Estimation of environmental flow requirements for the river ecosystem in the Haihe River Basin, China

Tao Yang, Jingling Liu, Qiuying Chen, Jing Zhang and Yi Yang

ABSTRACT

The temporal and spatial environmental flow requirements (EFRs) for the river ecosystem of the Haihe River Basin were analyzed based mainly on the eco-functional regionalization of available water resources. The annual EFRs for the river ecosystem of the Haihe River Basin were 47.71×10^8 m^3, which accounted for 18% of the average annual flow (263.9×10^8 m^3). The EFRs for river reaches, wetlands, and estuaries were 22.67, 15.32 and 9.72×10^8 m^3, respectively. Moreover, the EFRs for the river ecosystem during the wet (June to October), normal (April, May, November), and dry (December to March) periods were 29.99, 9.51 and 8.21×10^8 m^3, respectively. Thus, toward a more integrated water resource allocation in the Haihe River Basin, the primary effort should focus on meeting the EFRs for river systems located in protected areas during the dry period.

Key words | environmental flow requirements, Haihe River Basin, river ecosystem

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INTRODUCTION

At present, many river ecosystems have been degraded extensively due to the increasing number of human population throughout the world and the corresponding overuse of water resources (Hofman *et al.* 2010). Such overuse has led to the emergence of a wide range of ecological crises in these areas (Gleick 1998). Specifically, the irrigation of agricultural lands, hydropower generation, and utilization for industrial and domestic water supply have had adverse effects on river ecosystems (Tharme 2003). The importance of implementing sustainable water resource management (Song *et al.* 2010), which ensures the integrity of a river ecosystem and the preservation of safe water resources, has become a relevant issue in various sectors of society (Acreman & Dunbar 2004).

Some water areas along a river must be preserved to ensure sustainable river ecological processes, continuously meet the needs of the population, and maintain the biodiversity of the river ecosystem (Poff *et al.* 1997, 2010). Preserving and restoring the natural flow regime (Alonso-González *et al.* 2008) and the healthy ecological functions of the river ecosystem are the key principles in river ecosystem management (Richter *et al.* 1996; Arthington *et al.* 2006). Environmental flow assessment is mainly used in water resource management (Gupta 2008) to maintain the integrity of the river ecosystem. This is achieved by adjusting the flow regime to make it as close as possible to natural conditions (Rapport *et al.* 1998). The proper assessment of the environmental flow requirements (EFRs) for degraded river ecosystems has become a major issue in the field of integrated water resource management (Love *et al.* 2006).

The approaches developed to determine the EFRs of a river ecosystem can be grouped into four types: the hydrological method, hydraulic method, habitat simulation method, and the holistic method. Each of these methods is selected based on the type of issue involved, management objectives (e.g., ecological, economic or social objectives), expertise, time and funds available. All these methods have a common characteristic, that is, they all require large amounts of hydrological, hydraulic and preferable habitat data, making it difficult to apply these methods. Alcáza *et al.* (2008) have presented a neural network model that considers hydrological and physical watershed characteristics to estimate the environmental flow of the Spanish Ebro River Basin. Yang *et al.* (2009) proposed a base flow index, through which they estimate the EFRs for the integrated water resource allocation in the Yellow River Basin in China. Alcáza & Palau (2010) utilized principal component analysis (PCA) and cluster analysis (CA) to establish the environmental flow regimes of the Spanish Ebro River Basin.

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However, these studies have been conducted in areas where the water resources are relatively abundant or the ecological integrity level is relatively well developed. In comparison, the Haihe River Basin is an area of seriously scarce water resources; moreover, the structure and function of the river ecosystem are extensively degraded by intensive human activities. The EFRs for a river ecosystem like the Haihe River Basin have been assessed based on the Tennant method (Yang *et al.* 2005; Liu *et al.* 2006). The assessments, however, do not consider the eco-functional regionalization of the water resources, the partitioning of rivers, and their corresponding locations in the water resource eco-functional area. Thus, their EFRs assessment results are generally larger than the actual water volume that can be allocated to implement it. Hence, the EFRs for a river ecosystem could not be implemented effectively in water resource management, and the ecological integrity of the basin has not been improved effectively.

In the present study, the EFRs for a river ecosystem are assessed based on the eco-functional regionalization of the water resources and the river ecological restoration type. The objectives of the present study are as follows: (1) to develop a method to assess the EFRs, and (2) to analyze the temporal and spatial variability of the EFRs for the river ecosystem of the Haihe River Basin in China. The estimation results will allow managers to implement better water resource management strategies and to improve the ecological integrity level of the basin.

MATERIALS AND METHODS

Study area

The Haihe River Basin (E112°00′to N35°00′-N43°00′) is a semi-arid and semi-humid area with a total size of 318,200 km^2. It is one of the seven major river basins in China. The climate of this region is characterized as a temperate continental monsoon type with an annual average rainfall of 480 mm. Average annual evaporation is 470 mm in land and 1,100 mm in surface water. There are four major river systems in the area, namely, the Tuhaimajia River System, Southern Haihe River System, and the Northern Haihe River Systems, as well as the Luan River and Coastal River Systems of Eastern Hebei Province (Table 1).

