Standards for environmental flow verification

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Abstract
Healthy river ecosystems are conducive to the sustainable use of water resources. As the climate change and human activities become more intense, the integrity of such ecosystems is seriously threatened. The maintenance of enough environmental flow (e-flow) for river ecosystems is the most effective way of protecting river health. Accurately and reasonably estimating e-flow is essential for river health maintenance. So far, few methods can quantitatively verify the e-flow results calculated by various e-flow methods, which reduces the success rate of ecological restoration projects on a global scale. Therefore, the Tennant method, wetted perimeter (WP) method, and adapted ecological hydraulic radius (AEHRA) method have been recognized by many scholars. The article used the combination of these three methods to calculate the e-flow and its meeting rate (actual flow/e-flow) and formed a new framework to verify e-flow results. First, the Shannon diversity index, index of biological integrity (IBI), and river health index are used to evaluate river health status. Then, we studied the relationship between e-flow meeting rates and three indices using field monitoring data on hydrology, water quality, and biological communities. Finally, we investigated the effects of different e-flow calculation methods on river health. Results show that the e-flow in the centre of the study area calculated by the Tennant and WP methods are relatively high (48.33–317 m³/s), whereas lower e-flow (0.03–21 m³/s) are observed in its southern and northern parts. The e-flow in the southern mountain area calculated by the AEHRA method (1.42 m³/s) is higher than those in the other regions determined by the same method. Furthermore, the highest values of river health—the Shannon diversity index (3.19), IBI (67.47), and river health index (0.65)—appear in mountainous areas that are less affected by human activities. The lowest values appear in the urban areas with river health values (0.97, 14.54, and 0.45, respectively) with high population density. For the river health scores, the values of the Shannon diversity index and IBI first increase and then decrease with the increase in the e-flow meeting rates. The values of river health index continuously increase with the increase in the WP- and AEHRA-calculated e-flow meeting rate and fluctuate with the increase of Tennant-calculated e-flow meeting rate. We concluded that the adoption of WP- and AEHRA-calculated e-flow values can maintain the health of river ecosystems with a certain degree of pollution, whereas the Tennant-calculated e-flow can only ensure the health of river ecosystems with little pollution, the reason for which is the pollution-affected relationships between river biota communities and stream flows, and the Tennant method uses historical stream...
flow records to calculate e-flow. WP and AEHRA methods, on the other hand, do not rely on flow records. The methodologies and results can provide a scientific basis for the selection of suitable e-flow methods and therefore facilitate the projects for ecological river restoration.

**KEYWORDS**
e-flow, river health, spatial variation, standards, verification

## 1 | INTRODUCTION

The climate change and human activities have resulted in the decline of river health, which negatively affects water resource utilization and socio-economic development (Tazioli, 2009; Joniak & Kuczyniska-Kippen, 2010; Tazioli, Conversini, & Peccerillo, 2012; Wilbers, Becker, Sebesvari, & Renaud, 2014; Aquilanti et al., 2016). A healthy river ecosystem is conducive to the sustainable use of water resources, and river health is most effectively evaluated by estimating the environmental flow (e-flow). The latter is also an integral part of the river basin ecosystem management. It focuses on the inherent relationship between the ecological environment and water resources (Almazán-Gómez, Sánchez-Chóliz, & Sarasa, 2018) and coordination between water resources, ecosystems, and the society in general (Rolls et al., 2018) and changes the traditional human-centred river basin management concept. E-flow is an important index indicating whether water resources are reasonably exploited and utilized, which is critical for maintaining balanced ecosystems (Yang, Flower, & Thompson, 2013), especially the river-containing ones.

Multiple e-flow calculation methods have been developed. They can be roughly classified into hydrological (Armentrount & Wilson, 1987; Li et al., 2012; Li, Bai, Lu, Zou, & Cai, 2011), hydraulic (Peng, Chen, Wang, & Li, 2012; Poff et al., 2010; Wang, Li, Li, & Li, 2009), habitat assessment (Mackie, Chester, Matthews, & Robson, 2013; Pan, Wang, Ban, & Yin, 2015; Wu, Xu, Yin, & Zuo, 2014), comprehensive (Gopal, 2016; Shokoohi & Hong, 2011), and other (Chen, Yang, Yu, & Yang, 2011; Li, 2012) techniques. Among different e-flow calculation methods, the Tennant method is a representative hydrological technique (Tharme, 2003). For its development, Tennant (1976) used 11 rivers in Montana, 58 cross-sectional areas, 33 flows, and results of hundreds of observations. In addition, data from 21 other countries were analysed. By utilizing this method, flow percentages were determined. The Tennant method is relatively simple and convenient to use, and its results can be easily applied to water resource planning. The wetted perimeter method is the most commonly used hydraulic technique, which has lower data requirements as compared with those of the hydrological methods and considers biological habitat issues. In this method, a direct relationship between the wetted perimeter and river habitat conditions is established. Finally, the adapted ecological hydraulic radius (AEHRA) method (Liu et al., 2011) estimated the e-flow of rivers by using aquatic biological and river channel information. It fully considered the hydraulic characteristics of aquatic habitats in river channels as well as the flow velocity and water level required for the survival and reproduction of aquatic organisms. This method ensured the survival of aquatic species and is particularly suitable for the rivers lacking hydrological and ecological data. These methods have various data requirements and can be applied to rivers with different parameters; as a result, they produce different data sets and require special criteria for their validation. E-flow estimation is widely used to monitor the health of river ecosystems. However, previous research rarely quantified the effects of various methods for calculating e-flow and their meeting rates on river health, which misled river administrators and stakeholders, significantly reducing the global success rate of ecological restoration projects (Palmer, Liu, Matthews, Mumba, & D’Odorico, 2015). Therefore, it is imperative to develop a new approach to the quantitative verification of the effects of different e-flow calculation methods and related meeting rates on river health.

