Yellow River (YRCC, 2003)

	Left bank floodplain width (km)	Transverse slope (left %)	Right bank floodplain width (km)	Transverse slope (right %)	Longitudinal slope (%)
Above Dongbatou	4.89	3.33%	3.80	Unconspicuous	2.3%
Dongbatou-Gaocun	5.5	5.15%	4.85	5.84%	1.7%
Gaocun-Taochengpu	4.2	9.8%	2.86	10.39%	1.5%
Below Taochengpu	2.2	27.8%	2.12	14.36%	1%

2.3 Water quality standard

The water quality goal of the YR firstly depends on water functions of each section. For domestic water, water quality should be at least class III standard, but water for agricultural purpose can be lowered properly. According to *The Water Functional Partition of China* (tentative), the YR mainstream is classified into 18 first-level water functional areas and 50 second-level water functional areas. Based on the water functional demands, the section down Lanzhou should meet class III standard and that above Lanzhou should be maintained at class II standard.

The restoration goal of water quality is restricted by the following three aspects: future runoff condition, that is whether flow for self-purification can be realized; the ratio of polluting sources with pollutant discharge meeting standards; and the total pollutant discharged into the YR.

Flow for self-purification is an indicator easily influenced by up to the standard pollutant discharge at polluting source and the scale of agricultural and industrial development. This paper has calculated the self-purification flow of important reaches, which takes the section below Lanzhou meeting class III standard as the goal and, chose COD_{Cr} and NH_3–N as pollution control factors, with the precondition that the sewage into the main watercourse of the YR entirely meet national standards, and the bayou of branches into the main watercourse of the YR meet the demand of water quality. Compared with monthly discharge in typical sections from 2000 to 2004, it is found that the flow demand for self-purification is not met all the time in every section except Xiaochuan and Lanzhou (Table 3). The period with insufficient self-purification in the section above Longmen accounts for 15% of the whole year and that down Tongguan accounts for 25%. But, the problem can be settled if the water volume can be increased by 0.6–1.0 billion m^3 through east and middle route projects of Water Transfer from South to North, and if the water quality goal of Xiaheyan-Tongguan could be lowered to class IV standard.

Table 3 Self-purification flow demand of the key sections of the mainstream of the Yellow River (m^3/s)

Section	Xiaochun	Lanzhou	Xiaheyan	Shizuishan	Hekouzhen	Longmen	Tongguan	Xiaolangdi	Huayuankou	Lijin
Discharge for self-purification (m^3/s)	120	230	420	360	80	260	380	260	290	60

Because the sewage discharged into the mainstream and tributaries scarcely meet the national standard, the water quality in the section down Lanzhou is below the national standard to a serious extent in a long time. At present, more than 10 standards have been constituted, which should be followed by the enterprises concerned. But, most of the YR basin is economically disadvantaged area; it is very difficult to make the sewage discharged meet the national standards. According to the experiences of developed countries, when the living conditions of people is greatly improved they should think much of the environmental protection, and the prevention of water pollution will be strengthened. Therefore, when economy of the YR basin is developed to a higher level, pollutant discharged that should meet standards could be realized.

In summary, the water quality in the section down Lanzhou should meet class III standard, of which the Xiaheyan-Sanmenxia section seriously polluted should be properly lowered to class III–IV standard before 2020, at present, which is of class V standard nearly all the year round; and the section above Lanzhou should strive to maintain present class II standard. The key is to realize pollutant discharged reaching the standard and the total control of pollutant entering the sea by provinces (regions).

2.4 River ecosystem

The river ecosystem mentioned in the paper refers to the ecological area of the mainstream, including aquatic ecosystem and wetland.

2.4.1 Aquatic ecosystem Aquatic ecological protection does not mean to protect all living creatures in the river, but realize the biodiversity in the YR mainstream by protecting the key species in the aquatic ecosystem. The most reliable method of recognizing key species is to do some removing experiments, and then observe the reaction of species combinations inside the system. But these experiments are not feasible at present. Key indices method is adopted in this paper. According to the difference of climate and ecological characteristics, various kinds of key index of species in the aquatic ecosystem of the section above Lanzhou, the Lanzhou-Huayuankou and the Huayuankou-Lijin sections are compared. The results show that fishes' key index is the biggest.