The average annual water resource of the Haihe River Basin is 370×10^8 m^3, due to the scarce surface water. The underground water, accounting for 65% of the available water resources, is the major source for living and industrial activities. There are many underground water cones of depression in the area for excessive exploitation of the underground water resources. The water resource development ratio was 108%, whereas the disposal ratio of wastewater was less than 40% in 2010. A large amount of non-disposed domestic sewage and industrial wastewater comprise the major water sources for the EFRs for the river ecosystem. Thus, the natural structure and function of the river ecosystem of the Haihe River Basin is degraded, and its ecological integrity is low.

Many large cities, such as Beijing and Tianjin, are located in the area (Figure 1). Ensuring the safe water resource supply and the ecological integrity of the river ecosystem are important factors for the sustainable development of the area. Therefore, the degraded river ecosystem and the ecological integrity of the Haihe River Basin must be restored and improved immediately.

EFRs methodology and method development

Considering the spatial structure of the river ecosystem, the EFRs for a river ecosystem comprise three components, namely the EFRs for river reaches, wetlands, and estuaries. The calculation method for the EFRs for a river ecosystem is as follows: (1) the respective EFRs for the river channels, wetlands, and estuaries are calculated; this is followed by (2) calculation of the EFRs for the different river reaches of the same river system; and (3) the calculation of the monthly and annual EFRs for the different river systems at the river

Table 1 | The values of ξ with three guarantee ratios

	Flood season (Jun. to Sep.)			**Non-flood season (Oct. to May)**		
Sub-ecosystem	**Poor (75% guarantee ratio)**	**Moderate (50% guarantee ratio)**	**Good (25% guarantee ratio)**	**Poor (75% guarantee ratio)**	**Moderate (50% guarantee ratio)**	**Good (25% guarantee ratio)**
River reach	0.25	0.50	0.70	0.20	0.30	0.45
Wetland	0.20	0.45	0.65	0.15	0.25	0.40
Estuary	0.15	0.40	0.60	0.10	0.20	0.35

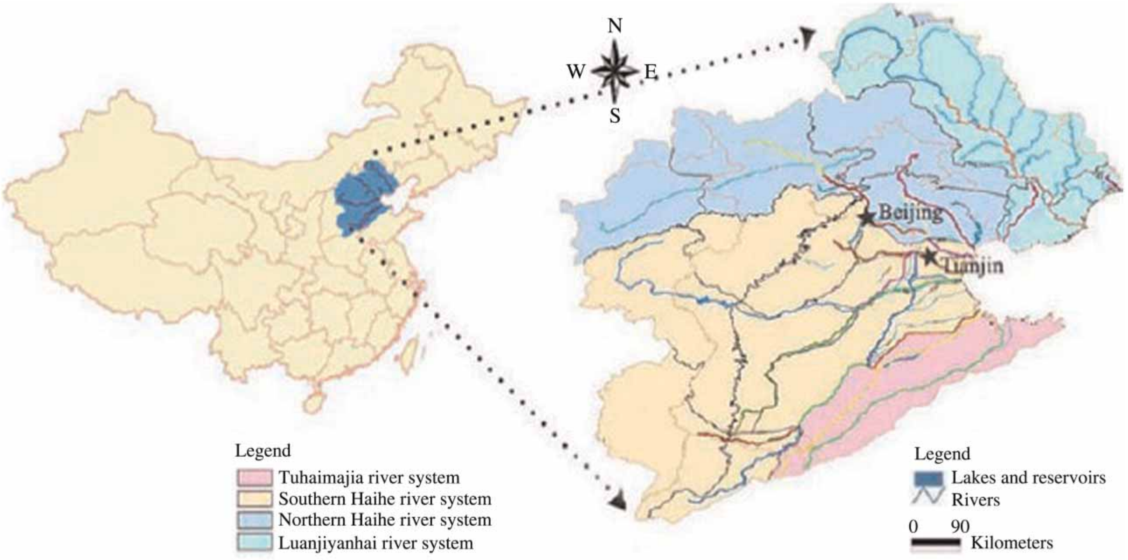

Figure 1 | The water system map of the Haihe River Basin.

basin scale. Therefore, the temporal and spatial EFRs for a river ecosystem can be determined using the detailed calculation method reported in our previous work (Yang *et al.* 2005). The assurance coefficient of the EFRs proposed in our study is a very important parameter in determining the EFRs for a river ecosystem.

The assurance coefficient of the EFRs

In the present study, the assurance coefficient of the EFRs consists of three parameters, namely, the assurance coefficients of: (1) the base flow (ξ), (2) the water resource eco-functional area (α), and (3) the river ecological restoration type (β).

