Research papers

Calculating e-flow using UAV and ground monitoring

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\textbf{ABSTRACT}

Intense human activity has led to serious degradation of basin water ecosystems and severe reduction in the river flow available for aquatic biota. As an important water ecosystem index, environmental flows (e-flows) are crucial for maintaining sustainability. However, most e-flow measurement methods involve long cycles, low efficiency, and transdisciplinary expertise. This makes it impossible to rapidly assess river e-flows at basin or larger scales. This study presents a new method to rapidly assessing e-flows coupling UAV and ground monitorings. UAV was firstly used to calculate river-course cross-sections with high-resolution stereoscopic images. A dominance index was then used to identify key fish species. Afterwards a habitat suitability index, along with biodiversity and integrity indices, was used to determine an appropriate flow velocity with full consideration of the fish spawning period. The cross-sections and flow velocity values were then combined into AEHRA, an e-flow assessment method for studying e-flows and supplying-rate. To verify the results from this new method, the widely used Tennant method was employed. The root-mean-square errors of river cross-sections determined by UAV are less than 0.25 m, which constitutes 3–5% water-depth of the river cross-sections. In the study area of Jinan city, the ecological flow velocity ($V_{EC}$) is equal to or greater than 0.11 m/s, and the ecological water depth ($H_{EC}$) is greater than 0.8 m. The river ecosystem is healthy with the minimum e-flow requirements being always met when it is close to large rivers, which is beneficial for the sustainable development of the water ecosystem. In the south river channel of Jinan, the upstream flow mostly meets the minimum e-flow requirements, and the downstream flow always meets the minimum e-flow requirements. The north of Jinan consists predominantly of artificial river channels used for irrigation. Rainfall rarely meets the minimum e-flow and irrigation water requirements. We suggest that the water shortage problem can be partly solved by diversion of the Yellow River. These results can provide useful information for ecological operations and restoration. The method used in this study for calculating e-flow based on a combination of UAV and ground monitoring can effectively promote research progress into basin e-flow, and provide an important reference for e-flow monitoring around the world.

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\textsuperscript{**}Abbreviations: BDK, Bingdukou; BDSH, Beidashahe; DSM, digital surface model; e-flow, environmental flow; $H_{EC}$, ecological water depth; HSI, habitat suitability index; HTQ, Huantiaqiao; IBI, index of biotic integrity; JYH, Juyehe; LK, Luokou; MHSI, multispecies-based HSI; NYZ, NieYingZha; $Q_{EC_{min}}$, minimum e-flow; RMSE, root mean square error; $V_{EC}$, ecological flow velocity; UAV, Unmanned aerial vehicle; ZGLNL, Zhanggongnanlin.

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1. Introduction

Today, the global increase in human activities has led to serious water pollution, water resource shortages, and uncontrolled mining and use of groundwater, resulting in river blanking, river drying, water and soil loss, water environment deterioration, and biodiversity loss (Tazioli, 2009; Joniak and Kuczyńska-Kippen, 2010; Tazioli et al., 2012; Wilbers et al., 2014; Aquilanti et al., 2016). Also groundwater scarcity and water loss can be serious environmental problems in a watershed, especially in some areas
of the world (Comodi et al., 2011; Tazioli et al., 2015). The river ecosystem is an important link between sediment transport and energy conversion, and is vital for maintaining a healthy basin ecosystem. However, the deterioration of basin water ecosystems and uncontrolled use of water resources cause river flows that are far below that required by the aquatic biota. This seriously affects the health of the river ecosystem. Environmental flow (E-flow) is an important index for evaluating whether water resources are reasonably exploited and utilized, and critical for maintaining a balanced ecosystem (Yang et al., 2013). Therefore, to maintain sustainable water resource use and healthy river ecosystems, it is important to further conduct valid e-flow research.

There are many methods for calculating e-flow. They can be divided into outer river and inner river methods according to ecosystem location (Cui and Zhang, 2010). The outer river mainly consists of wetlands, groundwater, vegetation, and city environments (Xu et al., 2005; Chen et al., 2012; Napíorkowska-Krzebietke and Dunalska, 2015); e-flow is indirectly calculated based on evapotranspiration, biomass, and remote sensing. In all e-flow methods, the proportion for inner river is far more than that for the outer river.

Inner river e-flow methods mainly include rivers, lakes, and estuaries, and can be roughly divided into hydrology (Armentrout and Wilson, 1987; Li et al., 2011, 2012), hydraulics (Wang et al., 2009; Peng et al., 2012; Yu et al., 2016), habitat (Stalnaker et al., 1995; Scharbert and Borcherding, 2013; Wu et al., 2014; Yang et al., 2008; Pan et al., 2015; Mackie et al., 2013), comprehensive (Shokooei and Hong, 2011; Wang et al., 2013b; Gopal, 2016), and other methods (Chen et al., 2011; Li, 2012; Shang et al., 2014). These methods have various data requirements and can be applied to rivers with different datasets, details please refer to Liu et al. (2011) and Tharme (2003). However, with most methods, it is difficult to acquire channel parameters, and obtaining accurate data is not time- and cost-effective, necessitating transdisciplinary expertise.