There are many kinds of fishes in different reaches. It needs to define which kind of fish is the key species to be protected. The key fish selection chiefly follows the following aspects: ecological significance, local value, special value and endangered degree. According to the pilot research, the protection coefficient of Gymnocypris eckloni is the highest in the section above Lanzhou, which is the representative original fish living in cold water in the source area; in the Lanzhou-Huayuankou section, the coreius hetreodon is of the highest protection coefficient; the second rank is the YR carp, which should also be included in the key species; the protection coefficient of coilia ectenes is the highest in the Huayuankou-Lijin section, therefore the key species of this section. To the manager of river water resource, the core to protect these key fishes is to protect their major spawning places, major habitats and important migratory channels by supplying enough runoff.

The protection of aquatic ecosystem depends on water quality of the river, and whether eco-water demand can be met to a great degree (Table 4). Eco-water demand of cross sections of the mainstream is calculated with Tennant method. Compared with observed runoff, it can be seen the water demand is at the same level of the 1980s. Based on the analysis, it is regarded that if water can be supplied to the YR through Water Transfer Project from South to North, it is possible to realize such a level. Therefore, it is possible to restore aquatic ecosystem of the YR to the level of the 1980s.

2.4.2 Wetlands Wetland protection has been a common understanding. From the view of river managers, it is vital to provide sufficient water with suitable quality, to protect the area and size of wetlands, and to create advantage for restoration of its healthy state. By analyzing the relationship between wetlands along the YR and its flow, it is found that the wetlands mainly depend on the runoff (partly on local precipitation) and is one of the competitors of water-user except the wetland in the YR source area. The competition exists not only between the wetlands and the human, but also between the wetlands of upstream and downstream. In recent years, with the promotion of ecological protection, the provincial governments alongside the YR have paid more attention to wetland protection, plotted out the wetland conservation reserving area and taken some relevant measures. The objective includes not only natural wetlands but also artificial wetlands. As for a province (or a region), the wetlands maintenance can give rise to the ecological or eco-social benefits, but the excessive protection will result in the harm to other ecological units in the downstream, in addition to the destruction of the local natural ecological balance. It is obvious that wetland protection must be integrated into the comprehensive planning of water resource management in the YR basin, on the basis of fully realizing the value of wetlands alongside the YR, reasonably ranking the priority sequence, scale and layout of wetlands alongside the YR in terms of total ecological benefits of the river ecosystem.

Table 4 Eco-water demand of the mainstream of the Yellow River (m^3/s)

Month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.
Xiaochuan	90	80	80	110	180	110	310	300	330	270	150	90
Lanzhou	90	90	90	130	200	240	370	360	390	310	170	110
Xiaheyan	90	90	90	250	390	420	370	360	390	310	170	110
Shizuishan	90	90	100	240	270	350	310	350	360	320	150	110
Hekouzhen	80	90	120	120	90	90	220	290	320	270	130	70
Longmen	90	110	160	310	220	200	270	390	360	310	170	90
Tongguan	110	140	190	380	340	280	360	490	510	430	240	120
Xiaolangdi	100	100	200	400	390	340	360	490	500	430	240	140
Huayuankou	110	100	200	410	410	340	410	550	550	490	280	150
Lijin	100	100	150	300	280	250	340	510	530	490	280	150

Combining expert appraisal and scientific calculation, 8 wetlands along the Yellow River are compared on their value of water sources reservation, flood regulation, biodiversity, rarity and habitat. The wetland in the YR source area and the wetland in the YR Delta should be reserved with the highest priority. The watercourse wetland formed by flooding has a high ecological value and should also be listed in the wetlands protected. But the reservation scale of other wetlands should be demonstrated comprehensively and carefully.

There are plenty of lakes and marshes distributed in the YR source area. Among them, Zoige wetland (0.166 million hm^2) with some dozens of endangered, rare and endemic species, is the largest and most typical alpine frigid swampy and the largest plateau wetland and peat wetland in the world. Due to draining with canals and overgrazing, it is developing into meadows or toward desertification. Wetlands in the source area have not only ecological value but are also of the significance to maintaining the water resources of the YR and sustaining the YR flow, which is the main water source of wetlands alongside the YR, so it must be rehabilitated with effective measures to recover it as much as possible.

