Water demand for ecosystem protection in rivers with hyper-concentrated sediment-laden flow

LUO Huaming, LI Tianhong, NI Jinren & WANG Yudong

Department of Environmental Engineering, Peking University, Beijing 100871, China; The Key Laboratory of Water and Sediment Sciences, Ministry of Education, Beijing 100871, China

Correspondence should be addressed to Li Tianhong (email: litianhong@iee.pku.edu.cn)

Received April 27,2004

Abstract Sediment transport is one of the main concerns in a river system with hyper-concentrated flows. Therefore, the water use for sediment transport must be considered in study on the water demand for river ecosystem. The conventional methods for calculating the Minimum Water Demand for River Ecosystem (MWDRE) are not appropriate for rivers with high sediment concentration. This paper studied the MWDRE in wet season, dry season and the whole year under different water-and-sediment conditions in the Lower Yellow River, which is regarded as a typical river with sediment-laden flows. The characteristics of MWDRE in the river are analyzed. Firstly, the water demand for sediment transport (WDST) is much larger than the demands for other riverine functions, the WDST accounts for the absolute majority of the MWDRE. Secondly, in wet season when the WDST is satisfied, not only most of the annual incoming sediment can be transported downstream, but also the water demands for other river functions can be satisfied automatically, so that the MWDRE in wet season is identical to the WDST. Thirdly, in dry season, when the WDST is satisfied, the water demands for other river functions can also be satisfied, but the low sediment transport efficiency results in significant waste of water resources. According to these characteristics and aiming at decreasing sediment deposition in the riverbed and improving the utilization efficiency of water resources, hydrological engineering works can be used to regulate or control flow and sediment so that the sediment incoming in dry season can be accumulated and be transported downstream intensively and thus efficiently in wet season.

Keywords: sediment-laden flow, the Lower Yellow River, water demand for river ecosystem, water demand for sediment transport

DOI: 10.1360/ 04ez0016

1 Introduction

The river system is one of the most important natural ecosystems, and it has quite intimate relationship with human beings. The primary riverine functions, such as water transfer, sediment transportation, flood release, self-purification, landscape for recreation or as biological habitats, navigation and so on, have given much convenience to human productive activities and daily life. On the other hand, the natural river system has been interfered extensively in recent years by human activities, and thus the river ecosystem has been damaged and riverine functions have been impaired, which in turn brings unfavorable influence upon the human society. For example, the construction of hydrological engineering works in the river and unreasonable exploitation of water resources have resulted in undesirable ecological aftereffects such as the disturbances on the habitat of river aquatic organism, sediment deposition in the river course, and the wetland ecosystem deterioration in the estuary, etc. Therefore, for exploitation and utilization of water resources in a high-efficiency and sustainable way, the Minimum Water Demand for River Ecosystem (MWDRE) that is needed for maintaining the health of the river itself must be satisfied.

A few concepts relevant to the MWDRE have been raised, such as Minimum Flow, Instream Flow Requirement, Environmental/Ecological Flow and so on. Based on a review of the previous studies, the Water Demand for River Ecosystem (WDRE)[1,2] could be defined as (Ni, et al.[3]) a variable of satisfying specific service object under certain spatial and temporal conditions, it is a generic term of the water satisfying the riverine functions at a certain level. Corresponding to different riverine functions, the water demand for river ecosystem protection includes water demand for pollution prevention, water demand for ecological protection, water demand for sediment transport, water demand for estuarine ecosystem protection, and water demand for river landscape and recreation, etc.

Due to the particularity of high sediment concentration in sediment-laden flows, the Water Demand for Sediment Transport (WDST) should be ensured so as to transport the sediment into the sea; otherwise severe sediment deposition in the lower reaches would cause significant rise of the riverbed, which not only aggravates the potential threat of floods, but also impairs the health of river ecosystem. As a world-known river with high sediment concentration, the Yellow River in general is short of water resources comparing with its abundant sediments. The major sources of water are spatially different from those of sediments, and water and sediment distribute unevenly between years and during one year. Because the water and the sediment do not match each other, as well as no-flow events have occurred frequently in the Lower Yellow River since 1970s under natural and human influence, the Lower Yellow River is suffering heavy sediment deposition, quick rise of riverbed and river channel shrinking. Furthermore, the severe sediment deposition also affects the utilization efficiency and operating lives of water conservancy facilities, which greatly impairs flood control, hydropower generation, irrigation, ecosystem protection and so on. Therefore, for rivers with hyper-concentrated sediment-laden flows, like the Yellow River, the WDST is a very important component of the MWDRE and should be stressed. The conventional methods for quantifying the MWDRE include: (i) Hydrological methodologies, which rely mainly on the historical hydrologic data, such as the “7Q10” Method and Tennant Method[4]; (ii) Hydraulic rating methodologies, which are based on the parameters of river hydraulics, such as Wetted Perimeter Method[5] and R2CROSS Method[6]; (iii) Habitat simulation methodologies such as the Instream Flow Incremental Methodology[7,8], which integrates a great deal of monitored hydrological and hydro-chemical data with the biological information of some specific aquatic organism in different growth phases, then assess the influence on the habitats resulting from the discharge increase; and (iv) Holistic methodologies, which start from the whole riverine ecosystem to carry out comprehensive study based on the knowledge and experiences of experts, such as the South Africa Building Block Methodology[9] and the Australian Holistic Approach[10]. Because of different characteristics of the studied areas, the aforementioned methods have not accounted for sediment transportation function of the river system. Some studies focused on calculation of the water demand or water use for sediment transport, the enhancement of sediment transport efficiency and the relationship between sediment transport and river channel regulation[11—16]. More studies on relationship between the WDST and the total MWDRE of the whole river from viewpoint of the riverine system are needed. With the Lower Yellow River as the studied area, this paper pays more attention to the relationship between the WDST and the MWDRE. The Lower Yellow River is spatially divided into several reaches and temporally the wet season, dry season and the whole year under different water-and-sediment conditions, which becomes the basis to analyze the characteristics of water demand for the MWDRE.