Rapid assessment of river e-flows is necessary to protect or restore aquatic ecosystems, ensure sustainable use of limited water resources under intensive human activities at basin or larger scales, and maintain sufficient river flows for biota. In recent years, due to the rapid development of UAV, it has become possible to rapidly, flexibly, conveniently, and efficiently acquire ground information. These advances in UAV can effectively increase the cost-effectiveness of data collection. Therefore, a combination of UAV and ground monitoring data can promote the necessary advances in e-flow assessment.

The objective of this study is to present a new method for rapid e-flow assessment based on UAV and ground monitoring data. River-course cross-sections are critical parameters for both river flow calculation and e-flow assessment. They are retrieved using high-resolution UAV stereoscopic images, and combined into AEHRA, an e-flow assessment method by Liu et al. (2011) for studying e-flows and supplying-rate. The method in this study can rapidly assess river e-flows and help to promote the understanding and assessment of regional river health.

2. Study area and data

2.1. Study area

Jinan City, the “City of Springs” (36.0–37.5 N, 116.2–117.7E), is a pilot city for the construction of a civilized and ecological city in China. Bordering by Mount Tai to the south and traversed by the Yellow River, it has steeper topography in the south than in the north (Fig. 1). Hilly areas, piedmont clinoplain, and alluvial plains span the city from south to north. The altitude ranges from –30 to 957 m above sea level, with steep relief. The semi-humid continental monsoon climate in the city is characterized by cold, dry winters and hot, wet summers. The average annual precipitation is 636 mm, 75% of which falls during high-flow periods. The average annual temperature is 14.3 °C. The average monthly temperature is highest in July, ranging from 26.8 to 27.4 °C, and lowest in January, ranging from 1.4 to 3.2 °C (Cui et al., 2009; Zhang et al., 2010). The city represents a typical developing city in China, with an area of 8227 km2 and a population of 5.69 million (Zhang et al., 2007). With rapid industrial development and urbanization in recent decades, the water resources in Jinan have become severely polluted and reduced through extraction (Hong et al., 2010; Zhao et al., 2015a). The pollutants mainly include high concentration of chemical oxygen demand, total nitrogen, total phosphorus and ammonia nitrogen. Policy-makers and stakeholders are aware of the need to rehabilitate the aquatic ecosystems in Jinan City. To ensure successful aquatic ecosystem restoration over all river sections at the basin scale, river administrators urgently require a method for rapid and timely estimation of e-flows to maintain sufficient river flows for aquatic ecosystems.

2.2. Data

To facilitate research programs into the rehabilitation of aquatic ecosystems in Jinan City, 59 routine monitoring stations were established, distributed evenly along main rivers (Fig. 1). At these monitoring stations, both hydrologic parameters and fish communities were concurrently measured during eight field campaigns from 2014 to 2016.

Of the 59 monitoring stations, we selected 6 typical points to assess e-flows and one to validate the method presented in this study. Among them, Bingdukou (BDK) is located on the southern-most mountain of the study area, and effectively represents the e-flow of south Jinan. Beidashahe (BSDH) is the entrance where the Yellow River enters the study area, reflecting the Yellow River e-flow in Jinan. Luokou (LK), Huangtaiqiao (HTQ), and Juyehe (JYH) are located in the city center, representing e-flow under intense human activities. Zhanggongnanlin (ZGLN) reflects e-flow in the northern plain area. NieYingZha (NYZ) has abundant historical hydrologic data; therefore, it is used to verify the reliability of the method.

At the routine monitoring stations, hydrological parameters including water depth and flow velocity, as well as fish data, were routinely monitored. Flow velocity data were acquired by combining an electric wave current-meter (Stalker II SVR V1.0) and a traditional current meter (No. LS25-1), thereby guaranteeing the precision of the measured results. Both water depth and river width were measured using tape. River flow was calculated using flow velocity and water depth.

Fish were collected during a 30-min period in three habitat types (i.e., pools, riffles, and runs) within a 500-m section along the river at each sampling site. Fish caught from the three habitats were combined to represent each site. In wadeable streams, fish collection was performed by a two-person team (Barbour et al., 1999). In unwadeable streams, seine nets (mesh sizes of 30 and 40 mm) were used to collect fish from a boat. In addition, electrofishing was conducted to ensure that a good representation of fish species was collected at each site. All fish collected were identified in situ by species according to Chen et al. (1987) and then counted, weighed, and recorded in field data sheets. Afterwards, all identified fish were released. A few specimens that could not be identified in the field were preserved in 10% formalin solution and stored in labeled jars for subsequent laboratory identification. Table 1 shows the fish species recorded in Jinan City during the eight field campaigns from 2014 to 2016.
3. Method

3.1. Using UAV to determine channel cross-section

Channel sections are critical parameters for calculating e-flow and are usually acquired by the traditional, artificial measurement method. In this study, UAV was employed to acquire high-resolution stereoscopic images, which were used to obtain high-resolution topographic data, and the channel section was then calculated using the 3D Analyst module of ArcGIS 10.4.