The assurance coefficient of base flow (ξ) is a very important parameter in assessing the EFRs for a river ecosystem (Liu *et al.* 2005). Its value ranges from 0 to 1. In our work, this parameter was identified based on: (1) the recommended percentage of average annual natural flow determined using the Tennant method, and (2) the calibration factor a_i (i.e., the ratio of annual natural flow to the average annual flow with three guarantee ratios of 25, 50, and 75%). The assurance coefficient of the base flow was determined using the following equations:

$$\xi = \max(a_i) \times 0.1 \tag{1}$$

$$a_i = \frac{Q_{ki}}{Q_n} \tag{2}$$

In Equation (2) above, Q_{ki} is the annual natural flow of the k sub-ecosystem (i.e., rivers, wetlands, and estuaries) with i as the guarantee ratio (25, 50, and 75%) (10^8 m^3/year); Q_n is the average annual flow (10^8 m^3/year); and a_i is the calibration factor with the 25, 50, and 75% guarantee ratios. The values of ξ with these guarantee ratios are shown in Table 1.

According to the results of the National Water Resources Planning and Regionalization (MWR 2002), the Haihe River Basin is categorized into four water resource eco-functional areas, namely, the protected area (PA), the reserved area (RA), the buffer area (BA), and the development and utilization area (DUA) (Lin *et al.* 2002). Ecological restoration level of these is in decreasing order, and water resources allocation for EFRs in the four areas also decrease (Lu *et al.* 2010). The 21 river reaches within the Haihe River Basin can be grouped into three types based on their specific degraded characteristics (Shi *et al.* 2010): habitat recovery type (HR), water quality recovery type (WQR), and vegetation recovery substitute water quantity recovery type (VRSWQR). According to the recommended percentage of average annual flow based on the Tennant method, and the ecological service function of the four water resource eco-functional areas, the values of the assurance coefficients of the four eco-functional areas (α) were then computed. The results are shown in Table 2. The values of the assurance coefficients of the river ecological restoration type (β) were also computed. The results are shown in Table 3.

Table 2 | Values of the assurance coefficients of the water resource eco-functional area (α)

Water resource eco-functional area	Coefficient (α) (Oct. to Mar.)	Water resource eco-functional area	Coefficient (α) (Apr. to Sep.)
PA	1	PA	1
RA	0.67–0.8	RA	0.67–0.83
BA	0.67–0.8	BA	0.67–0.83
DUA	0.2–0.6	DUA	0.33–0.67

Table 3 | Values of the assurance coefficients of the river ecological restoration type (β)

River ecological restoration type	Value of β
VRSWQR	0.6–0.9
WQR	1.8–1.9
HR	1.5–1.8

EFRs for the river channels

The EFRs for the river channels are determined using the following equation:

$$Q_L = \sum_{i=1}^{N} \xi_1 \times \alpha_i \times \frac{l_i}{L} \times \beta \times Q_n \tag{3}$$

where Q_L is the EFR for the river channel [(m^3/month) ($\times 10^8$ m^3)], ξ_1 is the assurance coefficient of base flow for the river channel, α_i is the assurance coefficient of the ith water resource eco-functional area, l_i is the length of the river reach located in the ith water resource eco-functional area (km), L is the total length of the river reaches (km), β is the assurance coefficient of a river ecological restoration type, and Q_n is the average monthly flow [(m^3/month) ($\times 10^8$ m^3)].

EFRs for the wetlands

The EFRs for the wetlands consist of three components, namely, the respective EFRs for wetland vegetation, wetland soil, and those that preserve suitable habitats for wild animals. Thus, the EFRs for the wetlands represent the summation of these three components. Moreover, the compatible rule or the 'maximum' principle (Yang *et al.* 2009) is also used to assess EFRs for the wetlands, which can be determined using the following equation:

$$W_w = \{W_p + W_b + \xi_2 \times \alpha [Q_s + \mathrm{Max}(W_q, Q_e) + W_n + W_y]\}/T \tag{4}$$

where W_p is the EFR for wetland vegetation [(m^3/month) ($\times 10^8$ m^3)], W_b is the water volume that groundwater supplements the wetland [(m^3/month) ($\times 10^8$ m^3)], ξ_2 is the assurance coefficient of base flow for wetland, α is the assurance coefficient of a water resource eco-functional area; Q_s is the EFRs for wetland soil [(m^3/month) ($\times 10^8$ m^3)], W_q is the EFRs that preserves suitable habitats for wild animals [(m^3/month) ($\times 10^8$ m^3)], Q_e is the EFRs that preserves suitable wetland landscape and entertainment for human beings [(m^3/month) ($\times 10^8$ m^3)], W_n is the EFRs that protects the coast from erosion [(m^3/month) ($\times 10^8$ m^3)], W_y is the EFRs for salt-dissolution and salt-washing [(m^3/month) ($\times 10^8$ m^3)], and W_n and W_y represent specific parameters that determine the EFRs for the coastal wetland. Therefore, W_n and W_y are zero for the inland wetland. Moreover, T is the coefficient of water exchange for a wetland (day). The calculation procedure of the above parameters is presented detailed by Cui & Yang (2002) and Yang *et al.* (2003).