2 Structure analysis of the water demand for river ecosystem in the Lower Yellow River

The Yellow River Basin is mostly situated at arid and semiarid zone. As a whole, the water resources in the system are not rich. However, as the important water source of the northwest and north China, the Yellow River assumes the responsibility of water supply for numerous cities and large irrigation districts in the basin. Since 1972, the no-flow events have frequently occurred in the Lower Yellow River, which not only incurred great economic losses to the riparian area, but also caused severe damage to the ecological environment in lower reaches. In order to retain health and vitality of the Yellow River as well as achieve sustainable utilization of water resources, researches on the MWDRE in the Lower Yellow River have received broad recognition.

The Yellow River is remarkable in the world for its high sediment concentration. The average annual sediment runoff is 1.6 billion tons at the Sanmenxia Hydrological Station, where the mean annual measured sediment concentration reaches 35 kg/m^3. The magnitude of sediment runoff and sediment concentration of the Yellow River is unparalleled all over the world[17]. Large quantities of sediments require much more water to transport them to the sea. Otherwise, the sediments will deposit on the riverbed in the lower reaches, which will result in river channel shrinking and river bed elevation, and possibly aggravate the potential threat of floods. Therefore, the Yellow River, characterized with high sediment concentration demands the unique part of water for sediment transport among the MWDRE in the lower reaches. From this point, the MWDRE in the Lower Yellow River is obviously distinct from those in most other rivers.

The MWDRE should be determined according to some certain principles and steps. The issues should be considered to include riverine functions, temporal sequence, spatial sequence, priority and harmonization of the issues, water use efficiency, aftereffect and optimization, etc.[11] According to the actual conditions of the Lower Yellow River, the primary riverine functions mostly considered while quantifying the MWDRE can be determined to be pollution prevention, sediment transport, and ecological protection, while a minimum critical discharge or critical runoff is required to meet each function. In relevant studies, researches have been done to the MWDRE in the Lower Yellow River[11], the minimum water demands for various functions under different conditions of incoming water and sediment since 1950s are analyzed and calculated at every reach of the Lower Yellow River, and the MWDREs at 4 main reaches have been computed under typical condition of incoming water and sediment (see table 1). Hereinto, the minimum water demand for pollution prevention uses the monthly average discharge during the driest month in 1970s, the minimum water demand for ecological protection is estimated by 10 percent of the average annual discharge under the natural condition (1950s), and the water demand for sediment transportation is calculated by the following formula:

$$W_s = \frac{W_{up}}{M_{up} - D}, \tag{1}$$

in which, W_s refers to the water demand for sediment transportation (m^3/t); W_{up} refers to the amount of incoming water from upper reach during certain period of time (wet season or dry season) (10^8 m^3); M_{up} refers to the amount of incoming sediment from upper reach (10^8 ton); and D refers to the amount of sediment scouring or silting within the reach (10^8 ton). The percentage of water demand for sediment transport (WDST) over the total MWDRE is also listed in table 1. As is shown in the table, the WDST in wet season takes over 80% of the total annual MWDRE at every reach. Thereby, the WDST accounts for the absolute majority of the MWDRE in the Lower Yellow River.