The stereoscopic images were processed by the rapid and automatic professional processing software Pix4Dmapper (https://pix4d.com/). Image treatment includes data importing, initial processing, point cloud encryption, digital orthophoto map (DOM) generation, and digital surface model (DSM) generation (Turner et al., 2014; Ruzgiene et al., 2015).

UAV images can only acquire above ground topography information; it is difficult to obtain underwater topography. To acquire a full cross-section, above ground topography was confirmed by UAV and underwater topography was fitted using the measured water depth and cross-section. In a natural river channel, the

Fig. 1. Study area and the monitoring points.
cross-sections can be divided into four types: circular arc, box culvert, trapezoid, and "V" shape (Liu et al., 2007). In this study, circular arc cross-sections include JYH and ZGNL, box culvert includes BDK and HTQ, and "V" shape includes BSDH and LK. The underwater topography can be generalized as shown in Table 2.

### 3.2. Determination of dominant fish species

Abundance and biomass are fundamental indices for biological monitoring. The two indices often rank differently, which makes it difficult to objectively assess the dominance or importance of a species in a community (Liu et al., 2011). To overcome this, Liu et al. (2011) combined them into one index using Eq. (1).

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

where "importance" stands for the dominance of a species and \( I_{\text{abundance}} \) and \( I_{\text{biomass}} \) refer to the ratio of the species’ abundance and biomass to the total for the communities, respectively. The larger the "importance," the more the species contributes to its community, and the more important it is in the community. Parameters \( \omega_1 \) and \( \omega_2 \) are the weightings of abundance and biomass, \( \omega_1 + \omega_2 = 1.0 \), which are determined in our research (Zhao et al., 2015a) as 0.41 and 0.59, respectively.

### 3.3. Determination of ecological velocity and water depth for AEHRA

The habitat suitability index (HSI), varying between 0 and 1, is an effective indicator quantifying the response of a species to a set of habitat attributes (Ban et al., 2009; Vadas and Orth, 2001; Vismara et al., 2001). It is widely used to indicate the degree of preference of a species to various habitats (Leclerc et al., 2003; Ahmadi-Nedushan et al., 2006). Highly preferred habitats usually have high HSI values. Previous methods for determining HSI typically target one species (Wakeley, 1988; Tikkkanen et al., 2007; Gong et al., 2012; Zohmann et al., 2013) instead of multiple species or a community, which makes it difficult to estimate the synthetic effect of a habitat factor on the ecosystem community (Zhao et al., 2015b). For this purpose, Zhao et al. (2015b) developed a new multispecies-based HSI (MHSI) to estimate the multi-species response to habitat environmental factors (Eq. (2)). In this method, the accumulated suitability probability, based on the preference of multiple dominant species (Eq. (5)), is used to represent the effect of habitat factors on the community at a certain gradient.

\[
\text{MHSI}_k = \sum_{i=1}^{K} p_{ki} \cdot \frac{n_i}{N_i}
\]

where \( k \) stands for the \( k \)th gradient of a certain habitat environmental factor, e.g., flow velocity, water depth, \( k = 1, \ldots, K \); \( K \) is the total number of gradients along the habitat factor; \( i \) stands for the \( i \)th dominant species (\( i = 1, \ldots, I \)); \( I \) is the total number of the dominant species; \( n_i \) is the abundance of the \( i \)th species in the \( k \)th gradient of the habitat factor; \( N_i \) is the abundance of the \( i \)th species in all gradients of the habitat factor, \( N_i = \sum_{k=1}^{K} n_{ki} \); \( p_{ki} \) is the suitability probability of the \( i \)th species in the \( k \)th gradient; \( \text{MHSI}_k \) is the multispecies-based HSI, i.e., the suitability probability of all dominant species in the \( k \)th gradient, varying between 0 and 1.

Biodiversity index and IBI (Index of Biotic Integrity) are often used as indicators for ecosystem health (Weaver and Shannon, 1949; Wu et al., 2014; Zhao et al., 2015b). The goal of e-flow monitoring is to maintain the health of river ecosystems. Therefore, the biodiversity index and IBI were introduced to this study to help determine the ecological velocity and water-depth for AEHRA.

### 3.4. Calculating e-flow and supplying-rate

#### 3.4.1. E-flow assessment (Q_E) using AEHRA

The basis of AEHRA is the determination of ecological velocity (\( V_E \)). The velocity requirements of fish species vary by season, which can be determined using the HSI (Eq. (2)). Having obtained the \( V_E \), e-flow, \( Q_E \), in the river section can be estimated using

---

**Table 1**

Fish species recorded in Jinan City during the eight field campaigns from 2014 to 2016.