The earliest river health assessment was performed in Europe in the 19th century. For this purpose, river composition and various indicators of aquatic organisms were gradually incorporated into a river health assessment system containing physical and chemical water quality indices (Patrick, 1973; Smith et al., 1999; Wu, Xu, Yin, & Zuo, 2014; Zhang, Meng, Xia, Wu, & She, 2018). Many traditional quantitative methods for assessing river health are currently utilized including the River Invertebrate Prediction and Classification System (Wright, Moss, Armitage, & Furse, 1984), index of biological integrity (IBI; Karr, 1981; Petesse, Siqueira-Souza, de Carvalho Freitas, & Petere, 2016; Yang, Wang, et al., 2018; Yang, You, et al., 2018), Shannon diversity index (SHDI) (Ginebreda et al., 2010), channel and environment inventory (Peterson, 1992), rapid bioassessment protocols (RBPs) (Barbour, Graves, Plafkin, Wissman, & Bradley, 1992), and index of stream condition (Ladson et al., 1999) as well as a combined indicator system including physical, chemical, and biological elements (Zhang, Meng, Xia, Wu, & She, 2018). Among these methods, the IBI, SHDI, and RBPs are widely used by researchers. However, RBPs are a semi-quantitative technique. Therefore, Zhao, Pan, et al. (2019) quantified its qualitative indicators, formulated an objective, and performed quantitative river health assessment. Using this approach, it is possible to quantitatively determine various hydrological and biological attributes and increase the accuracy of distance- and area-related indices, thus minimizing subjective errors during their estimations.

In summary, there is a large amount of rich experience in previous studies on the use of Tennant, wetted perimeter, and AEHRA methods, so they can be applied together to study the impact of aquatic organisms on ecosystem health and human activities.
Therefore, in this article, these three kinds of technology are used to determine the e-flow and their meeting rates, and the SDHI, the IBI, and the river health index (RHS) evaluation of the influence on the river ecosystem health are also used. At the same time, the relationship between the e-flow meeting rate obtained by different methods and the three indicators is established through regression analysis and further improves the ecological restoration project worldwide success.

2 | STUDY AREA

Jinan City (36.0°–37.5°N, 116.2°–117.7°E) or ‘Spring City’ is a pilot city for the construction of a civilized ecologically safe city in China. It is bordered by Mount Tai in the south and by the Yellow River in the north and west, and the topography of its southern part is much steeper than that of the northern part (Figure 1). Hilly areas, a piedmont clinoplain, and alluvial plains span across the city from the north to the south. The altitude within the area ranges from −30 to 937 m above the sea level with a highly contrasting relief. The semi-humid continental monsoon climate in the city area is characterized by cold dry winters and hot wet summers. The average annual precipitation is 636 mm with 75% falling during the high-flow periods, and the average annual temperature is 14°C. The highest average monthly temperature ranging from 26.8 to 27.4°C is observed in July, and its lowest value ranging from 3.2 to 1.4°C is achieved in January.

Jinan City represents a typical developing city in China with an area of 8,227 km² and population of 8.90 million in 2019. Owing to the rapid industrial development and urbanization in recent decades, water resources in Jinan are severely polluted and reduced in quantity through extraction. The resulting high spatial heterogeneities of the water quality and quantity represent a considerable threat to the entire ecosystem, cleanliness of drinking water, human health, and human well-being. Due to the existence of serious ecological problems that must be urgently resolved, it is necessary to develop a facile e-flow measurement method to restore the degraded water ecosystems and sustainably manage water resources in the entire city area.

3 | DATA AND METHODS

3.1 | Data

In the springs, summers, and falls of years 2014 (hydrologically dry year), 2015 (hydrologically normal year), and 2016 (hydrologically wet year), nine large-scale field investigations were conducted to identify 37 hydrologic, water quality physical, and water quality chemical factors (Table 1). The three representative years were used to analyse the ecosystem changes that occurred under different climatic conditions.

Water depth and flow velocity were routinely monitored at the monitoring stations. The flow velocity was measured by a radio flow metre (Stalker II SVR V1.0) and traditional flow metre (LS25-1) to ensure high accuracy of the results. Water depth and river width were measured with a tape gauge. An unmanned aerial vehicle (UAV) was used to retrieve river course cross sections by taking high-resolution stereoscopic images (Zhao et al., 2017).

During nine field investigations, 480 water samples were collected. The water quality physical factors listed in Table 1 were obtained in situ with portable equipment, and the water quality chemical factors in the same table were determined by testing the water samples obtained from the monitoring sites in a laboratory within 24 h (Zhao et al., 2015).

Concurrently, fish were collected from three different habitats (pools, riffles, and runs) along a 500-m river stretch within 30 min (Barbour, Gerritsen, Snyder, & Stribling, 1999). In addition, electrofishing was conducted to ensure that a representative sample of fish species was collected at each site. All individuals collected were identified by species in situ and then counted, weighed, and recorded in field data sheets. Finally, all the identified fish were released. Specimens that could not be identified in the field were preserved in a 10% formalin solution and stored in labelled jars for the subsequent laboratory analysis (Zhao et al., 2015).

3.2 | Methods

Three methods were used to calculate the e-flow at each station. The Tennant method was applied to determine the e-flow from the measurement data. The wetted perimeter method combined the river information (such as river shape) with the measurement results (such as a time series of flow data). The ecological velocity and water depth were utilized to determine e-flow by the AEHRA method. SHDI, IBI, RHS, e-flow, and e-flow meeting rate were obtained for each sampling station at different sampling times. Finally, regression analysis was performed to verify the e-flow meeting rates calculated by different methods and examine the e-flow responses to the ecosystem health indicators.