Table 1 Integrated MWDRE and the percentage of water demand for sediment transportation

Hydrological station	Corresponding reach	Critical discharge in wet season /m^3 • s^{-1}	Critical discharge in dry season /m^3 • s^{-1}	Annual total MWDRE /10^8 m^3	Percentage of water demand for sediment transportation (%)
Huayuankou	SMX-HYK	1972.3	231.5	252.5	80.99
Gaocun	HYK-GC	2321.9	234.3	289.3	83.20
Aishan	GC-AS	2190.5	158	259.9	87.38
Lijin	AS-LJ	2140.2	155.6	254.2	87.29

The critical water demands for pollution prevention, sediment transport and ecological prevention at every reach in the Lower Yellow River are shown in fig.1 respectively, including wet season and dry season, without taking into account the principle of harmonization among water demands for different functions. The relatively abundant rainwater in wet season causes plentiful soil erosion in the loess plateau area in the upper and middle reaches of the Yellow River. As a result, the water demands for sediment transport at every reach in the Lower Yellow River are all above 200×10^8 m^3 during wet season. In dry season, the sediment incoming is relatively small compared to that in wet season, yet the water demands for sediment transport at every reach are still around 150×10^8 m^3. Compared with the WDST, the water demands for pollution prevention and ecological protection are significantly smaller, which are less than 50×10^8 m^3 in general. It is obvious that sediment transport function plays a pivotal role among the whole ecosystem functions for a river like the Yellow River with hyper-concentrated sediment-laden flows. Consequently, whether the MWDRE is satisfied is to a large extent determined by the WDST.

Fig. 1 demonstrates the water demands for different ecological functions of the riverine ecosystem at every reach of the Lower Yellow River under typical condition of incoming water and sediment. Actually, great changes have taken place to the incoming water-and-sediment condition since 1950s. As a whole, 4 different conditions of incoming water and sediment can be generalized, i.e. the "natural condition" represented by 1950s which is before the construction of the Sanmenxia Reservoir, the "engineering-controlled condition" represented by 1970s which is after the regular operation of the Sanmenxia Reservoir, the "complex condition" represented by 1980s when the no-flow events occurred occasionally in the Lower Yellow River under the combined

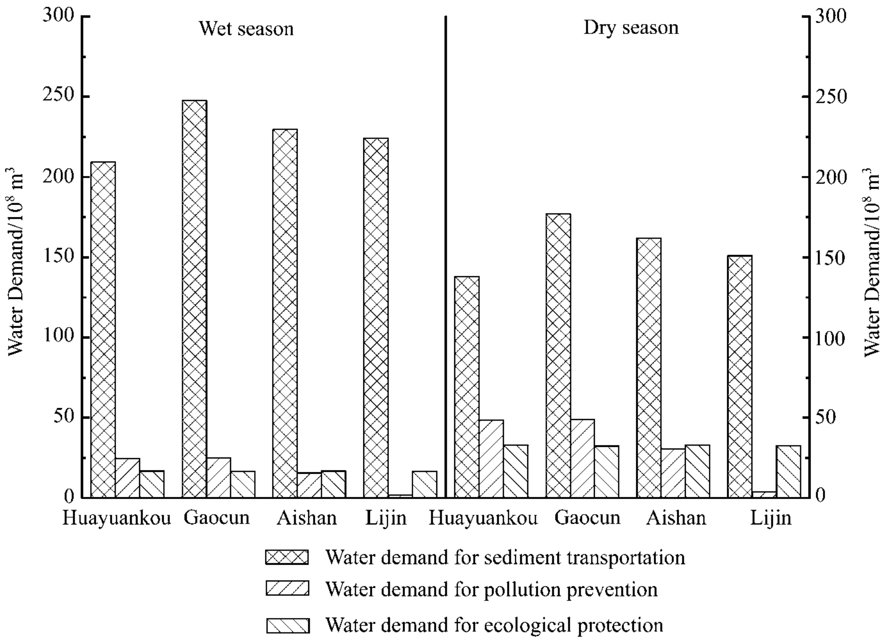

Fig.1. Critical water demand for the primary river functions in wet season and dry season.

influence of the soil and water conservation in the upper and middle reaches, water diversion works, reservoir operation and the utilization of water resources in lower reaches; and the "abnormal condition" represented by 1990s when the incoming water-and-sediment condition from the upstream turned abnormal, the sediment deposition on the river channel became serious, and the severity levels of no-flow events increased[12]. As the MWDRE will vary with the change of external conditions or the alternation of predominant functions on different temporal scale or different periods of time in a specified temporal scale, it is necessary to give further analysis on the interrelation between the WDST and MWDRE under different conditions of incoming water and sediment.