<table>
<thead>
<tr>
<th>No.</th>
<th>Species</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Opsariichthys indens Gunther</td>
</tr>
<tr>
<td>2</td>
<td>Carassius auratus</td>
</tr>
<tr>
<td>3</td>
<td>Pseudorasora parva</td>
</tr>
<tr>
<td>4</td>
<td>Mastacembelus aculeatus</td>
</tr>
<tr>
<td>5</td>
<td>Hemichalon lacustris</td>
</tr>
<tr>
<td>6</td>
<td>Sarcocheilichthys marmoratus</td>
</tr>
<tr>
<td>7</td>
<td>Gnathopogon imberbis</td>
</tr>
<tr>
<td>8</td>
<td>Misgurnus anguillicaudatus</td>
</tr>
<tr>
<td>9</td>
<td>Monopterus albus</td>
</tr>
<tr>
<td>10</td>
<td>Huigulus chinensis</td>
</tr>
<tr>
<td>11</td>
<td>Rhodorus ocellatus</td>
</tr>
<tr>
<td>12</td>
<td>Ctenogobius cliffordiropaei</td>
</tr>
<tr>
<td>13</td>
<td>Hypseleotris swomanonis</td>
</tr>
<tr>
<td>14</td>
<td>Ctenogobius giurinus (Rutter)</td>
</tr>
<tr>
<td>15</td>
<td>Percottus glenii</td>
</tr>
<tr>
<td>16</td>
<td>Lepisosteus osseus</td>
</tr>
<tr>
<td>17</td>
<td>Ctenobogus clifordiropaei</td>
</tr>
<tr>
<td>18</td>
<td>Pelteobagrus jadavdraco</td>
</tr>
<tr>
<td>19</td>
<td>Piceus</td>
</tr>
<tr>
<td>20</td>
<td>Ceratobagrus gemmifer</td>
</tr>
<tr>
<td>21</td>
<td>Paramisgobius danaobius (Sauvage)</td>
</tr>
<tr>
<td>22</td>
<td>Silurus asotus Linnaeus</td>
</tr>
<tr>
<td>23</td>
<td>Cyprinus carpio Linnaeus</td>
</tr>
<tr>
<td>24</td>
<td>Pseudorasora jadavdraco (Nichols)</td>
</tr>
<tr>
<td>25</td>
<td>Clarias fuscus</td>
</tr>
<tr>
<td>26</td>
<td>Aphyocypris latipes</td>
</tr>
<tr>
<td>27</td>
<td>Lateolabrax japonicus</td>
</tr>
<tr>
<td>28</td>
<td>Spaludobagrus curriculus</td>
</tr>
<tr>
<td>29</td>
<td>Hypophthalmichthys molitrix</td>
</tr>
</tbody>
</table>

---
AEHRA (Eq. (3)). Cross-sectional data used as essential input variables were rapidly retrieved using the method in Section 3.1.

\[
Q_E = \frac{1}{n} P^2 \sqrt{A_E J} \quad \text{with} \quad R_e = n^2 V^2 E J \quad \text{Liu et al., 2011}
\]  

\(Q_E\) is e-flow in m³/s; \(R_e\) refers to the watercourse hydraulic radius (ratio between cross-sectional flow area and its wetted perimeter) corresponding to \(V_e\) in m; \(A_E\) is the flow area for e-flows in m²; \(n\) is a dimensionless roughness value; and \(J\) is the hydraulic slope in %.

### 3.4.2. E-flow supplying-rate calculation

For calculating e-flow supplying-rate, a supplying-rate evaluation model was built combining minimum e-flow (\(Q_{E_{\text{min}}}\)) and measured flow (Eq. (4)). If the supplying-rate is greater than 1, there is no lack of water; if the supplying-rate is less than 1, the flow cannot meet the requirements of \(Q_{E_{\text{min}}}\). The water deficit rate is calculated using Eq. (5).

\[
\text{Supplying-rate} = \frac{\text{Measured flow}}{Q_{E_{\text{min}}}} \quad \text{(4)}
\]

\[
\text{Water deficit rate} = \frac{\left| \text{Measured flow} - Q_{E_{\text{min}}} \right|}{Q_{E_{\text{min}}}} \quad \text{(5)}
\]

\[
|\text{Supplying-rate}| + |\text{Water deficit rate}| = 1 \quad \text{(6)}
\]

### 4. Results

#### 4.1. Inverting river cross-sections using UAV

Through the method described in Section 3.1, cross-sections were fitted using UAV (Unmanned Aerial Vehicle) and measured data. Fig. 2 clearly shows that circular arc cross-sections include JYH (Juyehe) and ZGNL (Zhanggongnanlin), box culvert cross-sections include BDK (Bingdukou) and HTQ (Huangtaiqiao), and “V” shape cross-sections include BDSH (Beidashahe) and LK (Luokou), highlighting the rapid and flexible acquisition of underwater topography using this method.