The delta wetland is formed by multifarious swing of river channel in the estuary, sedimentation and floodplain. It is the important district to connect the terrestrial ecosystems with the ocean ecosystems, the home of many precious plants, the protective gene bank of plants, also the station for rare migratory birds, the habitat for overwintering, and the breeding place for rare birds in the world. The freshwater wetland is the key unit for maintaining the equilibrium of estuarine system and protecting the biodiversity. The area of estuarine wetland is large. The freshwater wetland in this paper refers to the freshwater wetland below Yuwa section of the YR, with an area of 0.153 million hm^2, of which the key area is 79,000 hm^2. Though there are wetlands in other areas, they are relatively sparse. Due to agricultural development, restriction of incoming water conditions, and reduction of water and sediment entering the YR since the 1990s, the area of the YR freshwater wetland ever decreased by nearly 50%.

The possible area of freshwater wetland that can be maintained is mainly restricted by the guarantee of eco-water demand and the stability of coastline. Suitable eco-water demand is calculated at about 2.8 billion m^3 (Lian, 2005). Compared with Table 4, it is much less than estuarine aquatic eco-water demand (9.17 billion m^3). That means only if aquatic eco-water demand can be met, the water demand of freshwater wetland can be met. Lots of researches have proved that sediment runoff which can keep the balance of coastline is 0.3 billion t (Hu, 2005), is likely to be ensured in the future. In general, the protected area of estuarine wetland can be set as 79,000 km^2 in recent period, and all should be protected in a long term.

2.5 Water supply capacity

Water supply capacity relies on the balance of human water demand in the river basin and related areas and environmental water demand. Human water demand includes domestic, industrial and agricultural water demands.

According to national controlling objective of population, the population will not increase till the mid-21st century. In 2020 and 2050, domestic water demand of the basin will reach respectively 4 billion m^3 and 5 billion m^3, and corresponding water consumption nearly reaches 2 billion m^3 and 2.5 billion m^3. Agricultural water demand is the total of water resources for farmland, forest, grassland, fishery, etc. With the improvement of the urbanization rate, adjustment of the industrial structure and popularization of agricultural water-saving technology, the agricultural water demand will be reduced gradually, and will maintain a certain level finally. According to estimation, after 2010, the agricultural water demand of the YR basin will keep about 37.5 billion m^3 basically, among which, the corresponding water consumption is about 33.8 billion m^3 basically after 2010. According to analysis on future water demand in the YR basin, industrial water demand will increase from 6.3 billion m^3 in 2000 to 11.2 billion m^3 in 2020 and 12.7 billion m^3 in 2050 in the basin, and the corresponding water consumption reaches 5.6 billion m^3 and 6.4 billion m^3 respectively. Under the condition of exploitation of groundwater being maintained without exceeding the available amount (11 billion m^3), surface water consumption in the river basin and related regions will be about 41 billion m^3 after 2020.

Environmental water demand of river channel is the coupling of water demand of sediment transportation, eco-water demand and self-purification water demand, etc. Calculation shows that water demand for sediment discharging at Lijin is 15 billion m^3, and the environmental water demand, which is to couple the water demand for sediment transportation, eco-water demand and water demand for self-purification together, is 22.5 billion m^3. Environmental water demand out of river channel including water demand for water and soil conservation on the Loess Plateau, eco-water demand of scenes in urban and rural areas, and water demand for sanitation purposes, etc. will reach 2.4 billion m^3 in 2020.

In principle, the available YR water to human should be about 28.6 billion m^3, after the deduction of the environmental water demand, about 22.5 billion m^3, and environmental water out of river channel, about 2.4 billion m^3, from natural runoff of 53.5 billion m^3. It is far from the future water consumption (41 billion m^3) by human being. That means when the YR water completely meets the water demand of natural function, the satisfaction of human being is less than 70%. Such a result obviously contradicts the essence of a healthy river. The standard of the healthy river should be the balance of natural and social functions of a river that can be realized. When the YR has not received water supply and its runoff is not able to satisfy both natural and social functions, they should be compromised with each other.

In fact, human water demand and environmental water demand are flexible to a certain degree. Based on calculation, under the condition of annual mean precipitation, when water supplied to human being and environment reaches 33.3 billion m^3 and 18.4 billion m^3 respectively, the balance between its social and natural functions can be realized basically. The environmental discharge of the mainstream can refer to Table 5. The environmental discharge is the indicator reflecting whether human water demand exceeds standards.