3.2.1 | E-flow calculation

Tennant method

The Tennant method, also called the Montana method, is the most widely used e-flow calculation method in the world (Tharme, 2003). It determines the e-flow from the measurement data and considers the impact of the flow averaged over years. Karakoyun, Yumurtaci, and Dönmez (2016) reported that the flow could be divided into two different groups with an optimum flow rate (annual average rate: 60%–100%) and a very low flow rate (annual average flow: 10% to zero). In the Tennant method, the year is divided into two 6-month parts. These time intervals can be adjusted in different world regions considering seasonal changes. Meanwhile, the Tennant flow model implied that the overflow and maximum (200% of the annual average flow) flow also had positive effects on habitat sustainability. In general, 10% of the annual average flow defines
the shortest momentary flow required for sustaining the short-term water life, and 30% or more of the annual average flow is necessary for ensuring the biological integrity and sustainability of the river (Tharme, 2003).

**Wetted perimeter method**

The most common hydraulic method for e-flow calculation is the wetted perimeter method. It combines the river channel information with the flow data and takes into account the river shape. By plotting
the wetted perimeter versus discharge and identifying the point of highest curvature as the index point, the minimum e-flow can be determined (Ayyoubzadeh & Hajiesmaeli, 2017; Shang & Shang, 2018; Choi, Kim, & Choi, 2019).

**AEHRA method**

The AEHRA method analyses the principal fish species collected at various stations to obtain the ecological flow velocity \( v_{\text{ecology}} \) and ecological water depth. According to these factors, the e-flow \( Q_E \) can be estimated via Equation 1 as follows (Liu et al., 2011):

\[
Q_E = \frac{1}{n} R_{\text{ecology}} A j^{1/2}.
\]

Here, \( Q_E \) is the e-flow expressed in m\(^3\) s\(^{-1}\), \( R_{\text{ecology}} \) denotes the watercourse hydraulic radius, \( A \) is the flow area in m\(^2\), \( n \) is the Manning's roughness coefficient, and \( j \) the hydraulic slope in %.

The principal fish species determine the behaviour of the entire fish community, which can be objectively evaluated using a dominance model (Equation 2) (Zhao et al., 2011) combined with a breakpoint identification method (Zhao et al., 2015):

\[
I_{\text{importance}} = \omega_1 PCT_{\text{abundance}} + \omega_2 PCT_{\text{biomass}}.
\]

where \( I_{\text{importance}} \) represents the dominance of a species and \( PCT_{\text{abundance}} \) and \( PCT_{\text{biomass}} \) denote the relative biomass and density of the species in the entire community, respectively. \( \omega_1 \) and \( \omega_2 \) are the weights of \( PCT_{\text{abundance}} \) and \( PCT_{\text{biomass}} \), respectively (\( \omega_1 + \omega_2 = 1.0 \)), which are estimated by the weighting determination method of the centre-of-mass system (Zhao et al., 2015). After calculating the dominances of various fish species via Equation 2, the principal fish species can be screened at a station by the breakpoint identification method developed by Zhao et al. (2015), where the maximum curvature is used to identify the breakpoint and thus the dominant species within the fish communities in the study area.

In order to ensure that the calculated e-flow satisfies the survival needs of the principal fish species, the integrated ecological flow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Abbreviation</th>
<th>Name</th>
<th>Unit</th>
<th>Range (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrologic</td>
<td>FV</td>
<td>Flow velocity</td>
<td>m/s</td>
<td>0–1.69 (0.31)</td>
</tr>
<tr>
<td></td>
<td>RW</td>
<td>River width</td>
<td>m</td>
<td>2.1–320 (60.2)</td>
</tr>
<tr>
<td></td>
<td>FL</td>
<td>Flow</td>
<td>m(^3)</td>
<td>0–1.110 (166)</td>
</tr>
<tr>
<td></td>
<td>WD</td>
<td>Water depth</td>
<td>m</td>
<td>0.01–4 (0.83)</td>
</tr>
<tr>
<td>Physical</td>
<td>AT</td>
<td>Air temperature</td>
<td>°C</td>
<td>3.0–33.1 (8.35)</td>
</tr>
<tr>
<td></td>
<td>WT</td>
<td>Water temperature</td>
<td>°C</td>
<td>5.6–33.40 (5.6)</td>
</tr>
<tr>
<td></td>
<td>pH</td>
<td>pH</td>
<td></td>
<td>6.9–9.20 (0.39)</td>
</tr>
<tr>
<td></td>
<td>EC</td>
<td>Conductivity</td>
<td>mS/m</td>
<td>287–5,775 (863)</td>
</tr>
<tr>
<td></td>
<td>Tran</td>
<td>Transparency</td>
<td>cm</td>
<td>0–650 (94.14)</td>
</tr>
<tr>
<td></td>
<td>Turb</td>
<td>Turbidity</td>
<td>degree</td>
<td>0.52–924 (118.6)</td>
</tr>
<tr>
<td>Chemical</td>
<td>Ca</td>
<td>Calcium</td>
<td>mg/l</td>
<td>17.63–486 (59.08)</td>
</tr>
<tr>
<td></td>
<td>Cl</td>
<td>Chlorine</td>
<td></td>
<td>11.62–1,156 (170.9)</td>
</tr>
<tr>
<td></td>
<td>SO(_4)</td>
<td>Sulfate</td>
<td></td>
<td>43.47–1,045.7 (185.8)</td>
</tr>
<tr>
<td></td>
<td>CO(_3)</td>
<td>Carbonate</td>
<td></td>
<td>0–38.50 (4.69)</td>
</tr>
<tr>
<td></td>
<td>HCO(_3)</td>
<td>Bicarbonate</td>
<td></td>
<td>50.05–2,247 (158)</td>
</tr>
<tr>
<td></td>
<td>TA</td>
<td>Total alkalinity</td>
<td></td>
<td>44.68–1,057 (88.75)</td>
</tr>
<tr>
<td></td>
<td>TH</td>
<td>Total hardness</td>
<td></td>
<td>119–1,400 (240.7)</td>
</tr>
<tr>
<td></td>
<td>DO</td>
<td>Dissolved oxygen</td>
<td></td>
<td>1.1–15 (2.296)</td>
</tr>
<tr>
<td></td>
<td>TN</td>
<td>Total nitrogen</td>
<td></td>
<td>0.25–80.03 (6.286)</td>
</tr>
<tr>
<td></td>
<td>NH(_4)</td>
<td>Ammonia</td>
<td></td>
<td>0.07–75.8 (4.7)</td>
</tr>
<tr>
<td></td>
<td>NO(_2)</td>
<td>Nitrite</td>
<td></td>
<td>0–1.97 (0.272)</td>
</tr>
<tr>
<td></td>
<td>NO(_3)</td>
<td>Nitrate</td>
<td></td>
<td>0–22 (3.51)</td>
</tr>
<tr>
<td></td>
<td>COD</td>
<td>Chemical oxygen demand</td>
<td></td>
<td>6.32–275 (21.42)</td>
</tr>
<tr>
<td></td>
<td>KMnO(_4)</td>
<td>Permanganate index</td>
<td></td>
<td>0.57–71.5 (4.83)</td>
</tr>
<tr>
<td></td>
<td>BOD</td>
<td>Biochemical oxygen demand</td>
<td></td>
<td>0–57.5 (4.89)</td>
</tr>
<tr>
<td></td>
<td>TP</td>
<td>Total phosphorus</td>
<td></td>
<td>0–8.06 (0.71)</td>
</tr>
<tr>
<td></td>
<td>F</td>
<td>Fluoride</td>
<td></td>
<td>0.18–2.30 (0.33)</td>
</tr>
</tbody>
</table>
velocity and ecological depth required for the principal fish are calculated by the habitat suitability index (HSI) model utilizing the sampling data collected for the entire Jinan City (Zhao et al., 2015). Before that, the ecological flow velocity \( V_{\text{ecology}} \) and ecological water depth of each station were obtained at different times.