### 4.2. Suitable flow velocity and water depth of dominant fish species

As successful spawning and survival during the early life stages of fish often dictate the strength of subsequent cohorts (Trippel and Chambers, 1997), understanding the influence of natural flow regimes on the early life stages of fish is vital to protect fish populations in flow altered rivers (Balcombe et al., 2006). Flow velocity is one of the most important variables determining the likelihood of successful fish spawning (Nelson and Lieberman, 2002; Liu et al., 2011). The MHSI (Eq. (2)) is used to estimate the responses of fish communities to habitat environmental factors to determine the optimum flow velocity and water depth as inputs for AEHRA (Fig. 3).
Regarding flow velocity, the dominant fish species of HTQ survive better under a low velocity of 0.2 m/s; the dominant fish species of LK are slightly more adaptable to flow velocity, preferring approximately 0.15–0.18 m/s. The flow velocity of the other sites shows little influence on the survival of fish communities. Regarding water depth, fish communities in BDK, ZGNL, and JYH prefer shallow water. In BDSH, fish communities survive in a water depth interval of 0.3–0.5 m. In LK, the suitable water depth is over 1 m or between 0.3 and 0.5 m. In HTQ, fish communities prefer a water depth interval of 0.3–0.7 m.

To ensure the best chances of egg survival, there are four types of egg specially adapted to the surrounding environment: floating, pelagic (semi-floating), demersal, and adhesive (Zhao et al., 2008). The information in Table 3 comes from the literature (He and Song, 1996; Li et al., 2006; Wang, 1992) and field sampling data. Fish that can produce pelagic eggs have a higher demand on flow velocity. As the fish hatch in a pelagic state, the larval hatching rate will be reduced when the eggs sink to the bottom due to low velocity or static water. For floating eggs, the flow velocity demand is generally less than 0.95 m/s, and the water depth demand is generally less than 2 m. For adhesive eggs, the requirements for laying eggs are lower, both water level and aquatic plants control the spawning conditions. Therefore, limited uplift and a constant water level can result in a larger spawning area, which benefits the spawning conditions for fish that lay adhesive eggs (Zhao et al., 2008). Table 3 shows the detailed spawning conditions of the dominant fish species.

4.3. Biodiversity and IBI of the fish community in Jinan city

Both water depth and flow velocity used in this study are actual values from fish community monitoring, and they can only partly reflect the water depth and flow velocity demands of fish communities. In this study, we also analyze suitable water depth and flow velocity by combining biodiversity (H) and the habitat adaptability index (IBI) (Fig. 4).

In Fig. 4, flow velocity and water depth should be equal to or greater than 0.11 m/s and 0.60 m, respectively, to ensure the two indexes are greater than the average value for Jinan. According to these flow velocity and water depth values, the ecological flow velocity ($V_{B}$) and ecological water depth ($H_{B}$) values for 2016 were calculated by combining the suitable flow velocity and water depth from Section 4.2 and considering the spawning water depth and flow velocity demands of fish communities, which are as follows.

![Fig. 2. River cross-sections for different monitoring stations. (a) BDK (dried up), (b) BDSH, (c) LK, (d) HTQ, (e) ZGNL, and (f) JYH.](image-url)
In BDK, the HE of the spawning period is greater than 0.8 m in 4 months of the year and greater than 1.5 m in 8 months, and the HE is greater than 0.6 m in non-spawning months. The VE is greater than 0.3 m³/s in 8 months and 0.11 m³/s in the remaining months.

In BDSH, the HE of the spawning period is greater than 0.8 m in 4–6 months of the year and greater than 1.5 m in 7 months, and the HE is greater than 0.6 m in non-spawning months. Annual VE is greater than 0.11 m³/s.

Fig. 3. Fitted curves for suitable flow velocity and water depth of dominant fish species: a–f represent sites BDK, BDSH, LK, HTQ, ZGNL, and JYH, respectively, and numbers 1 and 2 represent the flow velocity and water depth, respectively.

- In BDK, the HE of the spawning period is greater than 0.8 m in 4 months of the year and greater than 1.5 m in 8 months, and the HE is greater than 0.6 m in non-spawning months. The VE is greater than 0.3 m³/s in 8 months and 0.11 m³/s in the remaining months.
- In BDSH, the HE of the spawning period is greater than 0.8 m in 4–6 months of the year and greater than 1.5 m in 7 months, and the HE is greater than 0.6 m in non-spawning months. Annual VE is greater than 0.11 m³/s.
Table 3
Spawning demands of dominant fish species.