The proportion of WDST to the MWDRE at every reach under different conditions of incoming water and sediment are shown in fig. 2. First of all, we can see that the proportion varies among different conditions of incoming water and sediment. Under the natural condition, the river runoff was relatively abundant in the Yellow River and carried plentiful sediment at the same time, which inevitably required sufficient amount of water to transport the sediment to the sea. Yet the amplitude of variation of the water demands for other riverine functions with the change of runoff was far below that of the WDST. Therefore, the proportions of WDST to the MWDRE for all the four reaches are the highest under the natural condition among all conditions. To the contrary, under the abnormal condition, the Lower Yellow River fell short of water resource obviously, which caused frequent occurrence of the no-flow events, meanwhile the amount of incoming sediment from the upstream decreased with the decrease of incoming water, accordingly the WDST decreased remarkably. Here the importance of the water demands for other functions to the MWDRE was enhanced, and consequently the proportion of WDST to the MWDRE was reduced. Besides, the proportion under the complex condition is higher than that under the engineering-controlled condition. On the one hand, this is because the relatively abundant water incoming during the prior period of 1980s carried more sediment. On the other hand, it is also the result of the operation mode of the Sanmenxia Reservoir in 1970s. During this period, the Sanmenxia Reservoir started regulation and control operation according to the "storing clear water and releasing muddy water" mode after completing its second reconstruction at the end of 1973, which ignored part of the incoming sediment in the dry season and discharged it intensively in the wet season, especially in the flood season, thus the sediment transport efficiency was enhanced and the total water demand for sediment transport was reduced.

Although the proportion of WDST to the total MWDRE varies with the change of the incoming water-and-sediment conditions, it can be seen from fig. 2 that whatever the incoming water-and-sediment condition changes, the WDST always accounts for above 70 percent of the total MWDRE. Therefore, the alteration of the incoming water-and-sediment conditions does not change the characteristics of the Yellow River as a sediment-laden river radically. The WDST constitutes the principal part of the total MWDRE under all conditions of the incoming water and sediment.

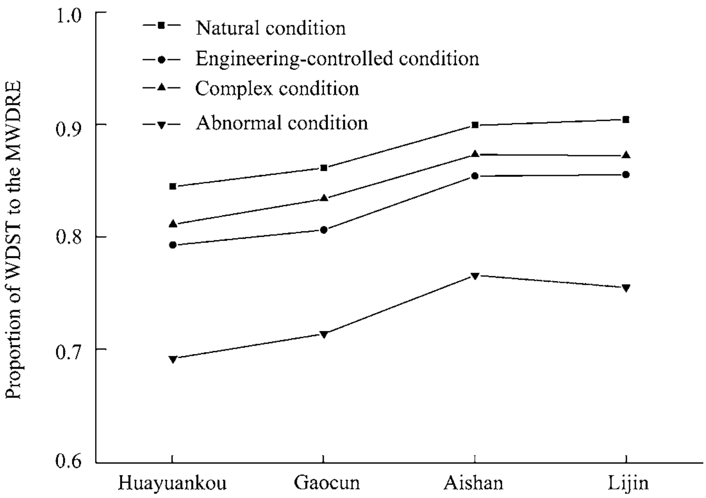

Fig. 2. Proportion of WDST to the MWDRE under different water-and-sediment conditions.

3 The characteristics of the water demand for river ecosystem in the Lower Yellow River

The incoming water-and-sediment conditions differ greatly between the wet season and dry season. This not only causes the variation of the WDST, but also has a significant effect on the determination of the total MWDRE at different reaches, which forms an outstanding characteristic of the MWDRE in the Lower Yellow River.

The amount of incoming sediment in wet season accounts for a majority of the annual total in the Lower Yellow River. Statistical analysis has obtained the average annual amount of incoming sediment under different water-and-sediment conditions for every reach in the Lower Yellow River, and the results are shown in table 2. According to the table, the amount of incoming sediment in wet season accounts for above 80 percent of the annual sediment incoming, except that the percentage is slightly smaller under the abnormal condition. If the incoming sediment in wet season cannot be fully transported downstream, a great deal of sediment will silt in the river channel inevitably, which sequentially results in continuous river bed lifting, so much as to accelerate the development of "suspended river" and aggravate the threat of floods. Therefore, the water demand for sediment transport in wet season should be satisfied in consideration of river

Table 2 Sediment incoming during the wet season and its proportion to the annual total sediment

Reach	Natural condition		Controlled condition		Complex condition		Abnormal condition	
	Amount /10^8t	Proportion (%)	Amount /10^8t	Proportion (%)	Amount /10^8t	Proportion (%)	Amount /10^8t	Proportion (%)
SMX-HYK	15.03	85.26	12.86	91.91	8.30	96.58	7.73	93.52
HYK-GC	13.34	85.47	10.54	85.29	6.71	86.49	6.09	83.79
GC-AS	12.68	85.91	8.65	79.91	5.83	82.99	3.89	74.88
AS-LJ	9.98	82.76	7.79	79.98	6.01	84.93	3.95	75.13

ecosystem protection, security and flood control in lower reaches.

In wet season, adequate amount of water is still needed within the channel to dilute the influent contaminant so as to reach certain water-quality standards. Besides, the maintenance of river ecosystem requires certain amount of water, too. However, as is shown in fig.3, the water demands for pollution prevention and ecological protection are far below the WDST under any condition of incoming water and sediment. When the WDST in wet season is satisfied, water requirements for other functions can be automatically met in course of the sediment transportation. Therefore, the integrated MWDRE at different reaches in the Lower Yellow River in wet season can be determined to be the amount of WDST. This could explain why the conventional methods mostly developed for rivers with low sediment concentration cannot be applied for estimation of the MWDRE for rivers with hyper-concentrated sediment-laden flows. Therefore, fundamental difference between the MWDRE in the Yellow River and those in most other rivers in other countries can be identified.