From the ecological flow velocity \( V_{\text{ecology}} \), channel roughness \( n \), and channel hydraulic gradient \( j \), the ecological hydraulic radius of the river cross section can be computed as \( R_{\text{ecology}} = n^2 \times V_{\text{ecology}}^2 \times j^2 \) (Liu & Men, 2007), after which Equation 1 is used to calculate the e-flow \( Q_e \) from \( n \), \( A \), \( j \), and \( R_{\text{ecology}} \).

### 3.2.2 | IBI calculation

IBI mainly reflects the ecosystem health from the perspective of the compositions and structures of biological groups (Karr, 1981). The most sensitive biological indicators of environmental interference were selected by quantitatively describing the relationship between the biological and abiotic factors, which primarily included indicators that reflected the community abundance, bioresistance capacity, and bionutrition status (Petesse et al., 2016). The use of IBI for assessing the health of ecosystems has been widely accepted by ecological researchers; it often includes the fish IBI (F-IBI) and zoobenthos IBI (B-IBI). In this study, F-IBI was utilized to evaluate the health status of fish communities (Zhao, Pan, et al., 2019).

Initially, we selected biometric parameters sensitive to environmental change and then screened biological parameters through analyses of their distribution range, discriminatory ability, and correlation. Distribution analysis was used to assess various biological parameters and compare their responses to human disturbance with those of established biological parameters. Only those parameters that showed a unidirectional increase or decrease with increased human interference were retained. Parameters that were considered too large, small, or unstable were accordingly screened out (Barbour et al., 1996).

The analysis of discriminatory ability was based on the boxplot method and used to analyse the distribution of the reference and interference sites of various biological parameters. Using the assessment method established by Barbour, Gerritsen, Snyder, and Stirling (1999), the overlap of the 25%–75% quantile ranges (Box IQ) between the reference sites and the interference sites was compared. Pearson correlation analysis was performed on the parameters distinguished by the boxplots, and only one of the two indices with a correlation coefficient of \( r > 0.9 \) was used. On the basis of the above analysis, the core parameters of the IBI assessment were determined, and the scores for core parameters were calculated from the distribution of the core parameters for all sites (Weigel, Henne, & Martinez-Rivera, 2002). According to the score, the 25th quantile of the IBI score distribution at the reference site was used as a criterion for health assessment. If the IBI score at a site was greater than the 25th quantile, it indicated that the site had suffered little interference and it was healthy (Zhao, Shao et al., 2019).

### 3.2.3 | Shannon’s index calculation

Several indices of species diversity have been used in biological diversity and ecological monitoring studies. Among them, ‘Shannon index’ or \( H \) is based on the communication theory and represents the uncertainty of predicting the next letter in a message or communication. This is a measure corresponding to the entropy concept as defined by Equation 3 (Hughes, 1978; Wang, Li, Liu, & Chen, 2019):

\[
H = -\sum_{i=1}^{n} p_i \ln p_i, \tag{3}
\]

where \( p_i \) is the proportion of total number of species made up of the \( i \)th species and \( n \) is the total number of species.

River health was assessed by the objective, quantitative, and comparative method developed by Zhao et al. (2019). The utilized assessment system consisted of three first-level indices (habitat, biological status, and water quality), while its nine, three, and ten second-level attributes were integrated. Weights for each index were determined at both levels using the entropy method to avoid subjectivity (Zhao et al., 2015). In these calculations, the weighted sum of the second-level indices should equal the weight of their respective first-level index. The weighted sum of the first-level indices was used to evaluate river health (Zhao, Pan, et al., 2019).