<table>
<thead>
<tr>
<th>Dominant fish species</th>
<th>Spawning time (month)</th>
<th>Spawning type</th>
<th>Water depth demand (m)</th>
<th>Flow velocity demand (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Saurogobio dabryi</em></td>
<td>3–4</td>
<td>Floating</td>
<td>0.2–1.0</td>
<td>0.027–0.95</td>
</tr>
<tr>
<td><em>Oryzias latipes</em></td>
<td>5–6</td>
<td>Floating</td>
<td>0.1–0.3</td>
<td>0.027–0.95</td>
</tr>
<tr>
<td><em>Spauliobarbus curriculus</em></td>
<td>5–7</td>
<td>Floating</td>
<td>1.5–2.0</td>
<td>0.027–0.95</td>
</tr>
<tr>
<td><em>Channa argus Cantor</em></td>
<td>4–7</td>
<td>Floating</td>
<td>0.2–1.0</td>
<td>0.027–0.95</td>
</tr>
<tr>
<td><em>Opsarichthys bidens Gunther</em></td>
<td>6–8</td>
<td>Pelagic</td>
<td>1.5–4.0</td>
<td>0.304–1.8</td>
</tr>
<tr>
<td><em>Colobitis sinensis Sauvage et Dabry</em></td>
<td>5–7</td>
<td>Pelagic</td>
<td>0.1–0.2</td>
<td>0.304–1.8</td>
</tr>
<tr>
<td><em>Carassius auratus</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.8–1.2</td>
<td>0.022–1.04</td>
</tr>
<tr>
<td><em>Pseudorasbora parva</em></td>
<td>4–6</td>
<td>Adhesive</td>
<td>0.3–0.4</td>
<td>0.001–1.5</td>
</tr>
<tr>
<td><em>Misgurnus anguillicaudatus</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.1–0.2</td>
<td>0.002–1.04</td>
</tr>
<tr>
<td><em>Abbottina rivularis Basilewsky</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.1–0.2</td>
<td>0.002–1.04</td>
</tr>
<tr>
<td><em>Paramisgurnus dabryanus Sauvage</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.1–0.2</td>
<td>0.002–1.04</td>
</tr>
<tr>
<td><em>Hemiculter leuciscus</em></td>
<td>5–7</td>
<td>Adhesive</td>
<td>0.5–1.0</td>
<td>0.001–1.5</td>
</tr>
<tr>
<td><em>Sinibrama wui</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.2–1.0</td>
<td>0.022–1.04</td>
</tr>
<tr>
<td><em>Acheilognathus chankaensis Dybowsky</em></td>
<td>5–6</td>
<td>Adhesive</td>
<td>0.8–1.2</td>
<td>0.002–1.04</td>
</tr>
<tr>
<td><em>Rhodeus lighti Wu</em></td>
<td>4–6</td>
<td>Adhesive</td>
<td>1.5–2.5</td>
<td>0.002–1.04</td>
</tr>
<tr>
<td><em>Cyprinus carpio Linnaeus</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.8–1.2</td>
<td>0.022–1.04</td>
</tr>
<tr>
<td><em>Rhodeus sinensis Gunther</em></td>
<td>4–6</td>
<td>Adhesive</td>
<td>1.5–2.5</td>
<td>0.022–1.04</td>
</tr>
<tr>
<td><em>Ctenogobius brunneus</em></td>
<td>4–5</td>
<td>Adhesive</td>
<td>0.1–0.3</td>
<td>0.002–1.04</td>
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</tbody>
</table>

Fig. 4. Biodiversity (H) and IBI indexes.

Fig. 5. E-flow satisfaction and shortage ratio for BDK.
In LK and HTQ, the HE and VE are respectively greater than 0.6 m and 0.11 m$^3$/s all year round. In ZGNL and JYH, the HE of the spawning period is greater than 0.8 m in 4–5 months of the year, and the HE is greater than 0.6 m in non-spawning months. The annual VE is greater than 0.11 m$^3$/s.

The above results indicate the demand for flow velocity and water depth during the fish spawning period in typical river sections. Locations where H and IBI were considered show values greater than the average value for Jinan, but the average flow velocity and water depth values were generally achieved during the non-spawning period. For the Jinan basin, the VE is...
equal to or greater than 0.11 m/s, and the $H_e$ is greater than 0.6 m.

4.4. Calculating e-flow and supplying-rate

With the ecological flow velocity and water depth determined in Section 4.3, e-flows were calculated using AEHRA, described in Section 3.4, and the relationships with e-flow supply were quantitatively evaluated by combining the measured water depth and supplying-rate evaluation model from Section 3.4. The calculation results show that study points can be divided into two types: one where all e-flows are satisfied, such as LK and HTQ; and one where e-flows are partly satisfied, such as BDK, BDSH, ZGNL, and JYH. LK and HTQ have no water deficit because of higher flow velocity and water depth all year round. Other study points lack water during some months because of intense human activities. Here, we quantitatively evaluated the e-flow supplying-rate relationship using the evaluation model in

![Spatial distribution of the satisfaction ratio of typical e-flows.](image)

**Fig. 9.** Spatial distribution of the satisfaction ratio of typical e-flows.
Section 3.4, which can provide reliable scientific input for water conservation projects.

4.4.1. BDK

The flow at BDK depends on an upstream reservoir and rainfall runoff. Fig. 5 shows that the e-flow supplying-rate and shortage ratio differ throughout the year; e-flow values are lower in spring and winter and higher in summer and autumn. Only one of the eight field sampling periods shows no water shortage because the upstream reservoir was sluiced during that month. Overall, the e-flows lack water all year around because regular dams (every 300–500 m) intercept the water upstream. For the sustainable development of a healthy ecosystem in BDK, we advise unified management of basin water resources.

