THE MINIMUM ENVIRONMENTAL FLOW OF POLLUTED RIVERS IN AREAS LACKING ECOLOGICAL DATA–A CASE STUDY OF A HEAVILY POLLUTED RIVER IN THE UPPER HAI RIVER, CHINA

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Abstract. Environmental flow (e-flow) is the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems. E-flows are crucial parameters for ecosystem restoration. However, few studies have focused on the e-flows of polluted rivers in areas lacking ecological data, which severely hinder the restoration of aquatic ecosystems. In this paper, taking the natural or near-natural flow regimes as the reference system, the recommended e-flow of the Xinxiang Section of the Wei River (XSWR) in China includes two parts: ecological water and water self-purification demand. The Tennant method was used to calculate the ecological water demand, and a one-dimensional steady-state water quality model (OSWQM) was used to calculate the water self-purification demand. The Tennant method was based on natural flow regimes before runoff mutation, and the water quality indicators in the OSWQM were identified by cluster analysis (CA) and discriminant analysis (DA). The results showed that the Hew Station was markedly short of water, and Liu Station has small amount of water shortage, while the e-flows of the other stations can be satisfied. Some guarantee measures were proposed to improve the ecological status of the studied river and canal. This study provides some methods to determine the minimum e-flow of polluted rivers in areas lacking ecological data considering water quantity and quality, which is beneficial to the protection of river ecosystems.

Keywords: *environmental flow, Wei River, Xinxiang, Tennant method, one-dimensional water quality model*

Introduction

The large-scale development and utilization of water resources and runoff regulation have severely altered the natural flow regimes of rivers (Gierszewski et al., 2020), caused changes in the structure and function of river ecosystems (Storer et al., 2021; Czerniawski et al., 2020), and have even caused serious water resource shortages (Xia and Zhang, 2008), water pollution (Meng et al., 2020) and degradation of river ecosystems (González et al., 2012). Environmental flow (e-flow) is the quantity, timing, and quality of water flows required to sustain freshwater and estuarine ecosystems, and the human livelihoods and well-being that depend on these ecosystems were proposed to retain natural flow regimes in rivers (Poff et al., 2010). E-flow is the basis of ecological health assessments of rivers and is an important factor in maintaining the structure and function of river ecosystems (Acreman and Ferguson, 2010). The study of e-flow has become a focus in the field of ecohydrology, especially for rivers frequently disturbed and polluted by human activities. Most polluted rivers are in densely

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populated areas, where the contradiction between water resource exploitation and ecological protection is particularly prominent. Developing countries/regions often lack long-term ecological datasets. The determination of the appropriate e-flow based on the consideration of water quantity and quality is critical in maintaining the ecosystems of polluted rivers.

There are more than 200 methods for e-flow assessment, which can be roughly divided into areas of hydrology represented by the Tennant method, hydraulics represented by the wet-circumferential method, habitat represented by instream flow incremental methodology (IFIM) and comprehensive measurement represented by ecological limits of hydrological alteration (ELOHA) (Poff et al., 2010; Tharme, 2003; Zhao et al., 2020). However, more accurate methods often require long-term hydrological and ecological data, which are not widely available for many rivers. The Tennant method in hydrology only requires long-term flow data to calculate the e-flow that maintains the structure and function of the river ecosystems, thus it is commonly used (Zhao et al., 2020).

Changes in water quantity and quality play decisive roles in the structure and function of river ecosystems (Zhao et al., 2018), especially for heavily polluted rivers. However, most calculation methods of e-flow mainly consider the quantity and delivery pattern of water, with less consideration of the impact of water quality. Few studies have focused on the e-flows of polluted rivers in areas lacking ecological data, which hinders the restoration of local river ecosystems and the efficient management of water resources. For the prominent problem of polluted rivers in China, Xu et al. (2016) used a one-dimensional steady-state water quality model (OSWQM) to calculate the water self-purification demand. Water self-purification demand is the minimum value for water demand for river water to meet the criteria of water quality protection through pollutant degradation (attenuation and assimilation processes (Zhao et al., 2018)). In their study, water self-purification demand was calculated using COD_{Cr} and NH_3-N needed to meet the water quality criteria. However, their study did not consider how to select the most important discriminating water quality indicators that were responsible for spatiotemporal variations. River water pollution presents very distinct spatiotemporal variation characteristics (Meng et al., 2020), and subjective selection of indicators can easily lead to calculation results deviating from the true conditions. If the corresponding significant water quality indicators are identified according to the pollution characteristics of different river reaches, the calculation results will be more scientific.

Cluster analysis (CA) and discriminant analysis (DA) in multivariate statistical methods (MSTs) can achieve dimensionality reduction of massive data, also it can identify spatiotemporal variation characteristics of water pollution, as well as significant water quality indicators, and achieve good results in surface water and groundwater (Shrestha and Kazama, 2007; Zhou et al., 2007). For example, Hajigholizadeh and Melesse (2017) used CA to group 16 monitoring sites into three groups in South Florida and used stepwise DA to identify the most important discriminating water quality parameters responsible for temporal variations and spatial variations. Singh et al. (2005) showed that the DA offers important data reduction using only ten variables discriminating spatial patterns and five variables for temporal variation in the Gomti River in India. In our previous study (Meng et al., 2020), CA and DA were used to identify the spatiotemporal variation characteristics of water pollution in the Xinxiang Section of the Wei River (XSWR), and two significant water quality indicators (COD_{Cr}

and BOD_5) responsible for the spatial variations were identified. Based on previous research results, these two indicators will be further adopted in the OSWQM to calculate the water self-purification demand in this paper.