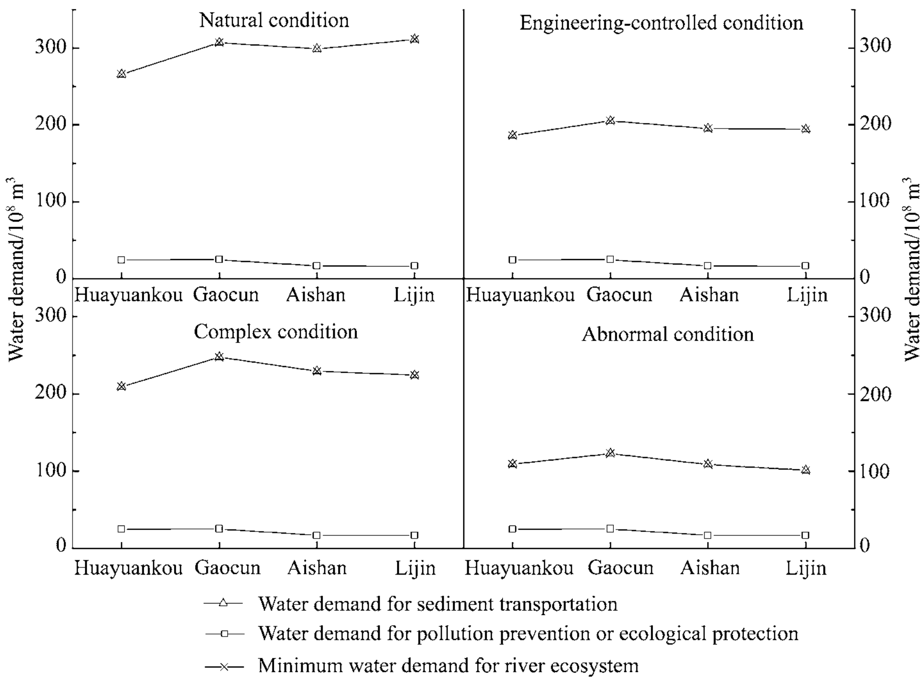

Fig. 3. Relationship among the WDST, WDPP/WDEP and the MWDRE in wet season.

Although the dry season is much longer than the wet season, it can be seen from table 2 that the amounts of incoming sediment at different reaches in the Lower Yellow River in dry season are obviously smaller than those in wet season, and will not exceed 20 percent of the annual incoming sediment. However, the river characterized by high sediment concentration makes the water demands for sediment transport at different reaches, as shown in fig. 4, be still higher than those for meeting other functions in dry season. Same as in wet season, when the WDST in dry season is satisfied, water requirements for other functions can be automatically met, too. Therefore, the integrated MWDRE at different reaches in the Lower Yellow River in dry season should also coincide with the amount of WDST under ideal conditions; hereby the ecological functions of the river system will be maintained.

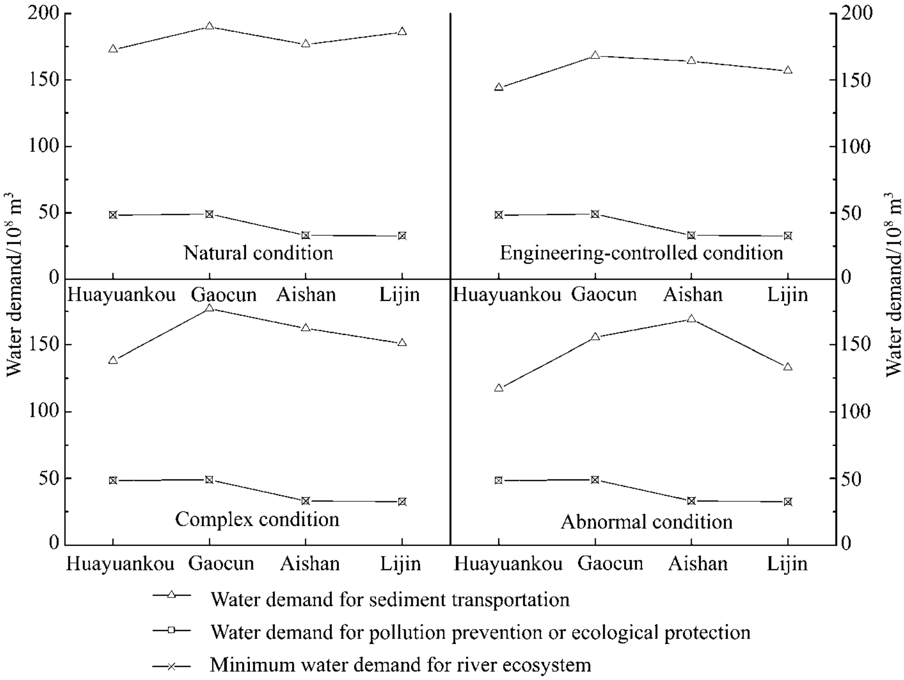

Fig. 4. Relationship among the WDST, WDPP/WDEP and the MWDRE in dry season.