4.4.2. BDSH

Of the eight field sampling periods (Fig. 6), there is an e-flow satisfaction ratio of 100% in three, and these benefit from the healthy development of the channel ecosystem. For the other five samples, the e-flow shortage ratio is 100%, indicating that the channel is dry and the channel ecological health is threatened. We conclude that the year of 2015 was dry because there is no water in the three field sampling campaigns of 2015. This is the consequence of excessive water use by agricultural irrigation.

4.4.3. ZGNL

ZGNL is located in the north of study area, its main land use is plowland. Many artificial rivers were constructed for irrigation by local departments. Of the eight field sampling campaigns (Fig. 7), the e-flow shortage ratio is 100% in two. In general, e-flows occur mainly in the fifth month of each year, and the intervening period is for irrigation. The flow volume in north Jinan mainly depends on diversion works and rainfall. Diversion water volume should be controlled wisely during irrigation periods because too much of diversion will inevitably influence the ecological health of the river channel.

None of the eight field sampling campaigns of JYH, except one (Fig. 8), completely satisfy the minimum e-flow. The river is dried up in the second and third sampling, which seriously affects healthy development of the river ecosystem. The satisfaction of e-flows is generally less than 100% in the long term, and this not only affects the growth and breeding of river biota, but also hinders the sustainable development of an ecological healthy channel.

After the analysis of individual sampling locations, their spatial distribution was comprehensively considered. We found that flow volume is essentially equal to the e-flows in rivers close to the Yellow and Xiaoqing Rivers (Fig. 9), and the ecosystem of these rivers is healthy. In the river networks of south Jinan, the upstream cannot always satisfy the minimum e-flow requirements, but the downstream generally satisfies the minimum e-flow requirements. In the north, there are artificial rivers to irrigate, and the flow volume produced by rainfall hardly satisfies the minimum e-flow and irrigation water requirements. Therefore, water from the Yellow River should be introduced by diversion works to rectify the water shortage.

5. Discussion

5.1. Validation of cross-sections determined by UAV

Traditional artificial measurement methods of channel cross-sections, such as Total Station and Level Gage, require large amount of time, materials, and power, and can be dangerous when one crosses the large-flow river with handing prism. In topographic surveys, 3D models of precipitous topography can be built to monitor displacement (Pierzchala et al., 2014; Clapuyt et al., 2016) and research the process of soil erosion (Neugirg et al., 2016) using stereoscopic images of UAV, and UAV can also be used to explore the melting processes of seasonal polar glaciers (Kraaijenbrink et al., 2016). Previous studies indicate that UAV-based topographic survey precision can reach centimeter levels (Anderson and Gaston, 2013; Zarco-Tejada et al., 2014; Neugirg et al., 2016). In this research, the channel cross-sections were measured by UAV, and the results were verified to ensure reliability using field data measured by the Total Station method.

The precision of two study locations were verified using the Total Station method (Fig. 10). The relative root mean square error (RMSE) was used to evaluate the precision of the UAV method.

\[
RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_{obs,i} - X_{model,i})^2}{n}}
\]  

(7)

The results show that the RMSE between UAV data and field data is 24 cm in BDK, where the channel is dried up (Fig. 11). The RMSE between UAV data and field data in ZGNL is 23.6 cm above the water, where the channel is influenced by the water,
but below the water topography was not measured because it is very difficult for the electromagnetic wave to penetrate the water surface. The topography below the water surface was fitted by combining the measured water depth and the channel section shape, and the resulting total RMSE is 24.8 cm, considering the topography above the water measured by UAV (Fig. 12). These results indicate that the RMSE for UAV determined channel cross-sections is less than 0.25 cm, which makes up 3–5% of the river’s depth. This fully meets the precision requirements of e-flow calculations.

5.2. Influence of hydrological parameters on fish communities

In terms of the aquatic ecosystem, one of the most obvious and unacceptable effects of anthropogenic activities is the collapse of the riverine fish community due to uninformed river regulation strategies that lead to reduced flow and a corresponding decrease in water quality. Stream flows that are adequate to maintain fisheries are usually sufficient to maintain macro-invertebrates and other aquatic life (Doledec et al., 2015). Fish communities are thus considered effective indicators of ecosystem health. As successful spawning and survival during the early life stages of fish often dictate the strength of subsequent cohorts, understanding the influence of natural flow regimes on the early life stage of fish is vital.

<table>
<thead>
<tr>
<th>Month</th>
<th>Min e-flow (m$^3$/s)</th>
<th>Min ecological water level (m)</th>
<th>Min ecological water depth (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.248</td>
<td>0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>2</td>
<td>0.248</td>
<td>0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>3</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>4</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>5</td>
<td>8.978</td>
<td>1.38</td>
<td>2.88</td>
</tr>
<tr>
<td>6</td>
<td>8.978</td>
<td>−1.38</td>
<td>2.88</td>
</tr>
<tr>
<td>7</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>8</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>9</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
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<tr>
<td>10</td>
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<td>0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>11</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
<tr>
<td>12</td>
<td>0.248</td>
<td>−0.59</td>
<td>0.91</td>
</tr>
</tbody>
</table>
for protecting fish populations in flow-altered rivers (Balcombe et al., 2006). Flow alteration also plays an important role in fish body shape changes, periodic life-history strategy, and fish community structure (Meyers and Belk, 2014; Lamouroux and Olivier, 2015; Pool and Olden, 2015).