The Wei River, as an important tributary of the upper Hai River in China, crosses Xinxiang city from east to west. In recent years, the XSWR has been frequently impacted by human activities such as impoundments, water extraction, and flow regulation, as well as industrial and domestic sewage discharge. During the dry season, some reaches of the XSWR often dry up, silt up, and smell, resulting in the disappearance of the indigenous fish and serious degradation of the river ecosystem. According to Xinxiang Water Conservancy Annals (Xinxiang City Water Conservancy Bureau, 2005), approximately 1980, water conservancy projects (reservoirs, dams, sluice, etc.) flourished in this area, and industry and agriculture have rapidly developed. In 2018, the water quality of the Wei River and the Communist Canal (the largest tributary of the Wei River) met Class V classification, indicating moderate-level pollution, and some reaches of the XSWR became black odorous water bodies (Xinxiang City Ecological Environment Bureau, 2018). Gu et al. (2015) investigated the fish resources in the XSWR from June to July 2014 and found that there were few fish collected and that the fish population structure was relatively simple, consisting mainly of crucian carp (*Carassius auratus*), stone moroko (*Pseudorasbora parva*) and pond loach (*Misgurnus anguillicaudatus*), which have strong adaptability to the environment. Fish in tributaries such as the Ximeng River have almost disappeared. Over the past 30 years, the species and quantity of fish have declined dramatically and even disappeared. In particular, mandarin fish (*Siniperca chuatsi*), which requires better water quality, has disappeared for many years. However, few studies have focused on the e-flow in the XSWR. It is therefore essential to study the minimum e-flow of polluted rivers, especially in densely populated areas lacking ecological data. A timely study would not only be essential but also instrumental in taking appropriate action to maintain the ecosystem of polluted rivers.

Consequently, quantitative determination of e-flows is the key to the sustainable management of river ecosystems (Wu et al., 2022). Natural or near-natural flow regimes are ideal for maintaining the health of river ecosystems (Poff et al., 1997). Taking the natural or near-natural flow regimes as the reference system, maintaining the key hydrological indicators, ignoring some hydrological indicators, and maintaining the regulated flow close to the natural or near-natural flow regimes can also improve the ecological status of river.

The purpose of this paper is to study the minimum e-flow of polluted rivers in areas lacking ecological data considering water quantity and quality. In this paper, taking the natural or near-natural flow regimes as the reference system, e-flow includes two parts: ecological water demand and water self-purification demand. The Tennant method was used to calculate the ecological water demand, OSWQM was used to calculate water self-purification demand, and the maximum values of the two were used as the recommended e-flow values of the XSWR. The former method considers the demand of aquatic organisms for water quantity, while the latter considers the demand of aquatic organisms for water quality. The Tennant method was based on natural flow regimes before runoff mutation. The water quality indicators in the OSWQM were identified by CA and DA. The range of variability approach (RVA) was used to calculate e-flows as independent values, which were then compared with the recommended e-flow values in this paper. Finally, the recommended e-flow values were compared separately with natural flow (1963-1982) and current flow (2009-2018) to analyze the surplus and deficiency of e-flows. The amounts of water left in rivers should be close to the recommended e-flow values by the regulation and scheduling of water conservancy projects, which is beneficial to improve the ecological status of rivers.

Materials and methods

Study area

The Wei River, as an important tributary of the upper Hai River in China, crosses Xinxiang city from east to the west (34°55′N -35°50′N, 113°25′E -115°0′E) (*Fig. 1*). The XSWR is approximately 80 km in length. The Communist Canal, the largest tributary of the Wei River, draws water from the Yellow River in the southern part of Xinxiang City and finally joins the Wei River in Hebi City, which shares an approximately 3-km-long watercourse of the Wei River in He Village. The mean annual flow of the Qi hydrometric station is 24.01 m^3/s, with the flow at Liu hydrometric station of 4.99 m^3/s. The study area belongs to the continental monsoon climate zone, with a mean annual evaporation of 898.0 mm and an average temperature of 14 °C. The mean annual precipitation is 610.8 mm, and approximately 70% of the annual precipitation occurs during the summer (June-September). Due to the XSWR located in densely populated areas with developed industry and agriculture, the utilization rate of surface water resources is high, and rivers often dry up. Most wastewater was directly discharged into rivers without any form of treatment. Tributaries such as the Dashilao River, Baiquan River, Ximeng River, and Dongmeng River have been seriously polluted.

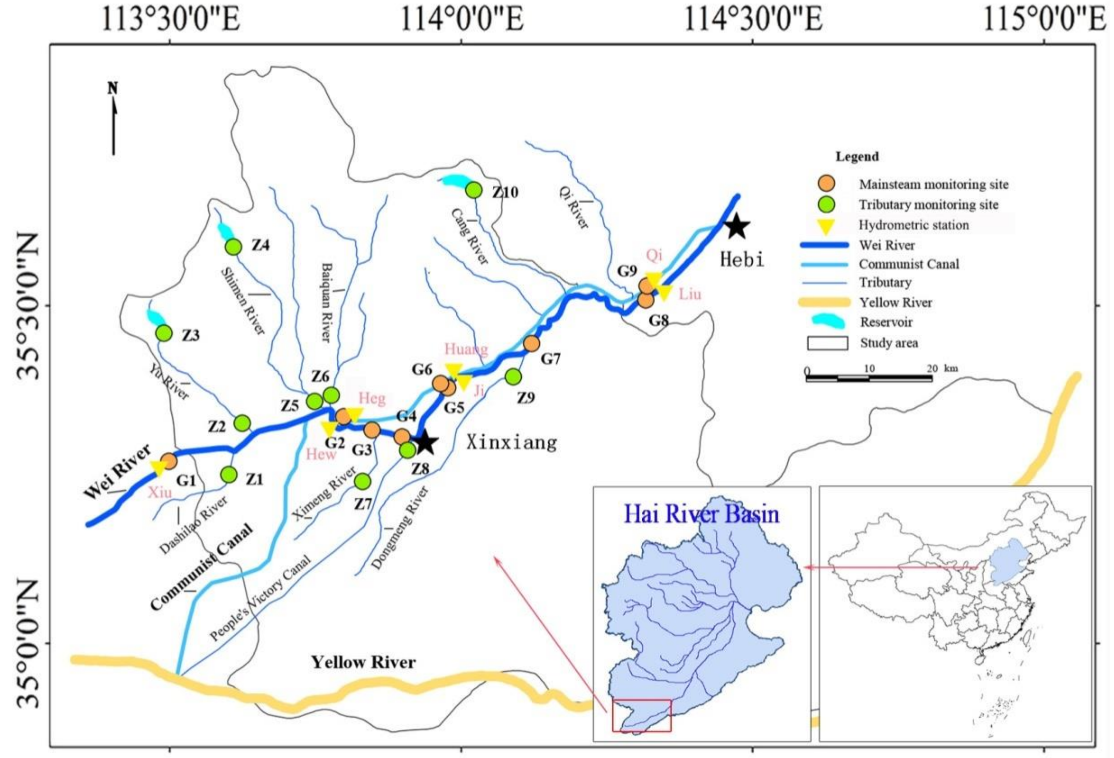

Figure 1. *Map of the study area and monitoring sites in the Xinxiang Section of the Wei River (XSWR)*

