Computation methods of minimum and optimal instream ecological flow for the upper Huaihe River, China

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Abstract Hydrological processes are a key driver of the presence and absence and structure of aquatic communities. In this paper relationships between river ecosystem processes and the hydrological regime of the upper Huaihe River, China, are investigated, and computation methods for determining minimum and optimal ecological flows are proposed. A series of minimum and optimal instream ecological flows are proposed for three hydrological stations and these are compared to that obtained by the Tennant Method. The results provide a reference for preserving river hydrological processes and maintenance of river ecosystem stability and health.

Key words minimum instream ecological flow; optimal instream ecological flow; the upper Huaihe River, China

INTRODUCTION

The hydrological regime of a river is a key driver of aquatic communities (Xia *et al.*, 2007). Specific hydrological and environmental conditions are required for certain life cycles of all river living organisms, and variations in river flows have significant influences on the alterations of all river communities and ecosystem structure. With increasing pressures on water resources because of population growth and intensive development, the hydrological regime of many of China's rivers have been altered to some extent (Hu *et al.*, 2008). This can result in situations where instream ecological water requirements cannot be guaranteed. Thus, it is essential to explore the relationship between the hydrological regime of river ecosystems and the aquatic communities they support in order to provide a theoretical basis for determining instream ecological flow and the protection of river ecosystem health.

This study was conducted on the upper Huaihe River, China, and uses hydrological stations upstream and above Xixian as a study site. The monthly natural runoff distributions were analysed at Dapoling, Changtaiguan, and Xixian hydrological stations, located on the main stem of the upper Huaihe River. These sites have catchment areas of 1640 km^2, 3090 km^2 and 10 190 km^2, respectively. On the basis of the intra-annual distribution, monthly natural runoff together with known requirements of several flow–ecological relationships, the minimum ecological flow processes, and optimal ecological flow processes at three typical hydrological stations were determined using time series of monthly natural runoff. Those obtained were evaluated by the Tennant Method. It is suggested that the outputs of this study could provide a reference for preserving river hydrological processes and characteristics, and maintaining river ecosystem stability and health in China.

IMPACTS OF THE HYDROLOGICAL REGIME ON RIVER ECOSYSTEM PROCESSES

The main impacts of altered hydrology on Chinese river ecosystems include the following:

(a) Changes in the hydrological regime occur at different temporal and spatial scales, and variations in these characteristics influence the river habitat space, substance and energy conditions required by different life cycles of aquatic organisms. Notably, changes in the distribution, abundance, and community composition and diversity of river aquatic animals and plants have been recorded. Aquatic organisms can adapt to complex and changing river habitat structures, and variations in river biodiversity and biomass are closely correlated to river hydrological regime and characteristics.

(b) The life cycles of aquatic organisms have adapted completely to the daily, monthly, seasonal and annual periodic variations of the hydrological regime. The entire recruitment process of breeding, growth and maturity, are closely associated with intra-annual variations of the hydrological regime. Variations in river flow are a driving force of the life cycles of plants, micro organisms, invertebrates and fish species in rivers and wetlands (Cai *et al.*, 2003).

(c) Intra- and inter-annual variations in the hydrological regime maintain the longitudinal, lateral and vertical continuity of river systems, as well as controlling substance exchange, energy exchange and species exchange between river systems and their conterminous lands, lakes and oceans. Changes to these connections lead to the isolation of populations of living organisms and local extinction of fish species and other living organisms.