### 3.2.4 | Relationship between the e-flow meeting rate and river health

By combining the e-flow obtained by different calculation methods with the measured flow, e-flow meeting rates of each site can be obtained at different sampling times. The Tennant method utilizes the e-flow meeting level, whereas the wetted perimeter and AEHRA methods use Equation 4 to calculate the e-flow meeting rate as follows:

\[
E - \text{flow meeting rate} = \frac{\text{flow}}{e - \text{flow}} \times 100\%, \tag{4}
\]

Fish are located at the top of the aquatic ecosystem food chain. Changes in fish species reflect changes in aquatic ecosystems, and the disturbance of fish communities caused by river water pollution affects the e-flow evaluation and verification. The water quality factors that have the strongest impact on fish include ammonia nitrogen, nitrate, and nitrite levels (Dos Santos Silva et al., 2018; Dolomato, Shekk, Zukow, & Kryukova, 2011). Therefore, the fuzzy clustering method (Zhao et al., 2017) classifies stations into three levels of the water quality impact (large, small, and none) according to these three criteria. For each site type, the e-flow meeting rate and various ecosystem health indicators (SHDI, IBI, and RHS) were calculated at different sampling times. After that, regression analysis was performed to obtain e-flow meeting rates for different methods.
4 | RESULTS

4.1 | E-flow calculation results

First, the e-flow calculation by the Tennant method was performed for nine sites with large flow. The obtained results are listed in Table 2.

The highest e-flow were obtained for J12 and J23 (70.88 and 48.33 m³/s, respectively) because these two stations were located on the mainstream of the Yellow River with large flow. In contrast, stations J1, J5, J8, J39, and J48 had the lowest e-flow (0.09, 0.13, 0.14, 0.14, and 0.03 m³/s, respectively), which was mainly due to the locations of J1, J5, and J8 in the mountainous area with low flow, whereas the plain agricultural areas of J39 and J48 had low e-flow, owing to the drought that occurred during the study period. According to Figure 1, the central area (J12 and J23) has a larger e-flow, whereas the southern mountainous (J1, J5, and J8) and northern original (J39 and J48) areas have smaller e-flow. In addition, the e-flow in April–September (a rainy season) was significantly higher than that in October–March (a dry season).

By combining the cross section of each point with the measured flow and water depth obtained by ecological monitoring in Jinan City, a flow (FL)–wet perimeter (P) curve was plotted for each point in Figure 2 to determine e-flow from the breakpoints.

Using Figure 2, a curve breakpoint position can be obtained to determine an e-flow by the wetted perimeter method. The J24 channel has a rectangular shape, indicating that the wetted perimeter method is not applicable here. According to the calculation results of the wetted perimeter method, the e-flow were obtained from the curve breakpoints. The results show that the e-flow in the downtown area is the largest one followed by the e-flow in the northern plains and southern mountainous areas.

### TABLE 2 | E-flow calculated by the Tennant method

<table>
<thead>
<tr>
<th>Station</th>
<th>Flow status</th>
<th>J1 October–March</th>
<th>April–September</th>
<th>J5 October–March</th>
<th>April–September</th>
<th>J8 October–March</th>
<th>April–September</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flushing or maximum</td>
<td>1.75</td>
<td>1.75</td>
<td>2.62</td>
<td>2.62</td>
<td>2.72</td>
<td>2.72</td>
</tr>
<tr>
<td></td>
<td>Optimum range</td>
<td>0.52–0.87</td>
<td>0.52–0.87</td>
<td>0.79–1.31</td>
<td>0.79–1.31</td>
<td>0.82–1.36</td>
<td>0.82–1.36</td>
</tr>
<tr>
<td></td>
<td>Outstanding</td>
<td>0.35</td>
<td>0.52</td>
<td>0.52</td>
<td>0.79</td>
<td>0.54</td>
<td>0.82</td>
</tr>
<tr>
<td></td>
<td>Excellent</td>
<td>0.26</td>
<td>0.44</td>
<td>0.39</td>
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<td>425.3–708.83</td>
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</table>
FIGURE 2  Flow–wet perimeter curves plotted for different stations
Finally, AEHRA was used for e-flow estimation. By identifying the dominant fish at each station, the HSI model was applied to obtain its ecological flow velocity and water depth by considering the requirements for these two factors during the fish spawning period.

From the results presented and river cross sections, e-flow were obtained by the AEHRA method (Table 3).

According to Table 3, the e-flow and ecological water depths at most stations in May and June are relatively large. Because of the changes in the dominant species in summer, the ecological velocity and water depth changed as well. The stations with high e-flow were J1, J5, and J12, which were located on the southern mountainous region of the study area. This region is less affected by human activities, and the species of dominant fish are rich, leading to the highest e-flow. Moreover, J23 and J24 were located on the city centre with high degree of human agglomeration. However, because these stations belong to an urban area, their management policies are relatively good. As a result, the dominant fish and ecosystem structure are well protected, and the dominant species are abundant. The area with low e-flow is located on the northern plains. It is mainly used for agricultural cultivation characterized by excessive water intake and

<table>
<thead>
<tr>
<th>Station</th>
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<th>J11</th>
<th>J12</th>
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sewage discharge, causing a serious damage to the water ecosystem and reduction of the dominant fish species.

The results presented above indicate that the e-flow calculated by the Tennant and AEHRA methods are lower than that determined by the wetted perimeter method. Meanwhile, the e-flow calculated in the middle region of the study area by the wetted perimeter and Tennant methods are higher than the magnitudes obtained for the northern and southern regions. Finally, the e-flow in the southern mountain area calculated by the AEHRA method is higher than the e-flow in the other regions determined by the same method.

4.2 Calculated ecosystem health indicators

The SHDI, IBI, and RHS of each station were calculated from the obtained hydrological, water quality, and biological data to comprehensively evaluate river health. Their values are listed in Table 4.

According to Table 4, the highest SHDI, IBI, and RHS are obtained for J1, indicating that the latter can maintain high degrees of biological diversity and integrity for a long time that ensure good health of the river ecosystem. Because J1 is located on the southern mountainous area of Jinan City, its hydrological factors including the flow and velocity are relatively low. However, this site is also less influenced by human activities; as a result, its water quality is good, and the biological community is minimally affected by external disturbances, maintaining good ecosystem health. Compared with the other stations, J24 has the lowest SHDI, IBI, and RHS mainly because the Xiaoqing River containing this site serves as a sewage channel for Jinan City. Hence, its water pollution is more serious, which influences the survival of aquatic life and reduces the degrees of biodiversity and integrity of the water ecosystem and negatively affects the entire ecosystem.