Table 5 Monthly environmental flow standards of the mainstream of the Yellow River (m^3/s)

Controlling point	1	2	3	4	5	6	7	8	9	10	11	12
Xiaochuan	90	80	80	110	180	110	310/2600	300	330	270	150	90
Lanzhou	230	230	230	230	230	>230	>230/2600	>230	>230	>230	230	230
Xiaheyan	420	420	420	420	420	420	420/2600	420	420	420	420	420
Shizuishan	360	360	360	360	360	360	360/2600	360	360	360	360	360
Hekouzhen	80	>80	>80	>80	>80	>80	110	150	160	140	>80	80
Longmen	260	260	260	310	260	260	>260	>260	>260	>260	260	260
Tongguan	380	380	380	380	380	380	380	>380	>380	>380	380	380
Xiaolangdi	260	260	260	>260	>260	>260	>260/4000	>300	>300	>300	260	260
Huayuankou	290	290	290	>290	>290	>290	>290/4000	>330	>330	>330	290	290
Lijin	100	100	100	300	280	250	340/4000	500	500	240	140	100

3 Conclusions

From the essence of river's health, it can be known that the healthy Yellow River means its runoff can basically meet the demand of healthy development of river ecosystem while the safety of human society and economic development can be ensured. At present, the indicators of the healthy YR can be denoted with the following items: continuous flow, safe river channel for water and sediment transportation, favorable water quality, sustainable river ecosystem, and water supply capacity. Based on in-depth analysis, minimum flow, maximum flood discharging capacity, bank-full discharge, transverse slope of floodplain, water quality class, aquatic biology, wetland area and available water to human being, altogether 8 items are put forward as indicators of the healthy YR, and quantitative standards for different reaches are provided, for example, the discharge entering the sea should not be less than 50–260 m^3/s; the discharge entering the YR from the Weihe River is 12–95 m^3/s; bank-full discharge of the lower YR should be larger than 4000 m^3/s; and water quality of the section below Lanzhou should be better than class III standard and river ecosystem should be recovered to the level of the late 1980s.

The symbols of the healthy YR are from understanding of river's health at present. These indicators based on them are characterized with the era. With the recovering of the Yellow River's health and the improvement of socioeconomic development, the basic contradiction of the river will change; therefore, the symbols and indicators of the healthy YR should keep pace with the times.

References

Department of Water Affairs and Forestry, Department of Environmental Affairs and Tourism, 2004. State-of-Rivers Report: Berg River System.

Gurtz M E, 1994. Design of biological components of the National Water-Quality Assessment Program. In: Leob S L, Spacie A (eds.), Biological Monitoring of Aquatic Systems. Boca Raton: Lewis Publishers.

Hu Chunhong, 2005. Water and Sediment Flow Changes and Relative Influence in Yellow River. Beijing: Science Press, 252-301. (in Chinese)

International Commission of Rhine River, 1994. Salmon 2000.

Katsuhide Yoshikawa, 2004. On the Progress of River Restoration and Future View in Japan and Asia. 3rd European Conference on River Restoration, Zagreb, Croatia.

Kleynhans C J, 1999. The development of a fish index to assess the biological integrity of the South African rivers. *Water SA*, 25: 265-278.

Lian Yu, Wang Xingong, 2005. Eco-water demand of the Yellow River Delta wetland. In: Report on National Tenth Five-Year Plan for National Science and Technology Development, 57-77. (in Chinese)

Liu Xiaoyan, Zhang Yuanfeng, Hou Suzhen, 2006. Mechanism of the main-channel modeling of Yellow River. *Yellow River*, (4): 4-8. (in Chinese)

Murray Darling Basin Commission, 2004. Living Murray Business Plan.

Nakamura K, Tockner K, 2004. River and Wetland Restoration in Japan. 3rd European Conference on River Restoration, Zagreb, Croatia.

Nijland H J, Cals M J R, 2000. River restoration in Europe. In: Proceedings of Conference on River Restoration Practical Approaches.

Scrimgeour G J, Wicklum D, 1996. Aquatic ecosystem health and integrity: problem and potential solution. *Journal of North American Benthlogical Society*, 15(2): 254-261.

Yellow River Conservancy Commission, 2003. The Secondary Suspended River of the Yellow River: Formation and Its Harness Strategy. Zhengzhou: Yellow River Conservancy Publishing House, 103-104. (in Chinese)

Yue Dejun, 1996. The water requirement for sediment transporting. *Yellow River*, (8): 14-16. (in Chinese)