EFRs for the estuaries

The EFRs for the estuaries consist of three components, namely, the respective EFRs for estuarine water circulation [(m^3/month) ($\times 10^8$ m^3)], estuarine animal metabolism [(m^3/month) ($\times 10^8$ m^3)], and those that preserve suitable habitats for estuarine animals [(m^3/month) ($\times 10^8$ m^3)]. EFRs for the estuaries represent the summation of these three components. These can be determined by the following equation:

$$F = F_a + \xi_3 \times \alpha (F_b + F_c) \tag{5}$$

where ξ_3 is the assurance coefficient of base flow for the estuary, α is the assurance coefficient of a water resource eco-functional area, F_a is the EFRs for estuarine water circulation [(m^3/month) ($\times 10^8$ m^3)], F_b is the EFRs that maintains natural metabolism for estuarine animals [(m^3/month) ($\times 10^8$ m^3)], and F_c is the EFRs that preserves suitable habitats for estuarine animals [(m^3/month) ($\times 10^8$ m^3)]. The calculation procedure of the above parameters is presented in detail by Sun & Yang (2005).

RESULTS AND DISCUSSION

The hydrological data were obtained from the Haihe River Water Conservancy Commission. Based on the average monthly natural flow data from 1956 to 1984, the ecological

Table 4 | River reach distributions in the water resource eco-functional areas and the corresponding restoration types

River system	River reach	Length of the river reach (km)	Length of the river reach located in water resource eco-functional areas (km)	Ecological restoration types
LRCRSEHP	LR	158	PA, 158	HR
	DR	120	DUA, 120	HR
NHRS	JC	189	BA, 76.4; DUA, 112.6	HR
	CBR	80	PA, 24; BA, 27; DUA, 29	HR
	NC	129	BA, 45.7; DUA, 83.3	HR
	YDR	166	BA, 144; DUA, 22	VRSWQR
SHRS	BGR	54	PA, 54	VRSWQR
	SJR	70	PA, 70	VRSWQR
	TR	140	BA, 47; DUA, 93	VRSWQR
	ZLR	96	RA, 96	VRSWQR
	HTR			
	HBZR-ST	59.2	DUA, 190	VRSWQR
	ST-XX	130.8		HR
	FYR	329	DUA, 329	HR
	ZYR	162	PA, 17; BA, 93.5; DUA, 51.5	HR
	ZR	114	DUA, 114	VRSWQR
	WR	272	RA, 39.4; DUA, 232.6	WQR
	WC	157	BA, 157	WQR
	SC	150	PA, 150	HR
	MSHR	72	PA, 33.5; BA, 38.5	HR
	ZWXR	165	BA, 165	WQR
THMJRS	THR	418	BA, 159.8; DUA, 158.2	WQR
	MJR	426	PA, 285; BA, 27; DUA, 114.2	HR

LRCRSEHP: Luan River and Coastal River Systems of Eastern Hebei Province; NHRS: Northern Haihe River Systems; SHRS: Southern Haihe River System; THMJRS: Tuhaimajia River System. LR: Luan River; DR: Dou River; JC: Ji Canal; YBR: Chaobai River; NC: North Canal; YDR: Yongding River; BGR: Baigou River; SJR: South Juma River; TR: Tang River; ZLR: Zhulong River; HTR: HutuoRiver (HBZR-ST: Huangbizhuang Reservoir-Shaotong Village; ST-XX: Shaotong Village-Xianxian); FYR: Fuyang River; ZYR: Ziya River; ZR: Zhang River; WR: Wei River; WC: Wei Canal; SC: SouthCanal; MSHR: Main stream of the Haihe River; ZWXR: Zhangweixin River; THR: Tuhai River; MJR: Majia River.

restoration types of the 21 river reaches (Table 4), and the water resource eco-functional areas of the Haihe River Basin are presented in Tables 4, 5, and 6. The monthly and annual EFRs for the 21 river reaches, 12 wetlands, and three estuaries of the Haihe River Basin were also calculated, with the results shown in Tables 7, 8 and 9, respectively.