As well as flow volume, other hydrological features such as water depth and flow velocity are essential for maintaining biodiversity and ecosystem integrity. A change in flow volume or flow velocity can easily alter the distribution of aquatic organisms and species composition. These features mainly alter hydrological processes and influence the water ecosystem (Cui et al., 2009).

In the above researches, many authors were aware of the importance of flow velocity and water depth on fish species, but few quantitative results were given closely related to the health of fish communities. Differently from the previous researches, two indices of biodiversity (H) and integrated biotic index (IBI) were used in this study as indicators of the health of fish communities, and the dominant fish species were selected using field data. The average flow velocity and water depth relating closely to the health of fish communities were calculated quantitatively as flow velocity (equal to/greater than 0.11 m/s) and water depth (greater than 0.8 m). The two threshold values not only are extremely significant to the remediation of river health and e-flows assessment in the study area but also could be important references for e-flow assessment in other areas across the world.

5.3. Evaluating the reliability of the method

The Tennant method was used to verify the reliability of the e-flow method proposed in this study. The NieYingZha (NYZ) station, with abundant historical data, was selected to verify the reliability, because the Tennant method is based on historical hydrological data. The e-flow was calculated for the downstream part of NYZ using AEHRA (Table 4) and the Tennant method (Table 5).

The AEHRA results are classed between Medium and Good during the non-spawning period, but are significantly larger during the spawning period. This phenomenon is due to the influence of dams causing large changes in flow volume. Sometimes, the river has no water because of the upstream dams being closed, and this makes calculating the e-flow by the Tennant method difficult. In addition, the Tennant method does not consider water depth and flow velocity, which are important parameters for the habitat of aquatic life. However, the AEHRA effectively considers the effect of dams on e-flow, especially the water depth and flow volume demands of fish during spawning periods.

On the whole, the AEHRA method effectively takes into account changes in biological life, as well as the specific demands for velocity, water depth, and flow during important periods; e.g., spawning and migration. When used as a method to calculate e-flow, it can help effectively protect the healthy development of river ecosystems.

6. Conclusions

The calculation of e-flow and supplying-rate for dominant fish species is crucial for evaluating the health of a channel ecosystem. This study presents a new method for rapid e-flow assessment based on UAV and AEHRA. E-flows at several locations in Jinan were calculated and their satisfaction ratios were analyzed. The results show that:

1. The RMSE of the UAV-measured channel cross-sections was less than 0.25 m, which constitutes 3–5% of the river depth. This fully meets the precision demands of e-flow calculations.
2. Flow velocity and water depth in the Jinan basin was equal to or greater than 0.11 m/s and greater than 0.6 m, respectively.
3. Using the Tennant method, the AEHRA results are medium to good in the non-spawning period but significantly larger in the spawning period. The AEHRA method can effectively consider changes in biological life and specific velocity, water depth, and flow demands during certain periods, such as spawning and migration periods. This e-flow calculation method can effectively promote the overall healthy development of river ecosystems.
4. Flow volume meets e-flow requirements in rivers close to the Yellow and Xiaoqing Rivers, and these river ecosystems are healthy. In the river networks of south Jinan, the upstream cannot always satisfy the minimum e-flow requirements, but the downstream generally satisfies the minimum e-flow requirements. In the north, there are artificial rivers to irrigate, and the flow volume produced by rainfall hardly satisfies the minimum e-flow and irrigation water requirements. Therefore, water from the Yellow River should be introduced by diversion works to rectify the water shortage.
5. The survey locations can be divided into two types: one where e-flows are satisfied, such as HK and HTQ, and the other where e-flows are partly satisfied, such as BDK, BDSH, ZGNL, and JYH. HK and HTQ do not lack water because of a higher flow velocity and water depth all year round. Other locations lack water in some months of the year because of intense human activities. In this research, we quantitatively evaluated the e-flow supplying-rate relationship, the results of which can provide reliable scientific advice for water conservation projects.

Overall, the usage of UAV to acquire channel parameters in this study provided a novel prospect for rapid e-flow assessment. The method can effectively promote research progress into basin e-flow, and provide an important reference for global e-flow monitoring. As such, the protection and restoration of aquatic ecosystems under intensive human activities at basin or larger scales turn time- and cost-effectively. All methodologies and according results could be important references for e-flow assessment in other areas across the world.

During data acquisition, the field sampling can be disturbed by human factors, which leads to unavoidable uncertainties. Therefore, the influence of human factors should be reduced to improve e-flow calculation precision in future research. Moreover, floods can modify cross-sections during a hydrological year and therefore effects of floods on results should be carefully considered for further investigations to further improve the precision of results.
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