However, the shortage of water resources in the Lower Yellow River does not allow low efficient water use. Taking the amount of water required to transport per unit mass of sediment in the stream flow to reflect the water use efficiency for sediment transport, we can see from fig.5 that the water use for transporting per ton of sediment at different reaches in dry season is generally above 3 times of what required in wet season, i.e. the sediment transport efficiency of water flow in dry season is far below that in wet season. Noting that the sediment incoming is small and sediment transport efficiency is low in dry season, the MWDRE by taking sediment transportation as the major riverine function would imply a significant waste of water resources in the Lower Yellow River, which will aggravate the existing water shortage and bring about difficulties in water resource allocation. Therefore, priority should be given to the water demands for pollution prevention and ecological protection in dry season, while determining the integrated MWDRE in the Lower Yellow River. The pollution prevention and ecological protection functions of the Lower Yellow River are indivisible from each other and of equal importance in dry season. In order to meet requirements of both functions, the larger one of the two minimum critical flows is adopted, which might as well be expressed as WDPP/WDEP here. The integrated MWDRE in dry season under different conditions of incoming water and sediment are shown in fig.4, from which the MWDRE herein coincides with the WDPP/WDEP. The water resource conditions and temporal distribution feature of sediment transportation of the Yellow River determine the choice of the predominant riverine function and the quantification of integrated MWDRE during dry season in the Lower Yellow River. Approximately 100×10^8 m^3 of water can be saved for the lower reaches on condition that part of the incoming sediment in dry season is allowed to silt in the reservoirs and river channel.

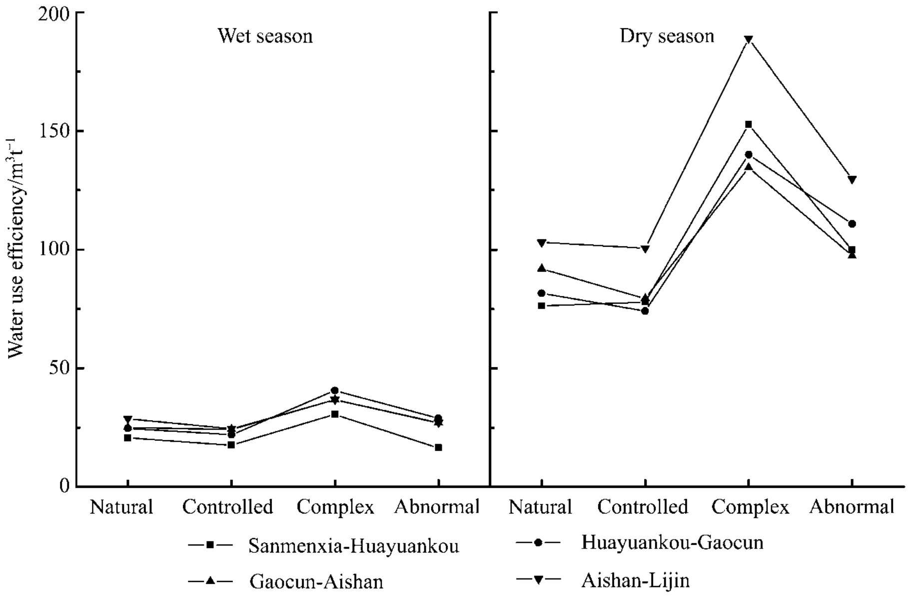

Fig. 5. Efficiency of water use for sediment transport in wet season and dry season.

During different periods, the predominant riverine function is different for varying water use efficiency. When quantifying the integrated MWDRE at different reaches in the Lower Yellow River, priority is given to the WDST in wet season and to the water demands for pollution prevention and ecological protection in dry season. Therefore, the annual integrated MWDRE should be between the annual total WDST and the annual total WDPP/WDEP as shown in fig. 6. In this way, the water demands for pollution prevention and ecological protection can be satisfied in the whole year, and the incoming sediment in wet season can also be fully transported downstream. As for the dry season, although part of the incoming sediment will silt in the reservoirs and river channel, the amount of silted sediment takes up only a small part of the annual total sediment incoming. The amount of water saved from ignoring the water requirements for sediment transport in dry season and the corresponding proportion of silted sediment over the annual total sediment incoming are listed in table 3, from which a significant annual water saving over 100 × 10^8 m^3 from the WDST could be made at different reaches except in the reach from Sanmenxia to Huayuankou.