Temporal variability of the EFRs for the river ecosystem

The monthly EFRs for river reaches are maximal in August at 5.49×10^8 m^3 and minimal in February at 1.19×10^8 m^3 (Figure 2). The monthly EFRs for the wetlands are maximal in June, July, and August at 9.40×10^8 m^3 and minimal in December, January and February at 4.27×10^8 m^3. The monthly EFRs for the estuaries are maximal in August at 2.05×10^8 m^3, and are minimal in February at 0.004×10^8 m^3. Furthermore, the EFRs for the river ecosystem during the wet (June to October), normal (December to March), and

Table 5 | Distributions of the 12 wetlands in the water resource eco-functional areas

River system	Wetland	Coverage (km^2)	Water resources eco-functional areas
NHRS	BYD	160	PA
NHRS	QLH	60	DUA
NHRS	HZW	339	DUA
NHRS	DHPW	110	DUA
NHRS	QDW	65	DUA
SHRS	NDG	98	DUA
SHRS	HSL	40	DUA
SHRS	BDG	150	DUA
SHRS	TPW	60	DUA
SHRS	DLD	50	DUA
SHRS	NJW	150	DUA
THMJRS	EXW	100	DUA

NDG: Nandagang; BYD: Baiyangdian Lake; HSL: Hengshui Lake; BDG: Beida gang; QLH: Qilihai; TPW: Tuanpowa; HZW: Huangzhuangwa; DHPW: Dahuangpuwa; DLD: Dalangdian; QDW: Qingdianwa; NJW: Ningjingwa; EXW: Enxianwa.

Table 6 | Distributions of the three estuaries in the water resource eco-functional areas

River system	Estuary	Average annual water volume flow into the Bohai Sea ($\times 10^8$ m^3)	Water resource eco-functional areas
LRCRSEHP	ELR	19.9	PA
SHRS	EHR	2.84	DUA
SHRS	EZWXR	1.7	PA

EHR: Estuary of Haihe River; ELR: Estuary of Luan River; EZWXR: Estuary of Zhangweixin River.

dry periods (April, May, November) of the Haihe River Basin are integrated and calculated by the monthly EFRs for the 21 river reaches (Table 7), the monthly EFRs for the 12 wetlands (Table 8) and the monthly EFRs for the three estuaries (Table 9), and the EFRs for the river ecosystem during the three water periods are 29.99, 9.51 and 8.21×10^8 m^3, respectively.

In addition, the Haihe River Basin is located in the semi-arid region of North China, where the precipitation has seasonality, and the annual precipitation is unbalanced. Moreover, the available water resources of the Haihe River Basin are scarce; in fact, the surface water resource only reached 115.60×10^8 m^3 in 2009 (HWCC 2009). Thus, the limited water resources should be allocated to ensure adequate EFRs during the dry period.

Spatial variability of the EFRs for a river ecosystem

Water allocation for river ecological restoration should be based on the degraded condition and the corresponding restoration objective of the river reach. The EFRs for the HR type of the river reach are 11.40×10^8 m^3, which accounts for 4.320% of the average annual flow; the EFRs for the WQR type of the river reach are 11.38×10^8 m^3, which

Table 7 | Monthly EFRs for the 21 river reaches ($\times 10^8$ m^3)

River reach	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
LR	0.050	0.050	0.100	0.130	0.080	0.110	0.550	0.590	0.250	0.160	0.120	0.060	2.250
DR	0.000	0.000	0.000	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.010	0.000	0.080
JC	0.000	0.000	0.000	0.000	0.000	0.030	0.030	0.040	0.030	0.010	0.000	0.000	0.140
CBR	0.040	0.040	0.060	0.050	0.030	0.050	0.260	0.400	0.160	0.100	0.070	0.040	0.330
NC	0.050	0.040	0.040	0.020	0.020	0.020	0.070	0.120	0.050	0.040	0.030	0.050	0.100
YDR	0.020	0.010	0.020	0.010	0.030	0.040	0.060	0.070	0.050	0.030	0.010	0.020	0.350
BGR	0.010	0.010	0.010	0.010	0.010	0.020	0.020	0.040	0.020	0.020	0.010	0.010	0.160
SJR	0.010	0.010	0.010	0.010	0.010	0.020	0.030	0.030	0.020	0.010	0.010	0.010	0.110
TR	0.010	0.010	0.010	0.020	0.030	0.030	0.030	0.030	0.030	0.010	0.010	0.010	0.210
ZLR	0.010	0.020	0.020	0.020	0.030	0.040	0.060	0.070	0.050	0.030	0.010	0.010	0.370
HTR													
HBZR-ST	0.020	0.020	0.050	0.080	0.130	0.080	0.070	0.170	0.110	0.050	0.040	0.020	0.830
ST-XX	0.010	0.010	0.010	0.020	0.030	0.040	0.040	0.030	0.030	0.020	0.010	0.010	0.230
FYR	0.010	0.010	0.010	0.020	0.030	0.030	0.030	0.030	0.030	0.020	0.010	0.010	0.210
ZYR	0.090	0.100	0.100	0.070	0.080	0.090	0.200	0.670	0.500	0.260	0.160	0.110	2.430
ZR	0.010	0.010	0.010	0.020	0.020	0.020	0.020	0.030	0.020	0.020	0.010	0.010	0.180
WR	0.350	0.350	0.420	0.350	0.350	0.280	0.600	0.840	0.460	0.460	0.670	0.280	5.410
WC	0.300	0.240	0.130	0.090	0.110	0.090	0.540	1.240	0.700	0.610	0.370	0.240	4.660
SC	0.130	0.100	0.090	0.100	0.100	0.090	0.220	0.500	0.310	0.270	0.190	0.130	2.230
MSHR	0.030	0.020	0.040	0.050	0.080	0.100	0.100	0.100	0.080	0.030	0.040	0.030	0.700
ZWXR	0.006	0.010	0.006	0.008	0.008	0.009	0.120	0.290	0.090	0.130	0.010	0.006	0.690
THR	0.020	0.020	0.020	0.020	0.040	0.040	0.100	0.140	0.120	0.060	0.040	0.020	0.640
MJR	0.010	0.010	0.020	0.020	0.030	0.040	0.050	0.050	0.050	0.040	0.030	0.010	0.360
Total	1.190	1.090	1.180	1.130	1.260	1.280	3.210	5.490	3.170	2.390	1.860	1.090	22.670

