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A New Method of Assessing Environmental Flows in Channelized Urban Rivers

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ABSTRACT

Assessing environmental flows (e-flows) for urban rivers is important for water resources planning and river protection. Many e-flow assessment methods have been established based on species' habitat provision requirements and pollutant dilution requirements. To avoid flood risk, however, many urban rivers have been transformed into straight, trapezoidal-profiled concrete channels, leading to the disappearance of valuable species. With the construction of water pollution-control projects, pollutant inputs into rivers have been effectively controlled in some urban rivers. For these rivers, the e-flows determined by traditional methods will be very small, and will consequently lead to a low priority being given to river protection in future water resources allocation and management. To more effectively assess the e-flows of channelized urban rivers, we propose three e-flow degrees, according to longitudinal hydrological connectivity (high, medium, and low), in addition to the pollutant dilution water requirement determined by the mass-balance equation. In the high connectivity scenario, the intent is for the e-flows to maintain flow velocity, which can ensure the self-purification of rivers and reduce algal blooms; in the medium connectivity scenario, the intent is for the e-flows to permanently maintain the longitudinal hydrological connectivity of rivers that are isolated into several ponds by means of weirs, in order to ensure the exchange of material, energy, and information in rivers; and in the low connectivity scenario, the intent is for the e-flows to intermittently connect isolated ponds every few days (which is designed to further reduce e-flows). The proposed methods have been used in Shiwuli River, China, to demonstrate their effectiveness. The new methods can offer more precise and realistic e-flow results and can effectively direct the construction and management of e-flow supply projects.

1. Introduction

Rivers have suffered severe ecological degradation under the increasing influence of human activities [1]. A major reason for ecological degradation is water shortages [2]. Ever-increasing water demands around the world have resulted in an intensifying, complex conflict between water diversion from rivers for social-economic uses and water retention in rivers for ecological uses [3]. Satisfying the water requirements of the rivers themselves has become a basic tenet of river protection and management [4,5]. Accordingly, assessing rivers' water requirements, or environmental flows (e-flows), has become important work for researchers and managers in this field [6].

Many methods have been established for e-flow assessment; these can be grouped into four general categories: hydrological, hydraulic rating, habitat simulation, and holistic [3]. Hydrological methods are the simplest. These are based on historical hydrological data, and usually set a specified percentage of naturalized historical flows as the e-flow in order to maintain river health at some acceptable level [7]. Because hydrological methods do not take into account the geomorphology of rivers, real habitat quantity varies significantly under the same specified e-flow for different rivers. To take geomorphology into account, hydraulic rating methods have been proposed. These methods use changes in simple hydraulic variables, such as wetted perimeter, as a surrogate for habitat, and take the breaking point for the hydraulic variable-discharge curves as the e-flow [8,9]. Habitat simulation methods are a further development of hydraulic rating methods, as they take into account the habitat preferences of target species (e.g., depth and velocity). Habitat–discharge curves for the target species are

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used to predict optimum flows as e-flows [10]. Holistic methods emphasize the importance of the natural flow regime to the whole riverine ecosystem, and attempt to maintain the natural flow regime and flow variability. In that context, e-flows are defined in terms of acceptable degrees of departure from the natural flow regime [11].

These e-flow assessment methods emphasize the requirement of habitat provision for species, and consider how to meet that requirement. The current methods are quite suitable for natural or semi-natural rivers, which have high species diversity and in which the species that need protection are easily identified. However, for fully artificial rivers, especially channelized urban rivers, the abovementioned methods are not very suitable. To mitigate flood risk, many urban rivers have been transformed into straight, trapezoidal-profile concrete channels [12–14]. Natural rivers with high habitat diversity have been altered to channels with homogenous habitats. River channelization results in the removal of sediment from the riverbed and increased flow velocities [15–17]. As a result, natural species compositions have been altered, and some protected species, such as fish, have declined [18–20]. The altered species compositions are dominated by common phytoplankton and zooplankton, which do not require protection. Thus, the habitat provision function becomes unimportant in e-flow assessment for channelized urban rivers due to the infeasibility of providing the required flow characteristics for protected species in these rivers.