Data collection

Hydrologic and water quality data were obtained from the Henan Hydrology and Water Resources Survey Bureau. There are 7 hydrometric stations in the study area, 4 of which (Xiu, Hew, Ji, Qi Station) are in the Wei River, and 3 of which (Heg, Huang, Liu Station) are in the Communist Canal. There are 19 water quality monitoring sites, 9 of which (G1-G9) are in the mainstream of the Wei River and the Communist Canal, and 10 of which (Z1-Z10) are in tributaries. Among them, G2 is in the shared watercourse of the Wei River and the Communist Canal. The 15 water quality indicators and water quality criteria of the mainstream are shown in *Table 1*, and the water quality criteria of tributaries are not described in detail. Flow data were collected from 1963 to 2018, and water quality data were collected from 2013 to 2018.

China divides rivers into different reaches of water function zones according to environmental functions and protective objectives, and implements the corresponding water quality criteria (GB3838-2002) (*Table 2*) (Environmental Protection Administration of China, 2002).

Table 1. *Water quality indicators and water quality criteria of the mainstream XSWR*

River name	Code	Water quality criteria	Indicators
Wei	G1	V	Water temperature (Temp), pH, dissolved oxygen (DO), chemical oxygen demand (COD_{Cr}), 5-day biochemical oxygen demand (BOD_5), ammonium nitrogen (NH_3-N), total phosphorus (TP), fluorine (F^-), cyanide (CN), volatile phenol (VP), cuprum (Cu), zinc (Zn), lead (Pb), cadmium (Cd), and chromium (Cr^{6+})
Wei	G3	IV	
Wei	G4	IV	
Wei	G5	V	
Wei	G7	V	
Wei	G8	V	
Wei/Communist	G2	IV	
Communist	G6	V	
Communist	G9	V	

Table 2. *Criteria of the water classification system*

Water quality criteria	Environmental functions and protective objectives
I	Mainly for source of water and national nature reserve
II	Mainly for Class I protection areas for surface water sources of centralized drinking water, habitats for rare aquatic species, spawning ground for fishes and shrimps as well as feeding ground for young fishes
III	Mainly for Class II protection areas for surface water sources of centralized drinking water, wintering ground for fishes and shrimps, migration pathway, aquiculture area as well as swimming area
IV	Mainly for industrial water area and recreational water area not directly touched by human body
V	Mainly for agricultural water area and landscape water area

Methods

First, the comprehensive water quality index (CWQI) was used to assess the water quality of rivers. CA and DA in MSTs were used to classify 19 water quality monitoring sites and identify significant water quality indicators. The Mann-Kendall mutation test was used to detect the mutation points in the annual runoff series (1963-2018) and to distinguish natural from regulated flow. The Tennant method was used to calculate ecological water demand, and natural flow regimes before runoff mutation were the basis for calculations using the Tennant method. The OSWQM was used to calculate the water self-purification demand, and the water quality indicators in the model were identified by CA and DA. The maximum values of ecological water demand and water self-purification demand were used as the recommended e-flow values of the XSWR. The RVA was used to calculate e-flows as independent values, which were then compared with the recommended e-flow values in this paper. Finally, the recommended e-flow values were compared separately with natural (1963-1982) and current flow (2009-2018) to analyze the surplus and deficiency of e-flows. All mathematical computations were performed using Microsoft Office Excel 2007 (Microsoft Corporation, Redmond, WA, USA) and SPSS 22.0 (IBM Corporation, Armonk, NY, USA). The RVA analysis was performed using Indicators of Hydrologic Alteration (IHA, Version 7.1.0.10, the Nature Conservancy, USA).

Comprehensive water quality index

The CWQI (Xu, 2005) converts multiple water quality indicators into a single number to reflect the status of water quality. The CWQI is based on five levels of the environmental quality standards for surface water (GB3838-2002), with COD_{Mn}, BOD_5, DO, NH_3-N, and TP being the primary physiochemical variables (Wu et al., 2019). The CWQI value increases with an increasing degree of pollution. If the CWQI value falls in the range $1.0 \leq CWQI \leq 4.0$, corresponding to Classes I-III. If the CWQI value falls in the range $4.0 < CWQI \leq 5.0$, corresponding to Class IV. If the CWQI value falls in the range $5.0 < CWQI \leq 6.0$, corresponding to Class V. If the CWQI value falls in the range $6.0 < CWQI \leq 7.0$, corresponding to inferior Class V. If the CWQI value falls in the range $7.0 < CWQI$, the water quality meets the classification of the inferior Class V and indicates black-odorous water. The formulae of the CWQI can be found in reference (Wu et al., 2019).

Tennant method

Based on observation data from Montana and 21 other countries, the Tennant method established the relationship between the living environment of fish, amphibians, mollusks, and other aquatic organisms and different flow percentages of the rivers (*Table 3*) (Zhao et al., 2020). Ten percent of the annual average flow defines the shortest momentary flow amount for sustaining short-term water life, and 30% or more of the annual average flow is thought to be necessary for providing the biological integrity and sustainability of the river (Karakoyun et al., 2016). This paper focuses on the minimum e-flow due to water shortages and the high degree of exploitation and utilization. Therefore, 10% of the annual average flow was selected as the minimum ecological water demand in the river.

The large-scale exploitation of water resources and runoff regulation have severely altered the natural flow regimes of the XSWR. A nonparametric method, the Mann-Kendall mutation test, has been widely used to analyze the mutation points of hydrologic sequences (Güçlü, 2020). Therefore, this paper used the Mann-Kendall mutation test to analyze the mutation points of annual runoff series (1963-2018) to distinguish natural flow from regulated flow. Details of the Mann-Kendall mutation test can be found in reference (Güçlü, 2020). Significance analysis were tested at a two-tailed confidence level $\alpha = 0.05$. The calculation basis of the Tennant method was natural flow regimes before runoff mutation.