Table 8 | Monthly EFRs for the 12 wetlands ($\times 10^8$ m^3)

Wetland	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
BYD	0.74	0.74	0.91	0.91	0.91	1.58	1.58	1.58	0.86	0.86	0.86	0.74	2.63
QLH	0.10	0.10	0.12	0.12	0.12	0.20	0.20	0.20	0.11	0.11	0.11	0.10	0.35
HZW	0.61	0.61	0.75	0.75	0.75	1.29	1.29	1.29	0.71	0.71	0.71	0.61	2.16
DHPW	0.38	0.38	0.48	0.48	0.48	0.82	0.82	0.82	0.45	0.45	0.45	0.38	1.37
QDW	0.17	0.17	0.20	0.20	0.20	0.36	0.36	0.36	0.19	0.19	0.19	0.17	0.57
NDG	0.48	0.48	0.53	0.53	0.53	0.90	0.90	0.90	0.53	0.53	0.53	0.48	1.37
HSL	0.22	0.22	0.32	0.32	0.32	0.55	0.55	0.55	0.27	0.27	0.27	0.22	0.97
BDG	0.80	0.80	1.24	1.24	1.24	2.11	2.11	2.11	1.10	1.10	1.10	0.80	3.19
TPW	0.32	0.32	0.40	0.40	0.40	0.66	0.66	0.66	0.37	0.37	0.37	0.32	1.11
DLD	0.10	0.10	0.12	0.12	0.12	0.21	0.21	0.21	0.11	0.11	0.11	0.10	0.36
NJW	0.10	0.10	0.12	0.12	0.12	0.20	0.20	0.20	0.11	0.11	0.11	0.10	0.35
EXW	0.25	0.25	0.31	0.31	0.31	0.52	0.52	0.52	0.28	0.28	0.28	0.25	0.89
Total	4.27	4.27	5.50	5.50	5.50	9.40	9.40	9.40	5.09	5.09	5.09	4.27	15.32

Table 9 | Monthly EFRs for the three estuaries ($\times 10^8$ m^3)

Estuary	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.	Total
ELR	0.0013	0.0065	0.0260	0.0800	0.1900	0.3600	0.5200	0.6200	0.5200	0.3600	0.1900	0.0800	2.9538
EHR	0.0017	0.0084	0.0340	0.1000	0.250	0.4600	0.6700	0.8100	0.6700	0.4600	0.2500	0.1000	3.8141
EZWXR	0.0013	0.0065	0.0260	0.0800	0.1900	0.3600	0.5200	0.6200	0.5200	0.3600	0.1900	0.0800	2.9538
Total	0.0043	0.0214	0.0860	0.2600	0.6300	1.1800	1.7100	2.0500	1.7100	1.1800	0.6300	0.2600	9.7217

accounts for 4.312% of the average annual flow; and the EFRs for the VRSWQR type of the river reach are 1.54×10^8 m^3, which accounts for 0.584% of the average annual flow (Tables 4 and 7).

The annual EFRs for the four river systems in the Haihe River Basin (Figure 3), namely, the LRCRSEHP, the NHRS, the SHRS, and the THMJRS are 5.25×10^8, 8.00×10^8, 32.54×10^8 and 1.89×10^8, respectively. The annual EFRs