DEFINITION AND CLASSIFICATION OF ECOLOGICAL FLOW PROCESS

Definition of ecological flow process

River hydrological processes vary periodically and stochastically, and the life cycles and population structures of aquatic communities adapt to these. While under natural conditions, stochastic hydrological processes have no fundamental impacts on aquatic species and population structures, they do influence biomass and the size of species populations. Thus healthy river ecosystems have the capability of self-regulation and self-control according to environmental changes. It was these features that maintained river biodiversity and the characteristics of river species population structures. However, extreme hydrological events, both floods and droughts, are disturbance river ecosystems. Therefore, the definition of ecological flow processes in a narrow sense can be given as the flow process which can guarantee the stability and health of the river ecosystem under natural conditions. The ecological flow processes in a broad sense should not only satisfy the requirements of the river ecosystem for water, but also have the same temperature, sediment, water quality and nutrition characteristics as does the natural river flow process. When these characteristics are altered by human activities, even in the absence of major flow alterations, river ecosystem structures can also be altered and these changes impose negative impacts on the river ecosystem. Therefore, the flow processes required by the river ecosystem should vary to correspond with the development status of river basins to ensure the stability of river ecosystem structure. As a result, ecological flow process should not be a fixed or static but rather it should be determined by full consideration of the features of river flow, sediment, solutes, living organisms and water temperature, etc.

Classifications of ecological flow process

Natural river flow processes vary stochastically within a certain range, therefore, according to the narrow-sensed definition of ecological flow process, variation characteristics of natural river flow process and the corresponding responses of the river ecosystem, ecological flow process can be classified as minimum instream ecological flow process, maximum instream ecological flow process, and optimal instream ecological flow process.

Minimum instream ecological flow processes are the lower envelope of flow processes below which the stability and health of the river ecosystem cannot be maintained and aquatic communities cannot survive. The amount of water corresponding to minimum instream ecological flow process is the minimum instream ecological water requirement. As the life cycles of aquatic creatures have completely adapted to the periodic variations of river hydrological processes, minimum instream ecological flow process should also have the same intra-annual variation patterns as a natural river flow process, i.e. a flow process with high and low water periods. Under these extreme hydrological conditions, the damage to river ecosystems induced by water shortage can be recovered. On the other hand, maximum instream ecological flow processes can be regarded as the upper envelope of flow processes above which river ecosystem structure can be affected negatively and the stability and health of the river ecosystem cannot be maintained.

Optimal instream ecological flow process is the optimal flow process that benefits the maintenance of river ecosystem stability and biodiversity. Since the responses of river ecosystem, species and population structure to alterations in river hydrological processes vary, the flow process which can best maintain the health of the river ecosystem and the stability of species population structure is the optimal instream ecological flow process. The optimal instream ecological flow should also have apparent statistic characteristics as natural river flow processes do, and vary in a proper range.

COMPUTATION OF ECOLOGICAL FLOW FOR THE UPPER HUAIHE RIVER

Water resource development in the upper Huaihe River basin has altered the hydrological regime, and this has resulted in damage to the stream ecosystem stability, species diversity and biomass to some extent. Most common ecological flow methodologies used in China can be grouped into three categories: hydrological methodologies (Ni *et al.*, 2002; Yu *et al.*, 2004; Zhao *et al.*, 2005), including the 7Q10 method (consecutive 7-day low flow event with a 1:10 year return period), the Tennant method and the minimum continuous 30 days' mean discharge method; hydraulic and habitat rating methodologies (Ni *et al.*, 2002; Yu *et al.*, 2004; Zhao *et al.*, 2005), the former including the wetted perimeter method and the R2CROSS method, the latter including the in-stream flow incremental methodology (IFIM) and computer aided simulation model for instream flow requirement in diverted stream (CASIMIR); holistic methodologies, including the South Africa building block methodology and the Australia benchmarking methodology.

The application of some methodologies mentioned above is restricted by difficulties in the collection of river cross-section parameters and biological data. In addition, the above methodologies only consider the requirements of some single element for hydrological characteristics at specific river cross-sections, and do not take a river system as a whole to consider the requirements of a river ecosystem for hydrological processes and characteristics.

