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Computation of minimum and optimal instream ecological flow for the Yiluohe River

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Abstract Water is the source of life. The existence of stream species and the formation of stream population structure are closely associated with stream hydrological processes and their variations. However, with the utilization and development of water resources in river basins, river hydrological processes and characteristics have been altered by human activities to some extent, and, as a result, the stability and the biodiversity of river ecosystems have been affected. This paper analyses the relationship between the river ecosystem and its hydrological processes and characteristics, and proposes the computation methods of minimum ecological flow and optimal ecological flow. The paper selected the Yiluohe River, one of the tributaries of the Yellow River, as a case study site, employed the proposed methods to compute minimum instream ecological flow processes and optimal instream ecological flow processes at three typical hydrological stations and their corresponding ecological water requirements, and evaluated the computed minimum ecological flow and optimal ecological flow by the Tennant Method. The results provide a reference for preserving river hydrological processes and characteristics and maintaining river ecosystem stability and health.

Key words minimum instream ecological flow; optimal instream ecological flow; Yellow River; Yiluohe River

INTRODUCTION

Water is the source of life. The existence of river species and the formation of river population structure are closely associated with river hydrological processes and their characteristics. On one hand, specific hydrological and environmental conditions are required for the life cycles of all river living organisms; on the other hand the variations in river hydrological processes and characteristics have significant effects on the alterations in river living organism communities and ecosystem structure. However, with the utilization and development of water resources in river basins, river hydrological processes and characteristics have to some extent been altered by human activities. As a result, the stability and the biodiversity of river ecosystems have been affected. Therefore, it is essential to explore the relationship between river ecosystems and their hydrological processes and characteristics to provide a theoretical basis for the determination of instream ecological flow and the protection of river ecosystem health.

On considering that the variations in stream hydrological processes and characteristics have impacts on river ecosystem structure and that river hydrological processes and characteristics play a critical role in maintaining the stability of river ecosystems, the concepts of minimum instream ecological flow and optimal instream ecological flow, and their computation methods have been proposed. This paper selected the Yiluohe River, one of the tributaries of the Yellow River, and the Yihe River and the Luohe River, two tributaries of the Yiluohe River, as case study sites. Minimum ecological flow processes and optimal ecological flow processes at three typical hydrological stations on the three rivers, respectively, were determined by the use of their long time series of monthly runoff, and the results were evaluated by the Tennant Method. The output of this paper could provide a reference for preserving river hydrological processes and characteristics and maintaining stream ecosystem stability and health.

IMPACTS ON RIVER ECOSYSTEM OF RIVER HYDROLOGICAL REGIME AND CHARACTERISTICS

The main impacts on river ecosystem of river hydrological regime and characteristics and their spatial variations are as follows:

- On different temporal and spatial scales the river hydrological regime and the variation characteristics of river hydrological variables influence the river space, substance and energy conditions required by the life cycles of river living organisms, and river species distribution and abundance, and the community composition and diversity of river aquatic animals and plants. River living organisms have also adapted to complex and changing river habitat structures, and variations in river biodiversity and biomass are closely correlated to river hydrological regime and characteristics.
- The life cycles of all living organisms in river ecosystems have adapted completely to the daily, monthly, seasonal and annual periodic variations of hydrological phenomena, which result from the rotation and revolution of the Earth. The breeding, growth and maturity processes of aquatic plants and animals are closely associated with intra-annual variations of river hydrological processes. Variations in river flow processes are a driving force of the life cycles of plants, micro-organisms, invertebrates and fish species in rivers and wetlands (Cai *et al.*, 2003).
- Intra-annual and inter-annual variations in river hydrological processes can maintain the horizontal and longitudinal continuity of river systems, control substance exchange, energy exchange and species exchange between river systems and their conterminous lands, lakes and oceans. Any damage to horizontal and longitudinal continuity of rivers will lead to the separation of the population of living organisms and local extinction of fish species and other living organisms.