Table 3. *Ecological runoff standard of Tennant method (Karakoyun et al., 2016)*

Narrative description of flows	Dry season/%	Wet season/%
Flushing or maximum	200	200
Optimum range	60–100	60–100
Outstanding	40	60
Excellent	30	50
Good	20	40
Fair or degrading	10	30
Poor or minimum	10	10
Severe degradation	0-10	0-10

One-dimensional steady-state water quality model

The XSWRs are small and medium-sized rivers with small bending coefficients and breadth-depth ratios. Therefore, OSWQM (ignoring the dispersion coefficient) described in reference (Zhao et al., 2018; Xu et al., 2016) was adopted to calculate the water self-purification demand. The details are as follows.

A specific pollutant from upstream of the river section, with a concentration (C_0) much higher than that in the downstream due to excessive pollutant discharge upstream reach, flows in and continuously degenerates to the concentration of $C_0 e^{-kl/86.4u}$ (k is the integrated degradation coefficient of a specific pollutant; l refers to the distance of degradation for pollutant; and u is the mean flow velocity at cross-section), based on the first-order kinetics formula:

$$C = C_0 e^{-kt} \tag{Eq.1}$$

There are usually two strategies for water quality control: head control at the beginning and end control at the end section (Zhao et al., 2018). For a river reach, the head control is the maximum level measured at the uppermost section that is less than the maximum allowable pollution level (water quality criteria), while the end control is the maximum level measured at the lowermost section that is less than the maximum allowable pollution level. End control can only serve to control pollutants, while head control is helpful for water ecological remediation due to its lower allowances of pollutant input (Zhao et al., 2018). This paper focuses on the minimum e-flow due to water pollution. Therefore, end control has been adopted in this paper for minimum water self-purification demand. Tributaries were all defined as sewage outlets due to serious water pollution. The river section between two hydrometric stations is generalized for the convenience of e-flow calculation (*Fig. 2*).

The calculation process of water self-purification demand Q_s is as follows:

1. First, the river reach between two hydrometric stations (defined as hydrologic reach) is divided into n calculated river reaches with water function zones as the boundary.

2. Taking the i-th calculated river reach as an example, it is assumed that the water quantity is constant along this reach and that there are multiple sewage outlets. The Q_{i-1}

through the upstream control cross-section (UCC) can be calculated by the trial algorithm when a specific pollutant concentration meets the water quality criteria C_i through degradation. Q_{i-1} is the water self-purification demand of the UCC of the i-th reach (*Eq. 2*).

$$Q_{i-1} = \frac{\left(q_j s_j e^{-\frac{k_i l_j}{86.4u_i}} + q_{j+1} s_{j+1} e^{-\frac{k_i l_{j+1}}{86.4u_i}} + \cdots\right) - (q_j + q_{j+1} + \cdots) C_i}{C_i - C_{i-1} e^{-\frac{k_i x_i}{86.4u_i}}} \tag{Eq.2}$$

3. By analogy, the water self-purification demands $Q_0, Q_1, Q_2, \cdots, Q_{i-1}, \cdots, Q_{n-1}$ of n calculated river reaches can be calculated. To achieve water quality criteria for water function zones between hydrologic reaches, the water self-purification demand Q' of a specific pollutant in the hydrologic reach should be the maximum (*Eq. 3*).

$$Q' = \max\{Q_0, Q_1, Q_2, \cdots, Q_{i-1}, \cdots, Q_{n-1}\} \tag{Eq.3}$$

4. Q' refers to the water self-purification demand of a single water quality indicator. When there are multiple significant water quality indicators in the hydrologic reach, the water self-purification demands of each significant water quality indicator should be calculated separately, and the maximum value is used as the water self-purification demand Q_s of the hydrologic reach.

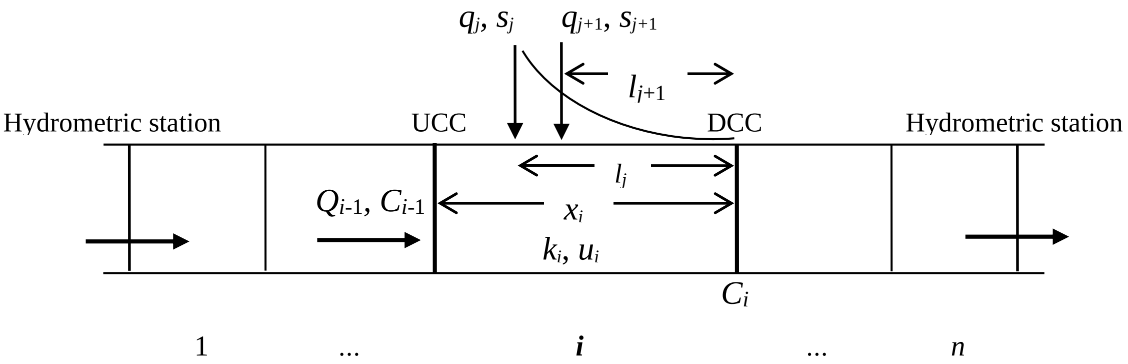

***Figure 2.** River section with sewage outlets and pollutant degradation process. i is the number of water function zones, i = 1, …, n; j is the number of sewage outlets j = 1, … m; Q_{i-1} is the flow through the upstream control cross-section (UCC) of the i-th reach, in m^3/s; C_{i-1} is the concentration of a specific pollutant at the UCC of the i-th reach, in mg/L; C_i stands for water quality criteria of the downstream control cross-section (DCC) of the i-th reach, in mg/L; q_j is a specific pollutant discharge rate at the j-th outlet, in m^3/s; s_j is the concentration of a specific pollutant corresponding to q_j at the j-th outlet, in mg/L; l_j refers to the distance from the j-th outlet to the DCC, in km; x_i refers to the distance from the UCC to the DCC of the i-th reach, in km; k_i is the integrated degradation coefficient of this pollutant of the i-th reach, in 1/d; u_i is the mean flow velocity at cross-section of the i-th reach, in m/s*

Range of variability approach

The RVA was proposed on the IHA and has been widely used to evaluate the degree of changes in river ecohydrological characteristics caused by human activities (Ban et al., 2019). Generally, 75% and 25% of the occurrence frequency of each ecohydrological indicator under natural flow regimes before runoff mutation are used as the upper and lower limits of the recommended variation range (RVA threshold) (Ban et al., 2019). The Ipswich River Fisheries Restoration Task Group proposed taking 1/4 of the difference between the upper and lower limits as the base flow in the Ipswich River to restore healthy fisheries in the Ipswich River (Ipswich River Fisheries Restoration Task Group, 2002). Shu et al. (2010) used the mean value and the difference values of the RVA threshold to calculate e-flow in the Niqu River, and the results were consistent with other methods. Ma et al. (2013) proposed using 1/2 of the difference between the upper and lower limits as a suitable e-flow in the Weihe River, and the results were compared with six previous studies. Because the study reaches are short of water resources and have high exploitation and utilization, 1/4 of the difference between the upper and lower limits was taken as the independent e-flow, which was then compared with the recommended e-flow in this paper.