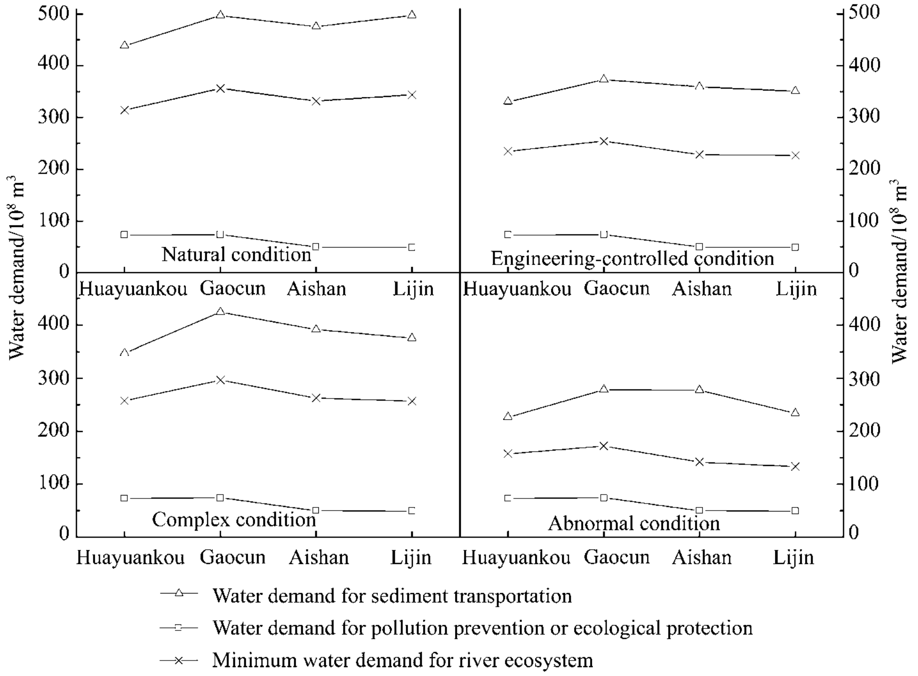

Fig. 6. Relationship among the WDST, WDPP/WDEP and the MWDRE in the whole year.

Table 3 Water saved from allowing some sediment deposition in dry season and the corresponding proportion of silted sediment to the annual total sediment incoming

Condition	SMX-HYK		HYK-GC		GC-AS		AS-LJ	
	Saved water /10^8 m^3	Silted proportaion (%)	Saved water /10^8 m^3	Silted proportaion (%)	Saved water /10^8 m^3	Silted proportaion (%)	Saved water /10^8 m^3	Silted proportaion (%)
Natural	124.36	10.81	140.89	11.70	143.72	11.31	153.41	11.80
Controlled	95.56	9.87	118.97	13.85	130.96	16.33	124.10	13.00
Complex	89.62	7.58	127.79	12.42	128.97	12.88	118.28	9.08
Abnormal	68.71	8.79	106.36	16.98	135.79	24.20	100.32	16.29

From the aforementioned discussion, the failure in fully meeting the WDST in dry season will possibly result in sediment deposition in the river. Moreover, sediment transport efficiency in wet season is much higher than that in dry season in rivers with high sediment concentration. On the annual basis, sediment transport efficiency could be modified with help of hydraulic engineering works by regulating or controlling the incoming water and sediment combinations, e.g. to accumulate sediment incoming in the reservoir in dry season and to flush it downstream intensively in wet season. The result of calculation shows that, by flushing down the incoming sediment of the whole year at the wet season, separately a volume of 4.947, 6.584, 8.899 and 7.256 billion m^3 of water can be saved at 4 main reaches below the Sanmenxia Station under abnormal condition of incoming water and sediment in 1990s, which takes up 20%—40 % of the average annual water incoming under abnormal condition at every reach. Consequently, the sediment deposition in the river channel can be lightened and the water use efficiency can be improved. Recent studies1) and practice[18] indicate that, by controlling the sediment concentration, the discharge and the time of the released flow from a reservoir, the WDST can be controlled and the water use efficiency for sediment transport can be enhanced greatly. Since the WDST is the principal part of the MWDRE in rivers with high sediment concentration, the improvement of water use efficiency for sediment transport implies the increase of water use efficiency for river sustainability.

4 Conclusions

One of the significant characteristics of the rivers with hyper-concentrated sediment-laden flow is the special requirement of flow for sediment transport, which dominates the riverine ecosystem functions. This unique characteristic makes conventional methods inappropriate for calculating the MWDRE in the Yellow River. The main conclusions drawn in this paper are as follows:

(i) Much more water is required for sediment transport in the Yellow River owing to its high sediment concentration in its flows. Moreover, the water demand for sediment transport is much larger than those for other riverine functions, i.e. the WDST accounts for the absolute majority of the MWDRE.