DEFINITION AND CLASSIFICATIONS OF ECOLOGICAL FLOW PROCESS

Definition of ecological flow process

River hydrological processes vary periodically and stochastically, and the life cycles and population structures of all river living organisms have adapted to these characteristics. Under natural conditions, river hydrological processes with stochastic variations have no fundamental impacts on river species and population structures, but they have impacts on biomass and the size of species population. Any flow processes, such as the ones in wet years, or dry years or average years, and their alternate occurrence have corresponding ecological effects. The river ecosystem provides a healthy environment for aquatic creatures' lives, which 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, such as extreme floods and extremely low flow, are harmful to the river ecosystem. Therefore, the definition of ecological flow process 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 process 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 the natural river flow process does. When these characteristics are altered by human activities, even with the flow condition unchanged, river ecosystem structures can also be altered and these alterations may 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, the ecological flow process should not be a fixed one and 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-sense definition of ecological flow process, variation characteristics of natural river flow process and the corresponding responses of 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 process it is the lower envelope of flow processes below which the stability and health of river ecosystem cannot be maintained and aquatic creatures 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 also should 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 damages to river ecosystem induced by water shortage can be recovered.

Maximum instream ecological flow process it is the upper envelope of flow processes above which river ecosystem structure can be affected negatively and the stability and health of river ecosystem cannot be maintained.

Optimal instream ecological flow process (Yu et al., 2004) 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 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 statistical characteristics as natural river flow processes do, and vary in a proper range.

COMPUTATION OF ECOLOGICAL FLOW FOR THE YILUOHE RIVER

Development and utilization of the water resources in the Yellow River basin have altered river hydrological processes and characteristics, and in turn caused damage to stream ecosystem stability, species diversity and biomass to some extent. The aim to analyse the ecological flow processes of the Yiluohe River is to determine the hydrological processes and characteristics required for maintaining its ecosystem stability under current development and utilization pattern of the Yellow River's water resources.

Most common ecological flow methods

Most common ecological flow methodologies 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 African building block methodology and the Australian 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 yearly life cycles of aquatic creatures have completely adapted to the periodic variations of river hydrological processes, a yearly minimum instream ecological flow process should also have the same intra-annual variation patterns as the yearly 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 ecosystem self-recovery (induced by the random occurrence of the minimum monthly flow rate in each month in the period having observed flow time series), it is assumed that the minimum monthly flow rate for each month is the lower limit of the monthly flow rate, below which the damage to the river ecosystem induced by the extreme low flow condition cannot be recovered. As a result, the minimum monthly flow rate for each month is taken as its minimum ecological flow. However, it should be noted that the real minimum monthly flow rate that occurred in the past may be lower than that obtained from short-term flow records. Therefore, the minimum ecological flow is not an absolute but a relative lower limit. Compared with the ecological flow gained by the minimum continuous 30-day mean discharge method, the minimum ecological flow proposed by this paper requires more water for environmental use and more benefits for the river ecosystem.

On the basis of monthly flow discharge data from Heishiguan hydrological station on the Yiluohe River, Luanchuan hydrological station on the Yihe River and Changshui hydrological station on the Luohe River, the minimum ecological flow rates for 12 months at each station constitute its yearly minimum ecological flow process. The intra-annual distribution of minima ecological flow process for each station is shown in Figs 1–3. Each month's minimum ecological water requirement is shown in Table 1 for all stations.

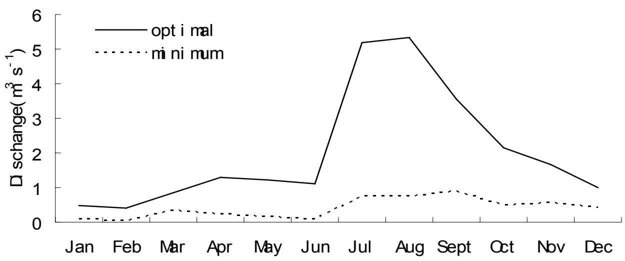

Fig. 1 Minimum and optimal ecological flow processes at Luanchuan.

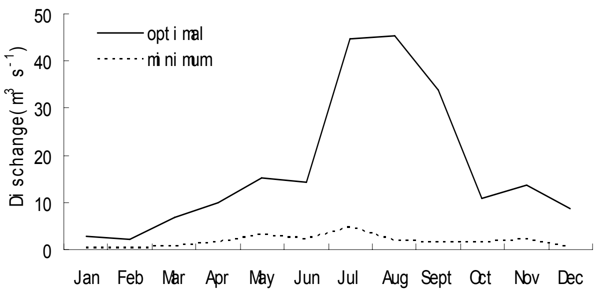

Fig. 2 Minimum and optimal ecological flow processes at Changshui.