Results

Evaluation of the river water quality

Based on the average monthly data of the 5 water quality indicators (COD_{Mn}, BOD_5, DO, NH_3-N, and TP) from 2013-2018 from 19 water quality monitoring sites, the CWQI was used to assess the status of water quality in the XSWR (*Fig. 3*). Of the 19 water quality monitoring sites, only 4 had concentrations that met the classification of Classes II-III, and 3 met Class IV, and 6 met Class V, whereas the remaining 6 monitoring sites met inferior Class V. Among the 9 monitoring sites in the mainstream, G1 met Class IV, and G9 met Class III, and the other 7 monitoring points met Class V and inferior Class V. Among the 10 monitoring sites in tributaries, Z3-Z5 met Classes II-III, Z8 and Z10 met Class IV, and Z1, Z2, Z6, Z7 and Z9 met Class V and inferior Class V. Site G1 is in the upper reaches of mainstream of the Wei River, and the CWQI value was 4.9, indicating that water quality of the upper reach was relatively good. G9 is in the lower reaches of the mainstream Communist Canal, and the CWQI value was 3.8, indicating that the water quality was good. It is speculated that the main reason for these results was that the water quality of the tributary (Qi River) was better, which diluted the water body of the Communist Canal. Z1, Z2, Z6, Z7 and Z9 are in the lower reaches of tributaries such as the Dashilao River, Yu River, Baiquan River, Ximeng River and Dongmeng River, respectively. The CWQI values were 6.3, 5.0, 6.1, 7.0, and 5.7, indicating that the water quality was poor. A large amount of industrial wastewater and domestic sewage along the river were directly discharged into the rivers without any form of treatment, resulting in serious pollution of these tributaries.

Calculation of environmental flows

Calculation of ecological water demand

The Mann-Kendall mutation test was used to detect the mutation points in the annual runoff series of 7 hydrometric stations from 1963 to 2018. Combined with the construction time of local water conservancy projects (approximately 1980) (Xinxiang City Water Conservancy Bureau, 2005), the flow regimes from 1963 to 1982 (20 years) can be regarded as natural flow, and the flow regimes from 1983 to 2018 can be regarded as regulated flow. Based on the annual average flow from 7 hydrometric stations from 1963 to 1982, the Tennant method was used to calculate the ecological water demand (*Fig. 4*).

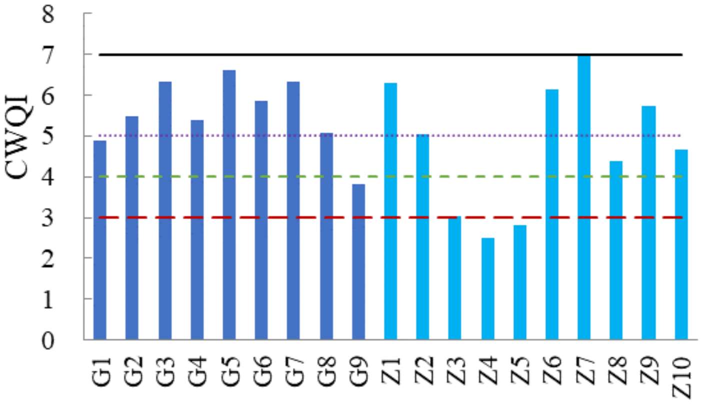

Figure 3. *CWQI values of water quality monitoring sites in the XSWR*

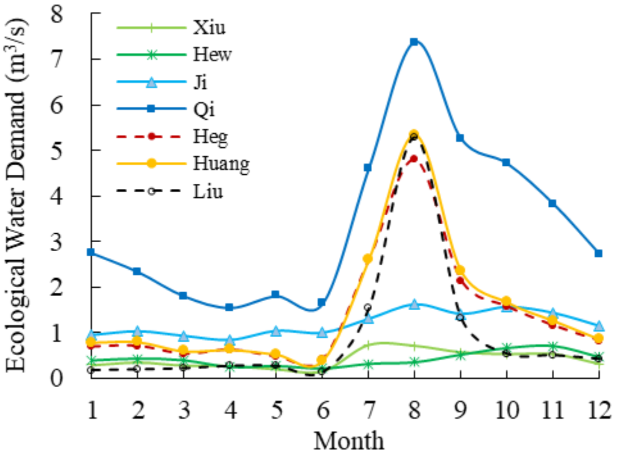

Figure 4. *The ecological water demands of 7 hydrometric stations in the XSWR*

This figure shows that the ecological water demands of the 7 hydrometric stations were different. On the whole, Qi Station has the largest water demand, while Xiu and Hew Station have smaller water demands. The water demand curve trends of Xiu, Hew, and Ji Stations were roughly the same. The curve trends of the water demands of Heg, Huang, Liu, and Qi Stations were similar, and the water demands in the flood season (June to September) were significantly higher than those in the nonflood season.

The results also show that the ecological water demands did not completely increase along the river; that is, the ecological water demands in the downstream reach were not necessarily greater than those in the upstream reach. The main reason may be that the Wei River and the Common Channel in the study area are close to each other and share a watercourse at He Village. In addition, when high flow occurs, some reaches of the two rivers also share floodplains and river water mixes. Moreover, rubber dams and sluice gates were built on the two rivers, so the river flow was artificially regulated.

Calculation of water self-purification demand

The water self-purification demand Q_s was calculated based on the data of flow, velocity, cross section, water quality, and sewage outlets of the XSWR in 2018 (*Table 4*). Two situations were used in the calculation: the actual situation of sewage discharge and the standard situation of sewage discharge. The actual situation of sewage discharge means that the concentrations of water quality indicators in sewage are the actual discharge values. The standard situation of sewage discharge means that the concentrations of water quality indicators in sewage meet the integrated wastewater discharge standard (DB41/777–2013) (Department of Ecology and Environment of Henan Province, 2013). This standard stipulates the corresponding sewage discharge standards of COD_{Cr} (50 mg/L) and BOD_5 (10 mg/L). The water quality of tributaries should meet the water quality criteria of the corresponding water function zone. Under the two situations, the water quality indicator concentrations at the UCC of each calculated reach were the water quality criteria for the water function zone upstream. If the water quality indicator concentrations at the UCC were the true discharge concentrations, some heavily polluted reaches usually have no water environmental capacity, a measure of the water's maximum capacity to accommodate a pollutant within a unit of time, which can be classified into attenuation capacity and assimilation capacity (Zhao et al., 2018).