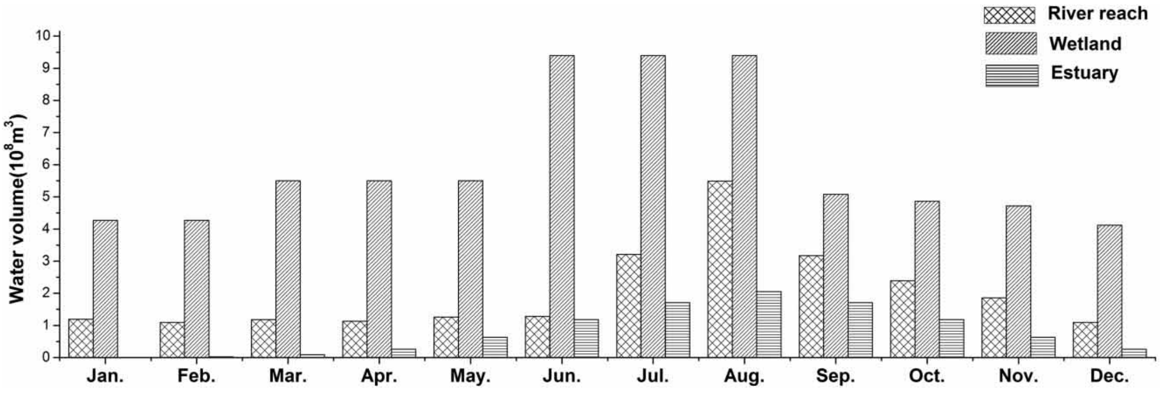

Figure 2 | Temporal variabilities of EFRs for the Haihe River Basin.

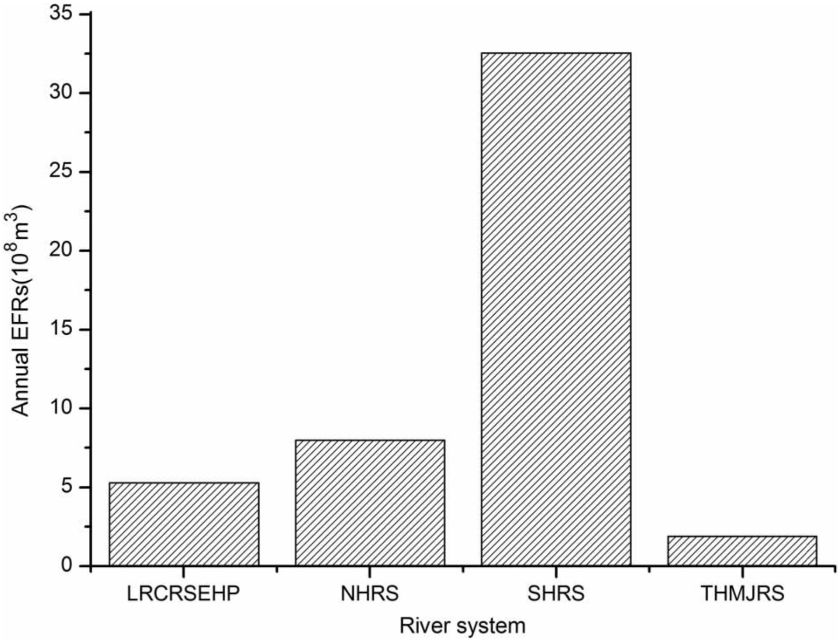

Figure 3 | Annual EFRs for the four river systems in the Haihe River Basin.

for the river reaches, wetlands, and estuaries are 22.67, 15.32 and 9.72 × 10^8 m^3, respectively (Tables 7, 8, and 9). Therefore, the annual EFRs for the river ecosystem of the Haihe River Basin are 47.71 × 10^8 m^3, which accounts for 18% of the average annual flow (263.9 × 10^8 m^3).

CONCLUSIONS

Assessing the EFRs for a river ecosystem and properly managing the allocation of water resources to meet the EFRs are very important in restoring a degraded river ecosystem. Water resource scarcity and river ecosystem degradation are the two main eco-environmental problems faced by the Haihe River Basin, a developed area in China. The EFR assessment should be based on the eco-functional regionalization of the water resources and the river ecological restoration type.

In addition, water allocation for river ecological restoration should consider temporal and spatial variability of the EFRs. For temporal variability of the EFRs, the EFRs for the river ecosystem during the wet (June to October), normal (December to March), and dry periods (April, May, November) are 29.99, 9.51 and 8.21 × 10^8 m^3, respectively. The annual EFRs for the river ecosystem of the Haihe River Basin are 47.71 × 10^8 m^3, which accounts for 18% of the average annual flow (263.9 × 10^8 m^3). Moreover, for spatial variability of the EFRs, the annual EFRs for the river reaches, the wetlands, and the estuaries are 22.67, 15.32 and 9.72 × 10^8 m^3, respectively.

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REFERENCES

Acreman, M. & Dunbar, M. J. 2004 Defining environmental river flow requirements – a review. *Hydrology and Earth System Sciences* **8** (5), 861–876.

Alcáza, J. & Palau, A. 2010 Establishing environmental regimes in a Mediterranean watershed based on a regional classification. *Journal of Hydrology* **388** (1–2), 41–51.

Alcáza, J., Palau, A. & Vega-Garcìa, C. 2008 A neural net model for environmental flow estimation at the Ebro River Basin, Spain. *Journal of Hydrology* **349** (1–2), 44–55.