4.3 E-flow response to ecosystem health

In order to minimize the impact of water pollution on the survival of fish and related e-flow, sampling was performed by the fuzzy clustering method that took into account various water quality factors (including the ammonium nitrogen, nitrate, and nitrite contents) strongly affecting fish populations (Kaur, Hewage, Sadiq, & Hu, 2019; Wang, 2019; Stein et al., 2020). For this purpose, all stations were divided into three categories of the water quality impact (large, small, and none) corresponding to different water quality conditions (Figure 3). After that, the categories with little or no water quality impact were selected to analyse the e-flow response to ecosystem health.

According to Figure 3, stations J1, J5, J12, J48, and J23 belong to the first category; J39 and J46 belong to the second category; and the third category includes stations J8, J24, and J11. The water quality

### Table 4 SHDI, IBI, and RHS calculated for each station

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### Table 4 continued

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Abbreviations: IBI, index of biological integrity; RHS, river health index; SHDI, Shannon diversity index.
data obtained for the first and second groups of stations satisfy the third-class surface water quality standard, and the stations in the third group do not meet the fifth-class water quality standard. Thus, it can be concluded that the water quality of the stations in the first and second clustering groups is good, while their aquatic organisms are minimally affected by water pollution. In contrast, the stations in the third group are strongly influenced by water pollution. Therefore, the stations from the first and second clusters were selected for the subsequent studies.

**Tennant method**

First, the Tennant method was used to calculate e-flow from the clustering data obtained in the previous section. By considering different meeting levels (from low to high), the e-flow meeting rate of each level was determined at various SHDI, IBI, and RHS by regression analysis (see Figure 4). The fitting curves in this figure are plotted for the first and second clustering groups.

In Figure 4, the seven levels of the e-flow meeting rate (from top to bottom: poor or minimum, ordinary, good, excellent, outstanding, optimum, and flushing or maximum) form a parabola, in which its value decreases first and then increases. Through the analysis of the breakpoint of each fitted curve, it has been found that as the e-flow meeting level increases (from top to bottom), the position of the parabola breakpoint (the red square in Figure 4) shifts to the left, indicating that the breakpoints of the SHDI, IBI, and RHS curves appear earlier with an increase in the e-flow meeting level. After the breakpoints, the three indices increase as the e-flow meeting rate gradually increases because the lower e-flow meeting rates correspond to larger flow, which ensure good health of aquatic organisms and river ecosystems.

**Wetted perimeter method**

The wetted perimeter method was used to calculate the e-flow meeting rate at each station from the obtained clustering data. Its values were divided into eight groups corresponding to 0%–0.5%, 0.5%–1%, 1%–5%, 5%–10%, 10%–20%, 20%–50%, 50%–100%, and 100% (e-flow meeting rates are greater or equal to 100%). The resulting e-flow meeting rates and SHDI, IBI, and RHS were subjected to regression analysis (see Figure 5). The fitting curves in this figure are plotted for the first and second clustering groups.

Figure 5 shows that the regression relationships between the SHDI and IBI and the e-flow meeting rates calculated by the wetted perimeter method are consistent. After increasing the e-flow meeting rate, the living conditions of aquatic organisms represented by SHDI and IBI first improve and then deteriorate. SHDI assumes the maximum value when the e-flow meeting rate reaches 1%–5%, and IBI reaches maximum when the e-flow meeting rate equals 0.5%–1%. Moreover, RHS increases with an increase in the e-flow meeting rate.
FIGURE 4  Relationships between the e-flow meeting rates determined by the Tennant method and SHDI, IBI, and RHS. IBI, index of biological integrity; RHS, river health index; SHDI, Shannon diversity index.
The SHDI and IBI reach maxima when the e-flow meeting rate is low, but the RHS continues to increase as the flow increases.

**AEHRA method**

The e-flow meeting rate was also calculated for each station by the AEHRA method from the obtained clustering data. The results were divided into eight groups corresponding to 0%–5%, 5%–10%, 10%–30%, 30%–50%, 50%–70%, 70%–90%, 90%–100%, and 100%. After that, their magnitudes and the SHDI, IBI, and RHS were subjected to regression analysis. The obtained results are presented in Figure 6. The fitting curves in this figure are plotted for the first and second clustering groups.

Figure 6 shows that the regression relationships between the e-flow meeting rates calculated by the AEHRA method and the three indices are consistent. After increasing the e-flow meeting rate, the health of the ecosystem represented by SHDI and IBI first improves and then deteriorates. SHDI reaches maximum when the e-flow meeting rate equals 5%–10%, and IBI reaches maximum when the e-flow meeting rate is equal to 10%–30%. The RHS increases with an increase in the e-flow meeting rate.

In summary, the SHDI, IBI, and RHS magnitudes decrease with increases in the e-flow meeting rates of the seven levels calculated by the Tennant method and then increased. The SHDI and IBI first increase and then decrease with increasing e-flow meeting rates calculated by the wetted perimeter and AEHRA methods, whereas RHS steadily increases with the e-flow meeting rate.

5  |  DISCUSSION

5.1 | Analysis of the e-flow calculated by different methods

In this study, it was found that the e-flow calculated by the Tennant and AEHRA methods were lower than those computed by the wetted perimeter method. The e-flow determined by the wetted perimeter and Tennant methods in the centre of the study area are higher than the e-flow in the northern and southern regions. Meanwhile, the e-flow in the southern mountain areas calculated by the AEHRA method are higher than those computed by the same method for the other regions. Because the calculations by the Tennant and wetted perimeter method are based on the flow and channel information (Poff et al., 2010), they produce larger e-flow in the centre of the study area due to the large flow. Note that AEHRA takes the survival and reproduction of dominant fish in the river into account (Liu et al., 2011), while the southern mountain area is less affected by human activities, and its dominant species are rich. Therefore, the AEHRA method produces the highest e-flow in this region.