In this table, the calculation results of the same hydrometric station were different under separate situations, and distinct hydrometric stations also had different results under the same situation. In general, the water self-purification demands under the actual situation were higher than those under the standard situation. The water self-purification demand of Xiu Station was lower. Because the water quality criteria of water quality monitoring site G1(upstream) was Class V and that of G2 (downstream) was Class IV, the greater the flow of the upper reaches, the greater the pollution load, and such the flow through the upper reaches should be reduced. The water demand of Xiu Station was 0.24 m^3/s (under the actual situation), and slightly less than 0.74 m^3/s (under the standard situation), indicating that the amount and concentration of sewage discharge along the reach from Xiu to Hew Station have little influence on the water self-purification demand. The water self-purification demands of Xiu Station were markedly lower than the average annual flows.

Under the actual and the standard situation, the Hew hydrometric station has the largest water self-purification demands, which were 15.13 m^3/s and 5.98 m^3/s, respectively. This indicates that the water pollution from Hew to Ji Station was very serious. Even if the concentrations of water quality indicators in sewage meet the discharge standard, the water self-purification demand still reached 5.98 m^3/s, which was much higher than the average annual flows. Under the actual situation, the water self-purification demand of Ji Station was 1.64 m^3/s, which was markedly lower than the average annual flows. Under the two situations, the water self-purification demands of Qi, Heg, Huang, and Liu Stations were all 0, indicating that the pollutant discharge along these reaches was lower and that the water body could meet the water quality criteria of the water function zone through pollutant degradation.

Considering the water resource shortage and continuous improvement of sewage treatment capacity in the XSWR, the water self-purification demand should not only serve as a reference for current management but also serve for long-term planning. Therefore, the calculation results of the standard situation were used as the recommended values of the water self-purification demand in this study.

Table 4. *The water self-purification demands Q_s and average annual flows of 7 hydrometric stations in the XSWR*

Flow (m^3/s)	**Situation**	**Xiu**	**Hew**	**Ji**	**Qi**	**Heg**	**Huang**	**Liu**
Water self-purification demand	Actual	0.24	15.13	1.64	0	0	0	0
	Standard	0.74	5.98	0	0	0	0	0
Average annual flows	1963-2018	4.14	1.78	7.59	24.01	10.68	12.06	4.99
	1963-1982	4.14	4.10	11.93	33.80	13.88	15.00	9.11
	2009-2018	3.52	0.29	4.28	17.01	7.91	9.43	1.58
The recommended water self-purification demand		0.74	5.98	0	0	0	0	0

It should be noted that our previous study (Meng et al., 2020) showed that pollutants in the XSWR came from point and nonpoint sources in the flood season (June to September), and point sources in the nonflood season (October to May). Compared with point source pollution, nonpoint source pollution (NPSP) is random, universal, and hysteretic, thus, the measurement and control of NPSP are difficult (Zeiger et al., 2021). Due to the limitation of data collection, this study only considered the water self-purification demand for point sources discharge.

Determination of e-flows

From the view of multifunctional water, the e-flows were determined according to the maximum values; that is, the maximum values of ecological water demand and the water self-purification demand were taken as the recommended e-flow values of the XSWR (*Fig. 5*). Based on daily data from 7 hydrometric stations from 1963 to 1982, the RVA was used to calculate e-flows as independent values, which were then compared with the recommended e-flow values in this study (*Fig. 5*).

The e-flow of Xiu Station was 0.74 m^3/s and that of Hew Station was 5.98 m^3/s. The e-flows ranged from 0.85 to 1.62 m^3/s at Ji Station, 1.55 to 7.38 m^3/s at Qi Station, 0.41 to 4.80 m^3/s at Heg Station, 0.40 to 5.35 m^3/s at Huang Station, and 0.13 to 5.29 m^3/s at Liu Station. According to the curves of the recommended e-flows, there was nonzero flow at 7 hydrometric stations. Extended periods of drought can directly lead to extinction or fragmentation of aquatic populations through mass mortality caused by the drying of habitat or decline in water quality (Lear et al., 2021). More recently, the importance of more frequent but smaller flow pulses in sustaining ecosystem processes has also been shown (Espinoza et al., 2021).

The e-flows of Xiu and Hew Station were mainly used to meet the demands of water self-purification, while the e-flows of the other five stations were mainly used to meet the ecological water demands. The e-flows of other hydrometric stations in the nonflood season were lower than those in the flood season, which was consistent with the natural flow regimes in the XSWR and met the demand of former river ecosystems for natural flow variability. Overflow and maximum (200% of the annual average flow) values also have positive effects on the sustainability of habitat quality (Zhao et al., 2020). Lateral exchange of water, nutrients, and organism exchange between river channels and floodplains can promote aquatic organisms to rapidly grow (Tockner et al., 1999). As native freshwater fishes have evolved within a localized flow setting, maintaining natural high-low variability of flow or key hydrological parameters in regulated rivers can achieve moderate protection for the former river ecosystems (Storer et al., 2021).