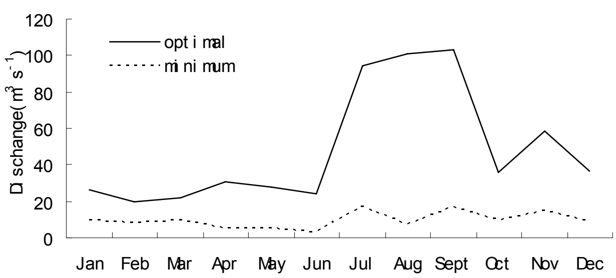

Fig. 3 Minimum and optimal ecological flow processes at Heishiguan.

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

Rivers	Stations	Jan	Feb	March	April	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Yihe	Luanchuan	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.02	0.02	0.01	0.01	0.01	0.12
Luohe	Changshui	0.01	0.01	0.02	0.04	0.08	0.06	0.13	0.05	0.04	0.04	0.06	0.01	0.55
Yiluohe	Heishiguan	0.26	0.19	0.26	0.13	0.14	0.08	0.46	0.19	0.43	0.26	0.38	0.23	2.99

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

Rivers	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
Yihe	Luanchuan	≥5.41	7–9	1.47–5.41	4–6, 10, 11	≤1.47	12–3
Luohe	Changshui	≥57.48	7–9	13.88–57.48	3–6, 10, 12	≤13.88	1–2
Yiluohe	Heishiguan	≥139.03	7–9	44.63–139.03	4–6, 10, 12	≤44.63	1–3

Computation of optimal instream ecological flow

According to hydrological and morphological characteristics of the Yiluohe River, the Yihe River and the Luohe River in different seasons, conditions required for maintaining river ecosystem stability and species survival and multiplication, frequencies of minima and maxima monthly flow rates and local climatic conditions, the dry, average and wet seasons were identified for each station (see Table 2), and different guarantee rates for river flow were assigned in different seasons, i.e. 90% for dry season, 70% for average season and 50% for wet season, respectively. On the basis of each month's long time series of monthly discharge data from Heishiguan, Luanchuan and Changshui 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 results are shown in Figs 1-3. Each month's optimal instream ecological water requirement at each station was calculated based on its optimal instream ecological flow process (see Table 3).

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 in three target rivers are excellent/good in both wet and dry seasons. The proposed optimal ecological flow process possesses the characteristics of natural river flow process, and can meet requirements of river ecosystems for hydrological conditions in different seasons of a year. Table 4 reveals that the hydrological conditions required by the Yiluohe River ecosystem can be ensured only when the proposed optimal ecological flow for the Yiluohe River can be guaranteed because the hydrological regime of the Yiluohe River has been altered significantly by human activities.

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

Rivers	Stations	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Total
Yihe	Luanchuan	0.01	0.01	0.01	0.03	0.03	0.03	0.12	0.12	0.07	0.04	0.03	0.02	0.52
Luohe	Changshui	0.07	0.04	0.17	0.22	0.33	0.31	1.07	1.17	0.84	0.25	0.29	0.23	4.97
Yiluohe	Heishiguan	0.43	0.28	0.34	0.67	0.61	0.54	2.07	2.52	2.24	0.71	1.13	0.75	12.29

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

Rivers	Gauges	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
Yihe	Luanchuan	9.92	17.03	52.11	42.31	severe	poor	excellent	excellent
Luohe	Changshui	5.67	4.37	55.44	31.03	severe	severe	excellent	good
Yiluohe	Heishiguan	8.62	16.21	52.50	37.44	severe	poor	excellent	good

DISCUSSION AND 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 the minimum ecological flow. To maintain the stability and recoverability of river ecosystems, runoff impoundment and regulation should ensure that river flow rates in different months are not to be lower than minimum ecological flow rates in dry years or seasons and optimal ecological flow rates in wet years or seasons.

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

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REFERENCES

Cai, Q., Tang, T. & Liu, J. (2003) Several research hotspots in river ecology. *Chinese J. Appl. Ecol.* **14**(9), 1573–1577.

Ni, J., Cui, S., Li, T. & Jin, L. (2002) On water demand of river ecosystem. *J. Hydraul. Engng* **9**, 14–19.

Yu, L., Xia, X. & Du, X. (2004) Connotation of minimum ecological runoff and its calculation method. *J. Hohai Univ. (Natural Sciences)* **32**(1), 18–22.

Zhao, Q., Liu, J., Wang, J. & Wei, P. (2005) Calculation of minimum ecological runoff in Manas River. *Arid Land Geogr.* **28**(3), 292–294.