Because the flow data obtained for the 10 collected samples were used to calculate the e-flow by the Tennant method, the latter did not consider the natural runoff. Hence, the multiyear average flow data, multiyear average flow reverting the natural runoff, and sampling data reverting the natural runoff were calculated in the same way. The obtained results are shown in Figure 7. The relative value of the

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**FIGURE 5**  Relationships between the e-flow meeting rates calculated by the wetted perimeter method and the SHDI, IBI, and RHS. IBI, index of biological integrity; RHS, river health index; SHDI, Shannon diversity index

**FIGURE 6**  Relationships between the e-flow meeting rates calculated by the adapted ecological hydraulic radius method and the SHDI, IBI, and RHS. IBI, index of biological integrity; RHS, river health index; SHDI, Shannon diversity index
e-flow meeting rate was used instead of the absolute e-flow to analyse the impact of e-flow on the ecosystem health. According to the definition of the e-flow meeting rate, when the three types of data including the multiyear average flow data, multiyear average flow data restoring the natural runoff, and sampling data restoring the natural runoff are used in the Tennant method, the e-flow in the denominator changes accordingly, but the measured flow in the numerator remains the same, which changes the resulting e-flow meeting rate. The corresponding SHDI, IBI, and RHS parameters remain unchanged; hence, the curves plotted for the three different types of data have the same shape (Figure 7) despite the changes along the x-axis. Therefore, using the measured flow instead of the natural runoff data to calculate the e-flow meeting rate by the Tennant method does not affect the conclusions of this study.

5.2 Analysis of the ecosystem health indicators

In this study, SHDI, IBI, and RHS were used to evaluate the health of river aquatic ecosystems. Their values were obtained from the number, richness, and integrity of aquatic species and by performing a comprehensive evaluation of the hydrological water quality and aquatic life. It was found that the water quality conditions were better in the mountainous areas that were less affected by human activities. They also possessed the highest SHDI, IBI, and RHS magnitudes, indicating that their aquatic ecosystems were the healthiest. In the urban areas with severe water pollution, the water quality conditions deteriorated, which ultimately decreased the SHDI, IBI, and RHS and strongly affected water ecosystems. In a previous study on the effect of water pollution on river health, it was found from the obtained physicochemical data that the river health rapidly deteriorated due to the impact of water pollution and habitat change. Wang and Yang (2016) assessed the river health status, and the obtained results showed that land usage and water pollution were the most important factors affecting river health (Wang & Yang, 2016). Both studies show that water pollution strongly influences river health, which is consistent with the conclusions of this work. Ginebreda et al. (2010) evaluated the effects of various compounds present in wastewater on the aquatic life in rivers. As a result, SHDI demonstrated a negative correlation with the contaminant concentration (Ginebreda et al., 2010). It was found that water pollution decreased the SHDI of river aquatic organisms, which was consistent with the results of our research.
Kimmel and Argent (2016) found that the IBI of fish and large invertebrate communities was strongly affected by the differences in the local environmental conditions of the Allegheny River in Pennsylvania. Azimi and Rocher (2016) found that 23 years of water pollution control increased the number of fish species in rivers and IBI of the Seine River around the Paris conurbation (France) (Azimi & Rocher, 2016). Their research suggested that water pollution could reduce the IBI. These conclusions are consistent with the lower SHDI, IBI, and RHS obtained in the regions with higher degrees of river water pollution caused by poor water quality. The survival of aquatic organisms in a river increases the degrees of biodiversity and integrity. At the same time, the river health assessment procedure includes not only the examination of aquatic organisms, but also the direct evaluation of water quality factors, which assume lower values in the regions with poor water quality. However, after implementing the pollution control of the water environment and a sufficiently long time of the water quality adjustment, various indices of the river ecosystem and the overall health index increase again. Nazeer et al. (2016) found that poor ecological conditions in streams were generally related to the urban sewage discharge and habitat fragmentation in the lower Himalayas. Their degrees of urbanization were relatively low, including superior ecological integrity (Nazeer et al., 2016). The results of these work show that the ecological conditions in the urban area are poor, whereas those of the streams in the grassland and forest areas are good, which is consistent with the conclusions reached in this study regarding the poor ecological health of the urban areas and good river health conditions in the mountainous areas. Snyder, Young, Villella, and Lemarie (2003) found that the urban land use interrupts the flow, reduces the water quality, and changes the river shape, which ultimately decreases IBI and influences the health of the Opequon Creek (Snyder, Young, Villella, & Lemarie, 2003), which is consistent with the poor aquatic health of the urban rivers and lower IBI in our work. These studies have shown that the urban land use and urbanization levels can affect the health of river ecosystems and that the grasslands and forests less affected by human activity exhibit high ecological integrity. Their water quality conditions are good, and the corresponding SHDI, IBI, and RHS are relatively large.

5.3 Analysis of the e-flow responses to ecosystem health indicators

The Tennant, wetted perimeter, and AEHRA methods were used to calculate the e-flow meeting rates from the flow measured at different sampling times and stations. Afterwards, the corresponding SHDI, IBI, and RHS were determined. The obtained results revealed that the SHDI, IBI, and RHS parameters first decreased with an increase in the e-flow meeting rate calculated by the Tennant method and then increased. The SHDI and IBI first increase and then decrease with the increases of meeting rates calculated by the wetted perimeter and AEHRA methods, and the RHS magnitude steadily increases with increasing meeting rate. The results obtained by the Tennant method are summarized in Figure 8.