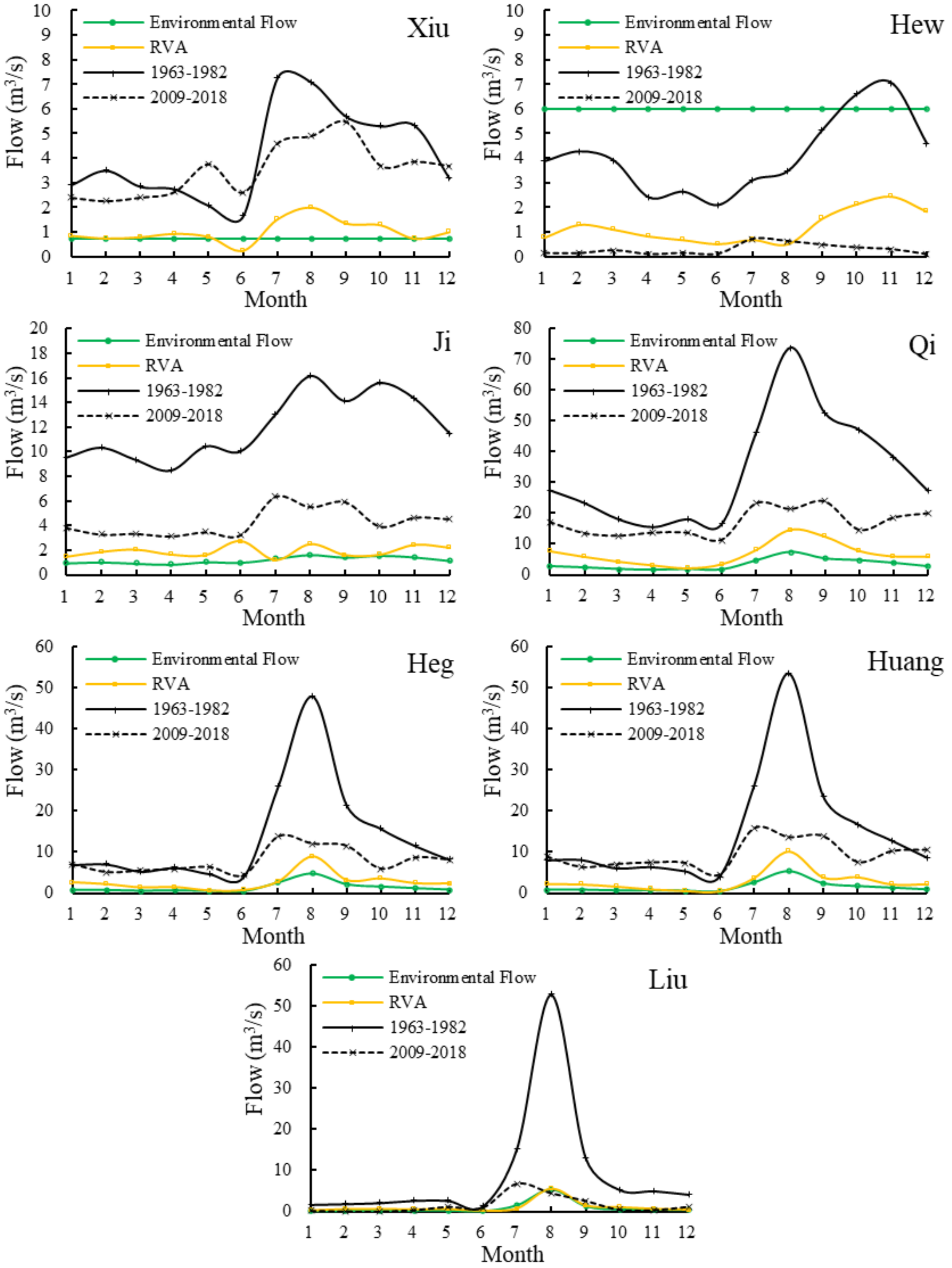

***Figure 5.** The recommended e-flows of 7 hydrometric stations in the XSWR*

By comparing the recommended e-flow values with the independent values calculated by RVA, it can be seen that the e-flow of Hew Station was much higher than that calculated by RVA. Because water pollution in this reach was very serious, high e-flow was needed to meet the demand of water self-purification. The recommended e-flows of other stations were close to the results calculated by RVA, the trend curves calculated by the two methods appeared to intersect, and the values calculated by RVA

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were slightly higher than the recommended e-flows. Considering the water shortage in the XSWR, lower e-flows are more easily guaranteed. Therefore, the recommended e-flows in this paper were reasonable and could be beneficial to the protection of river ecosystems.

Analysis of surplus and deficit of e-flows

The surplus and deficit of e-flows are directly related to water allocation. Only rational water resource allocation can maintain the healthy development of river ecosystems. The recommended e-flows in this paper were compared with the average monthly flows of natural (1963-1982) and current flow (2009-2018) (*Fig. 5*). If the recommended e-flow is smaller than the average monthly flow, there is no water shortage, and vice versa.

In this figure, compared with natural flow (1963-1982), the recommended e-flows of six stations except Hew Station were all less than the corresponding average monthly flows, so there was no water shortage during the year. At Hew Station, only the average monthly flows in October and November met the demands of the recommended e-flows, whereas water shortages in other months were large, ranging from 0.83 to 3.88 m^3/s.

In this figure, compared with the current flow (2009-2018), except Hew Station and Liu Station, the recommended e-flows of the other five stations were all less than the corresponding average monthly flows, so there was no water shortage in the whole year. The water shortage in Hew station from January to December was serious, ranging from 5.27 m^3/s to 5.89 m^3/s. The e-flow curve of Liu Station was close to that of the current flow, and the amount of water shortage was very small, ranging from 0.09 m^3/s to 0.83 m^3/s.

According to the above analysis of the surplus and deficit of e-flows compared with current flow (2009-2018), only Hew Station was markedly short of water among the 7 hydrometric stations, and Liu Station has small amount of water shortage, while the e-flows of the other stations can be satisfied.

Guarantee measures

To solve the water shortage problem at Hew and Liu Station, the following measures can be taken to ensure the e-flows and to improve the ecological status of the river.

At present, the water shortage of Hew Station is mainly caused by the low current flow in river and the high water self-purification demand. Therefore, the amount of water left in river should be increased by the regulation and scheduling of water conservancy projects. In a river system, intermittent fluctuation in flow caused by the operation of dams and sluice gate adjustments can result in zero flow in some river reaches, so intelligent regulation and scheduling of water conservancy projects are required to reduce the impact of water conservancy projects on river longitudinal continuity (Zhang et al., 2022). Second, external pollution input should be further controlled, such as implementing stricter effluent standards and improving the treatment capacity of sewage treatment plants. At present, the standard values in the integrated wastewater discharge standard (DB41/777–2013) implemented in China are higher than the water quality criteria of water functional zones. For example, the discharge standard of COD_{Cr} is 50 mg/L, while the Class III water quality criterion for water functional zones is 20 mg/L. Even if the water quality of sewage discharge is up to the discharge standard, sewage discharge along rivers will still pollute rivers. The third guarantee measure is to take active water treatment measures to control endogenous pollutants. Large amounts of pollutants accompanying untreated sewage water and storm runoff enter the river, accumulate in the sediments at the bottom of the river through settlement and diffusion, and form silt through accumulation and fermentation (Li et al., 2021). Under some conditions, pollutants in sediments are released into water bodies through diffusion, convection, and resuspension, causing secondary pollution called endogenous pollution (Hu et al., 2001). Endogenous pollution control measures mainly include dredging and revetment of the river and ecological restoration (Zhang et al., 2022). The careful comprehensive dredging of the river can effectively reduce the release of endogenous pollutants (Zhang et al., 2022). The restoration of river ecosystem health through ecological measures enables the recovery of damaged rivers (Li et al., 2018).