Alonso-González, C., Gortázar, J., Baeza Sanz, D. & García de Jalón, D. 2008 Dam function rules based on brown trout flow requirements: design of environmental flow regimes in regulated streams. *Hydrobiologia* **609** (1), 253–262.

Arthington, A. H., Bunn, S. E., Poff, N. L. & Naiman, R. J. 2006 The challenge of providing environmental flow rules to sustain river ecosystems. *Ecological Applications* **16**, 1311–1318.

Cui, B. S. & Yang, Z. F. 2002 Water consumption for eco-environmental aspect on wetlands. *Chinese Journal of Environmental Science* **22** (2), 219–224 (in Chinese).

Gleick, P. H. 1998 Water in crisis: paths to sustainable water use. *Ecological Applications* **8** (3), 571–579.

Gupta, A. D. 2008 Implication of environmental flow in river basin management. *Physics and Chemistry of the Earth* **33** (5), 298–303.

Haihe River Conservancy Commission of the Ministry of Water Resources 2009 Water Resources Bulletin of Haihe River Basin (in Chinese).

Hofman, J., Hofman-Caris, R., Nederlof, M., Frijns, J. & Loosdrecht, M. V. 2010 Water and energy as inseparable twins for sustainable solutions. *Water Science and Technology* **63** (1), 88–92.

Lin, C., Lu, Z. L., Zhi, D. G. & Guo, Y. 2002 Study on Eco-environmental Restoration of Haihe River Basin. *Water Resourcess and Water Environment Carrying Capacity Symposium*. China Water Science Information Network, Beijing (http://www.chinawater.net.cn/cwsnet/szycz/w020522-1.htm).

Liu, J. L., Yang, Z. F., Lin, C. & Wang, Q. 2006 Research on the rule of river basin eco-system demand. *China Water Resources* **13**, 18–21 (in Chinese).

Liu, J. L., Yang, Z. F., Xiao, F. & Sun, T. 2005 Conformity calculation models on river ecological basic flows. *Chinese Journal of Environmental Science* **25** (4), 436–441 (in Chinese).

Love, F., Madamombe, E., Marshall, B. & Kaseke, E. 2006 Preliminary estimate of environmental flow requirements of the Rusape River, Zimbabwe. *Physics and Chemistry of the Earth* **31** (15–16), 864–869.

Lu, Z. L., Zhang, S. H., Lin, C. & Liu, D. W. 2010 Study on ecological protection and recovery mode of plain rivers in the Haihe River Basin. 1st edition. *China Water Power Press*. Beijing, China, 67–76 (in Chinese).

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., Sparks, R. E. & Stromberg, J. C. 1997 The natural flow regime: a paradigm for river conservation and restoration. *Bioscience* **47** (11), 769–784.

Poff, N. L. & Zimmerman, J. K. H. 2010 Ecological responses to altered flows regimes: a literature review to inform the science and management of environmental flow. *Freshwater Biology* **55** (1), 194–205.

Rapport, D. J., Costanza, R. & McMichael, A. J. 1998 Assessing ecosystem health. *Trends in Ecology and Evolution* **13** (10), 397–402.

Richter, B. D., Baumgartner, J. V., Powell, J. & Braun, D. P. 1996 A method for assessing hydrological alteration within ecosystems. *Conservation Biology* **10** (4), 1163–1174.

Shi, W., Hou, S. Y., Cui, W. Y., Liu, D. W. & Lin, C. 2010 Calculation of the ecological water demand of plain rivers in the Haihe River Basin based on river ecological types classification. *Journal of Agro-Environmental Science* **29** (10), 1892–1899 (in Chinese).

Song, X., Ravesteijn, W., Frostell, B. & Wennersten, R. 2010 Managing water resources for sustainable development: the case of integrated river basin management in China. *Water Science and Technology* **61** (2), 499–506.

Sun, T. & Yang, Z. F. 2005 Study on the approaches for quantifying the environmental flow in estuaries. *Chinese Journal of Environmental Science* **25** (5), 573–579 (in Chinese).

Tharme, R. E. 2003 A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. *River Research Application* **19** (5–6), 397–441.

The Ministry of Water Resources of the People's Republic of China 2002 *Water Resourcess Regionalization Program of China*, Beijing, China (in Chinese).

Yang, Z. F., Sun, T., Cui, B. S., Chen, B. & Chen, G. Q. 2009 Environmental flow requirements for integrated water allocation in the Yellow River Basin, China. *Communications in Nonlinear Science and Numerical Simulation* **14** (5), 2469–2481.

Yang, Z. F., Liu, J. L., Xiao, F., Jiang, J. & Lin, C. 2005 Conformity calculation of river ecological basic flows in the Haihe River Basin. *Chinese Journal of Environmental Science* **25** (4), 442–448 (in Chinese).

Yang, Z. F., Cui, B. S., Liu, J. L., Wang, X. Q. & Liu, C. M. 2003 *Theory, Method and Practice of Eco-Environmental Water Demand*. Science Press, Beijing, China (in Chinese).

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