According to this figure, the largest SHDI and IBI are obtained when the e-flow calculated by the Tennant method reaches level 5, which is relatively high. The RHS magnitude does not significantly change as the e-flow increases from level 1 to level 7. When it reaches level 8, the river health suddenly improves because various types of aquatic organisms have their own adaptive velocities and flow. When the flow is moderate, it can increase the biodiversity index and IBI. When the flow is too high, it decreases the biodiversity index and IBI. However, because the RHS parameter takes the hydrological and water quality factors into account, when the flow increases, the hydrological score increases as well, and the water quality conditions gradually improve. The survival of aquatic organisms is also affected to a certain extent, changing the river health score, which exhibits a steady upward and downward floating trend. When the flow increases significantly, the improvements of the hydrological and water quality conditions mask the poor state of aquatic life, thus increasing the RHS.

The Tennant method was applied in this work, and e-flow responses to various indicators such as RHS were analysed. Owing to the complex terrain of the study area including mountains and plains, the rivers in the plains inhabited by humans have been extensively transformed; as a result, some calculation data do not meet the assumptions made at the time the method was established. The Tennant method is based on the existence of permanent rivers in dry and semi-dry areas. The recommended baseflow standard for evaluating the quality of habitat environment is set within the range from 10% to 200% of the average flow (Tennant, 1976). During the low-flow period, the e-flow in the rainy season is 30% of the average daily flow, and the e-flow in the dry season is 10% of the average daily flow. Tennant (1976) found that when the flow rate dropped from a 30% multiyear average flow to a 10% multiyear average flow, both the habitat conditions and river state changed significantly. Another important observation is that the close multiyear average flow percentages of most rivers correspond to similar aquatic habitat conditions, indicating that when flow are within 30%–60% of their multiyear average flow, good fish habitat can be maintained. These observations are consistent with the conclusions drawn in this work. When the ecological water demand satisfaction rate reaches the 'excellent' level, the biodiversity index and IBI of fish achieve their peaks corresponding to 30%–60% of the river flow averaged over years. In the case of high water quality impact, the Tennant method does not consider water quality factors when calculating the e-flow meeting rate, which strongly affects the relationship between the meeting level and ecosystem health, which exhibits a steady upward and downward floating trend. Along with continuing increase in water amount, the river water quality conditions are improved, ultimately improving the river health.

The wetted perimeter method indirectly considers water quality. It was developed to protect aquatic habitats in critical areas and provide adequate protection to habitats in non-critical areas. In a curve describing the relationship between the perimeter and water discharge, the flow at a breakpoint represents the minimum e-flow. The AEHRA method also potentially considers the impact of the river water...
quality conditions (Zhao et al., 2017), and the calculated e-flow meets
the aquatic living standards under these conditions. Both the wetted
perimeter and AEHRA methods utilize river cross sections and shapes,
which often change in the areas with intense human activities. The e-
flow calculation method based on river cross sections can reflect
the actual situation of the e-flow change with the cross section and thus is
more suitable for the areas strongly affected by human activities than
the Tennant method that does not consider the river cross section.
Therefore, along with increasing the e-flow meeting rates calculated
by the Tennant, wetted perimeter, and AEHRA methods, the SHDI and
IBI of fish increase first and then decrease. However, the RHS
continues to increase with increases in the e-flow meeting rates
calculated by the wetted perimeter and AEHRA techniques.

6 | CONCLUSION

In this study, the e-flow is calculated by the Tennant, wetted
perimeter, and AEHRA methods to obtain the e-flow meeting rates at
various stations and sampling times. The e-flow meeting rates
calculated by these methods and the SHDI, IBI, and the RHS para-
ters are subjected to regression analysis. From the obtained results,
the following conclusions have been drawn.

1. The data obtained by the Tennant and wetted perimeter methods
   show that the e-flow is high in the centre of the study area and
   relatively low in the southern and northern regions. The e-flow in
   the southern mountain area calculated by the AEHRA method is
greater than those in the other regions computed by the same
method.
2. In the mountainous areas that are less affected by human
   activities, the SHDI, IBI, and the RHS reach the highest values. The
domestic garbage generated in the areas with larger human
populations seriously threatens the urban river water environment,
whereas mountains, grasslands, and forests have maintained their
original ecological integrity very well, and the health of their river
ecosystems is good.
3. The Tennant method does not consider the water quality factors
   when calculating the e-flow meeting rate, which strongly affects
   the relationship between the satisfaction level and the ecosystem
   health. As the meeting level of the e-flow continues to increase,
   which promotes the improvement of the river water quality
   conditions, the effect of the water quality conditions on aquatic
   organisms gradually decreases. After the increase in the e-flow
   meeting rates calculated by the Tennant, wetted perimeter, and
   AEHRA methods, the SHDI and IBI of fish increase first and then
decrease. Meanwhile, the RHS parameter continuously increases
   with the increases of e-flow meeting rates calculated by the
   wetted perimeter and AEHRA methods.
4. We concluded that the adoption of wetted parameter- and
   AEHRA-calculated e-flow values can maintain the health of river
   ecosystems with a certain degree of pollution, whereas the
   Tennant-calculated e-flow can only ensure the health of river
   ecosystems with little pollution.

In this work, three different e-flow calculation methods that
considered the river conditions are used to analyse the relationships
between the e-flow meeting rate and the three indicators of
ecosystem health. The latter represent the true state of river health
with relatively high accuracy. However, due to the lack of a time
series of aquatic data, some of the obtained results have small errors.
In the future, it is necessary to develop some new methods to
increase the length of spatiotemporal data series at different
hydrological frequencies and ensure the practicality of e-flow
calculations for areas with insufficient data.

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CONFLICT OF INTEREST

None.

FIGURE 8  Relationships between the e-flow meeting levels calculated by the Tennant method and the corresponding SHDI, IBI, and RHS. IBI, index of biological integrity; RHS, river health index; SHDI, Shannon diversity index
DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

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