At present, the water shortage of Liu Station is mainly caused by the low current flow in river. Therefore, the regulation and scheduling of water conservancy projects should be required to increase the amount of water left in river, such as increase in the quantities of water released from reservoirs, and reduction in the number of rubber dams and sluice gates.

Discussion

Natural or near-natural flow regimes

It should be noted that due to the influence of human activities, the flow regimes from 1963 to 1982 were actually near-natural flow regimes. Because river ecosystems are in the process of continuous evolution, it is difficult to restore ecosystems under absolute natural flow regimes. Since 1980, the construction of a large number of water conservancy projects (reservoirs, dams, sluice gates, etc.) has caused significant changes in the flow regimes in the XSWR (Xinxiang City Water Conservancy Bureau, 2005). Natural or near-natural flow regimes are ideal for maintaining the health of river ecosystems (Poff et al., 1997). Therefore, the calculation of ecological water demand was based on a near-natural flow regime (1963-1982). Taking the natural or near-natural flow regimes as the reference system, the minimum ecological water demand for the studied river was calculated and then taken as the amounts of water left in rivers for regulated flow. This can also improve the ecological status of the studied river.

Identification of significant water quality indicators

A highlight of this paper is that significant water quality indicators (COD_{Cr} and BOD_5) responsible for spatial variations were used in the OSWQM to calculate the water self-purification demand.

Cluster analysis (CA) can be used to classify or cluster objects based on their similarity, among which hierarchical cluster analysis (HCA) is a commonly used method (Zhou et al., 2007). Discriminant analysis (DA) is usually used to confirm the clusters found by CA and to identify significant parameters (Hajigholizadeh and Melesse, 2017). Stepwise DA can gradually remove insignificant variables from the discriminant function until the variables with significant discriminant ability are screened out to establish the optimal discriminant function, which can be used for quantitative identification of significant variables (Hajigholizadeh and Melesse, 2017). In our previous study (Meng et al., 2020), the water quality monitoring points in the

XSWR were divided into groups by HCA, and stepwise DA was used to confirm the groups found by HCA and to identify significant indicators (COD_{Cr} and BOD_5) responsible for spatial variations. These two indicators can reflect the spatial difference of the overall water quality and have 100% accurate discrimination ability. Cluster A (Z3-Z5, Z8, Z10, and G9) and Cluster B (Z1, Z2, Z6, Z7, Z9, and G1-G8) corresponded to a low pollution region and a high pollution region, respectively. The river pollution showed significant spatial differences, which was consistent with the calculation results of the CWQI in this paper.

CA and DA can be used to analyze the spatiotemporal variation characteristics of water pollution and quantitatively identify the most important discriminating water quality indicators responsible for spatiotemporal variations, which avoid the subjective selection of water quality indicators in the past and gives full consideration to the different characteristics of polluted river reaches, resulting in more scientific calculations.

Calculation of water self-purification demand

It should be noted that there is one assumption for the calculation of water self-purification demand, that is, the water quality indicator concentrations at the UCC of each calculated reach were the water quality criteria for the water function zone upstream, rather than the actual concentrations. If the water quality indicator concentrations at the UCC were the true discharge concentrations, some heavily polluted reaches usually have no water environmental capacity, a measure of the water’s maximum capacity to accommodate a pollutant within a unit of time, which can be classified into attenuation capacity and assimilation capacity. Therefore, it is necessary to strengthen the control of pollution input.

The uncertainty in the determination of e-flow

In addition, e-flow is used to coordinate the contradiction of water demand between river ecosystems and human production and life and is usually calculated based on specific conservation objectives and hydrological characteristics of local rivers, so the recommended e-flow value is not unique but uncertain. Coupled with model parameter uncertainty (Wu et al., 2022), the e-flow can be adjusted by river administrators and stakeholders in special situations.

Conclusions

This paper studied the minimum e-flow of polluted rivers in areas lacking ecological data considering water quantity and quality. The results of the CWQI showed that the water pollution in the XSWR was serious, and only 4 of the 19 water quality monitoring sites met Classes II-III, while the other 15 monitoring sites all exceeded Class III. The significant water quality indicators (COD_{Cr} and BOD_5) reflected the spatial difference of overall water quality can be used in the OSWQM to calculate the water self-purification demand. The calculation results of the Tennant method showed that the ecological water demands of the 7 hydrometric stations were different, and the ecological water demands did not completely increase along the river. Under the standard situation of sewage discharge, the calculation results of OSWQM showed that the water self-purification demands of Xiu and Hew Stations were 0.74 m^3/s and

5.98 m^3/s, respectively. The e-flow of Xiu Station was 0.74 m^3/s and that of Hew Station was 5.98 m^3/s. The e-flows ranged from 0.85 to 1.62 m^3/s at Ji Station, 1.55 to 7.38 m^3/s at Qi Station, 0.41 to 4.80 m^3/s at Heg Station, 0.40 to 5.35 m^3/s at Huang Station, and 0.13 to 5.29 m^3/s at Liu Station. Except for Hew Station, the recommended e-flows of the other stations were close to the results calculated by RVA.

According to the analysis of the surplus and deficit of e-flows, only Hew Station was markedly short of water among the 7 hydrometric stations, and Liu Station has small amount of water shortage, while the e-flows of the other stations can be satisfied. Finally, some guarantee measures were proposed to improve the ecological status of the studied river and canal. These results can provide a reference for the study of e-flows of polluted rivers in developing countries/regions lacking long-term ecological datasets and contribute to ecological restoration and efficient management of water resources in these areas.

Data availability. The data used to support the findings of this study are available from the corresponding author upon request.

Conflict of interests. The authors declare that there are no conflicts of interests regarding the publication of this paper.

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