(ii) In wet seasons, once the WDST is satisfied, the major part of the annual incoming sediment can be transported downstream, and the water demands for other riverine functions can be satisfied automatically. Under this circumstance, the MWDRE is identical to the WDST.

(iii) In dry seasons, the water demands for all river functions can also be satisfied if the WDST is met, but the low sediment transport efficiency will result in significant waste of water resources. In view of efficient use of water resources, the MWDRE in dry seasons should be determined preferably by the largest critical water demands for other functions except sediment transport.

(iv) As the sediment transport efficiency in wet season is much higher than that in dry season in the Yellow River, hydraulic engineering works could be resorted to regulate or control the release of water and sediment, which makes the incoming sediment in dry seasons to be transported downstream intensively in wet seasons, the sediment deposition to be decreased in the channel, the MWDRE to be reduced, and the water use efficiency to be improved.

Acknowledgements The project was supported by the Major State Basic Research Program of China (No.1999043603).

---

1) Liu Xiaoyong, Water demand for sediment transport and its control methods in the Lower Yellow River, Dissertation for Doctor Degree (in Chinese), Peking University, 2003.

References

1. Qian Zhengying, Zhang Guangdou (ed.), The Comprehensive Report and Special Reports on Water Resources Strategic Research for China's Sustainable Development (in Chinese), Beijing: China Hydraulic and Hydroelectric Press, 2001, 15—16.
2. Yang Zhenhuai, Cui Zongpei, Xu Qianqing, et al. (ed.), Chinese Encyclopedia on Water Conservancy, vol.2, Beijing: China Hydraulic and Hydroelectric Press, 1990, 853.
3. Ni Jinren, Cui Shubin, Li Tianhong, et al., On water demand of river ecosystem, Journal of Hydraulic Engineering (in Chinese), 2002, (9): 14—19.
4. Smakhtin, V. U., Low flow hydrology: a review, Journal of Hydrology, 2001, 240: 147—186.
5. Reiser, D. W., Wesche, T. A., Status of instream flow legislation and practice in North America, Fisheries, 1989, 14: 22—29.
6. Espegren, G. D., Evaluation of the standards and methods used for quantifying instream flows in Colorado, Final Report, Colorado Water Conservation Board, Denver, Colorado, 1998,18.
7. King, J. M., Tharme, R. E., Assessment of the instream flow incremental methodology and initial development of alternative instream flow methodologies for South Africa, Water Research Commission Report No. 295/ 1/ 94,Water Research Commission, Pretoria, 1994, 590.
8. Stanlnaker, C. B., Lamb, B. L., Henriksen, J., et al., The instream flow incremental methodology: a primer for IFIM, National Ecology Research Center, Colorado: International Publication, 1994, 99.
9. King, J. M., Louw, M. D., Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology, Aquatic Ecosystem Health and Management, 1998, 1: 109—124.
10. Arthington, A. H., King, J. M., O'Keefee, J. H., et al., Development of an holistic approach for assessing environmental flow requirements of riverine ecosystem, in Proceedings of an International Seminar and Workshop on Water Allocation for the Environment (eds. Pigram, J. J., Hooper, B. P.), The Centre for Water Policy Research, University of New England, Armidale, Australia, 1991, 69—76.
11. Ni Jinren, Jin Ling, Zhao Yean, et al., Minimum water demand for ecosystem protection in the Lower Yellow River, Journal of Hydraulic Engineering (in Chinese), 2002, (10): 1—7.
12. Liu Xiaoyong, Li Tianhong, Zhao Yean, et al., Water demand for sediment transport in the Lower Yellow River, Journal of Basic Science and Engineering (in Chinese), 2002, 10(3): 253—262.
13. Yue Dejun, Hou Suzhen, Zhao Yean, et al., Study of water volume delivering sediment in the Lower Yellow River,Yellow River (in Chinese), 1996, (8): 32—33.
14. Zhao Wenlin (ed.), Sediment in the Yellow River (in Chinese), Zhengzhou: Yellow River Conservancy Press, 1996, 99—114, 705—746.
15. Fei Xiangjun, The mechanics and application of long-distance sediment transport by hyper-concentrated flow, Journal of Sediment Research (in Chinese), 1998, (3): 55—61.
16. Qi Pu, Sun Zanying, Ru Yuying, et al., Changes of runoff and sediment load and ponders of training of the Lower Yellow River, Journal of Sediment Research (in Chinese), 1999, (4): 12—19.
17. Chen Jiwei (ed.), Harness and Development of the Water Resources in the Yellow River, Integrated Volume (in Chinese), Zhengzhou: Yellow River Conservancy Press, 1998, 4.
18. Li Guoying, Water and sediment regulation in the Yellow River, Yellow River (in Chinese), 2002, 24(11): 1—5.