Computation of the minimum ecological flow

As the annual life cycles of aquatic organisms have adapted to periodic variations of the hydrological regime, annual minimum instream ecological flow process should also have the same intra-annual variation patterns as the annual natural river flow process, i.e. a flow process with high and low water periods, and should not be a flow process with a constant value. Considering the damage to river ecosystems, self-recovery is influenced by the random occurrence of minimum monthly natural flow rate. It is assumed that the minimum monthly natural flow rate for each month is the lower limit of the monthly flow rate, below which the damage to river ecosystem induced by the extreme low flow condition cannot be recovered. As a result, the minimum monthly natural flow rate for each month is taken as its minimum ecological flow. Compared with the ecological flow gained by the minimum continuous 30 days mean discharge method, the minimum ecological flow proposed by this study requires more water for environmental use and more benefits for the river ecosystem.

On the basis of monthly natural flow discharge data from Dapoling, Changtaiguan, and Xixian hydrological stations along the main stem of upper Huaihe River, the minimum ecological flow rates for 12 months at each station constitute its yearly minimum ecological flow process. The yearly minimum ecological flow processes at the three stations are similar, and the one at Dapoling station is shown in Fig. 1. Each month's minimum ecological water requirement is shown in Table 1 for all stations.

Computation of optimal instream ecological flow

According to hydrological character of the upper Huaihe River in different seasons, flow conditions required for maintaining river ecosystem stability and species survival and multiplication, frequencies of minima and maxima monthly natural flow rates and local climatic conditions, the dry, average and wet seasons were identified for the upper Huaihe River (see Table 2), and different guarantee rates for river flow were assigned in different seasons, i.e. 75% for dry season, 50% for average season and 45% for wet season. On the basis of each month's 46-year long time series of monthly natural discharge data from Dapoling, Changtaiguan and Xixian hydrological stations, 12 monthly flow rates with different guarantee rates for each station were obtained and they constitute its yearly optimal instream ecological flow process. The yearly optimal ecological flow processes at the three stations are similar, and the one at Dapoling station is shown in Fig. 1. Each month's optimal instream ecological water requirement at each station was calculated based on its optimal instream ecological flow process (see Table 3).

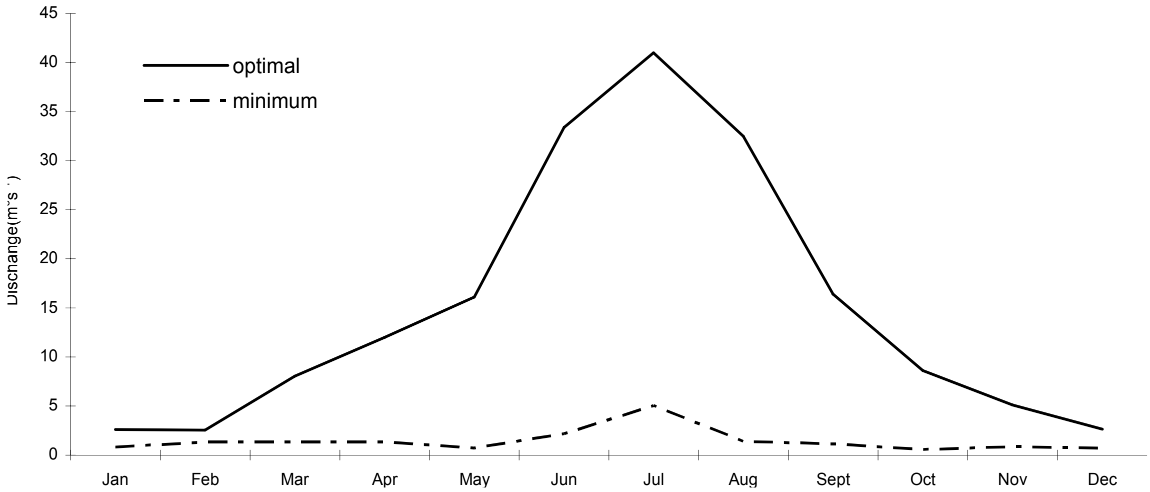

Fig. 1 Minimum and optimal ecological flow processes at Dapoling.

Table 1 Minima ecological water requirements (Unit: 10^8 m^3).

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dapoling	0.02	0.04	0.04	0.04	0.02	0.06	0.14	0.04	0.03	0.02	0.02	0.02	0.49
Changtaiguan	0.05	0.06	0.07	0.11	0.06	0.15	0.28	0.11	0.07	0.04	0.04	0.04	1.08
Xixian	0.17	0.19	0.27	0.39	0.43	0.37	0.88	0.43	0.37	0.06	0.11	0.13	3.80

Table 2 Division of wet season, average season and dry season.

Stations	Wet season		Average season		Dry season	
	Mean discharge (m^3 s^{-1})	Months	Mean discharge (m^3 s^{-1})	Months	Mean discharge (m^3 s^{-1})	Months
Dapoling	≥47.04	7–8	7.21–47.04	3–6, 9,10, 11	≤7.21	12–2
Changtaiguan	≥86.37	7–8	13.14–86.37	3–6, 9,10, 11	≤13.14	12–2
Xixian	≥271.14	7–8	47.51–271.14	3–6, 9,10, 11	≤47.51	12–2

Table 3 Optimal ecological water requirements (Unit: 10^8 m^3).

Stations	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Dapoling	0.07	0.06	0.22	0.31	0.43	0.87	1.10	0.87	0.43	0.23	0.13	0.07	4.79
Changtaiguan	0.13	0.11	0.38	0.45	0.75	1.00	1.98	1.63	1.06	0.85	0.23	0.11	8.68
Xixian	0.40	0.47	1.48	1.33	2.54	2.85	8.05	5.54	2.39	1.45	0.84	0.48	27.82

Table 4 Assessment of minimum and optimal ecological flow by the Tennant method.

Stations	Percentage of computed minimum/optimal flow in mean annual flow in the selected periods (%)				Assessment by Tennant method			
	Minimum flow		Optimal flow		Minimum flow		Optimal flow	
	Apr–Sep	Oct–Mar	Apr–Sep	Oct–Mar	Apr–Sep	Oct–Mar	Apr–Sep	Oct–Mar
Dapoling	5.89	9.65	70.23	50.6	severe	severe	optimum	outstanding
Changtaiguan	8.34	10.84	69.12	68.47	severe	poor	optimum	optimum
Xixian	8.64	9.57	65.24	53.54	severe	severe	optimum	outstanding

EVALUATION ON PROPOSED ECOLOGICAL FLOW BY THE TENNANT METHOD

According to the rating standards for flow conditions proposed by the Tennant Method, the flow conditions corresponding to the proposed minimum and optimal ecological flow in different target periods were evaluated (see Table 4). It can be seen that the flow conditions in line with optimal ecological flow at three target locations are optimum/outstanding in both wet and dry seasons. The proposed optimal ecological flow process possesses the characteristics of the natural river flow process, and can meet requirements of river ecosystems for hydrological conditions in different seasons of a year. Table 4 also reveals that the flow conditions in line with minimum ecological flow at three target locations are severe/poor in both wet and dry seasons. This indicates that more water than minimum ecological water requirements at three target locations should be kept in the river, to maintain the river stability and health, if sufficient water is available.

CONCLUSIONS

Studies on river ecological flow are an important research area for river ecosystem protection. Maintaining river ecological flow process and its variation characteristics is a critical measure to protect river ecosystem stability and health. Human activities associated with water resources utilization and runoff regulation in river basins should not alter the fundamental river hydrological characteristics. The degree to which water resources in river basins can be exploited and utilized should be determined by the critical flow condition set by minimum ecological flow. To maintain the stability and recoverability of river ecosystems, runoff impoundment and regulation should ensure river flow rates in different months are not lower than minimum ecological flow rates in dry years or seasons and optimal ecological flow rates in wet years or seasons.

For rivers such as the Huaihe River, where human activities have been highly intensified, it is more difficult to maintain their hydrological processes and characteristics as possessed by natural rivers and greater efforts are required in restriction of water resources utilization and runoff regulation.

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