In addition to habitat provision, two other ecological functions are usually considered in typical e-flow assessment methods for an urban river: pollutant dilution and aesthetics [21]. Compared with habitat provision, e-flow assessment methods to meet these functions are relatively easy to achieve. The water required for pollutant dilution is determined based on the mass-balance equation [22,23]. For aesthetics, the e-flow assessment method is even easier. The river bed of a channelized river has been transformed into a trapezoid shape, in which the water surface area usually does not increase significantly with increasing depth and does not have a breaking point on water surface area–discharge curves. Thus, for channelized urban rivers, aesthetic e-flows are required to ensure that the riverbed is not bare; the minimum water depth is usually set at 0.2–0.5 m [24]. For different rivers, the required water depth may be different, and the depth value is set accordingly.

With the increasing emphasis on pollution control, point-source (i.e., domestic and industrial wastewater) and non-point-source (initial rainwater) pollutions are effectively controlled in many cities. For the rivers in these cities, dilution water is not important. For channelized urban rivers with limited pollutant input, the e-flow requirements determined by the present methods will be quite small. These methods will implicitly set a very low priority for these river ecosystems in future water resources planning and allocation.

In addition to the three requirements (habitat provision, pollutant dilution, and aesthetics), hydrological connectivity should also be considered in e-flow assessment [25,26]. Hydrological connectivity for riverine ecosystem protection and restoration is defined as the ease with which organisms, matter, or energy traverse the ecotones between adjacent ecological units [27]. Hydrological connectivity consists of lateral, longitudinal, and vertical connectivity in rivers [28]. Lateral connectivity (between the watershed and the river) includes the roles of plants and animals in the watershed; the geomorphology of sedimentation and channelization; and the delivery of nutrients, soil, debris, and organisms between the water and its shores [29,30]. Longitudinal connectivity occurs in both flow directions and includes issues of species migration and the delivery of organic and inorganic materials up and down the river [31]. Vertical connectivity concerns exchanges between the river and groundwater; subsurface differentiation of habitats (such as surface vs. benthic or river-bottom environments); convection; and local differences in water quality, temperature, and turbidity [27,32]. For channelized urban rivers isolated by weirs, longitudinal connectivity is a key issue.

In this research, we further extend e-flow assessment methods for urban rivers by addressing the requirement of hydrological connectivity. Shiwuli River, a typical channelized urban river, serves as a case study. In the following sections, we describe the study site, propose three degrees of hydrological connectivity, and provide equations for determining the corresponding e-flows. Next, we compare e-flow results with the pollutant dilution water requirement in order to test the influence of pollution control on e-flows. Finally, we propose an e-flow supply route and scheme, based on the e-flow results.

2. Materials and methods

2.1. Study site

Shiwuli River is located upstream of Chao Lake, one of the five largest freshwater lakes in China, and runs through the urban region of Hefei City. The river is 22.64 km long with a basin area of 111.25 km^2. To enhance its flood transfer ability, the river has been channelized into a concrete trapezoidal shape. As a result, the natural riverbed is fully altered and the corresponding river ecosystem has been completely changed. Current species diversity is very limited. There are 49 types of phytoplankton, and common blue-green algae are the key species. Rotifers and protozoa, which are pollution-tolerant organisms, are the major zooplankton, while Cladocera, which are suitable for high-quality water, are very limited. There are only six types of zoobenthos, dominated by pollution-tolerant organisms such as *Limnodrilus hoffmeisteri* Claparède. Submacrophytes are very limited and no specific species need to be protected.

Industrial and domestic wastewater and occasional rainwater are the key water sources. As a result of the limited water input, the river flow is intermittent. To restore the landscape of the river and create an aesthetic site for citizens, the government plans to improve the water quality and secure the e-flows. To control the pollutant input, waste and rainwater pipes are being repaired or newly constructed. A new wastewater treatment plant—the Hudaying Plant, which will have a capacity of 10^5 t·d^{-1}—will be constructed before 2020, and the treatment capacity of the existing Shiwuli Plant will be expanded from 1×10^5 to 2.5×10^5 t·d^{-1} before 2020. All industrial and domestic wastewater discharged into the river is expected to be handled by the two plants to a water-release standard level IV—a very high standard for wastewater treatment plants. In addition, in order to control non-point-source pollution caused by rain, many stormwater retention tanks will be constructed, so that water can be treated to a water-release standard level IV before being released into the river. These wastewater control and treatment projects will effectively control the release of pollution into the river, such that the river water quality is expected to be better than the allowed water-release standard level V.

The treated water from the two plants will be used to meet e-flow requirements. The collected rainwater and water from Swan Lake will not serve as regular water sources. To retain water in the river for ecological requirements, eight weirs were built, as shown in Fig. 1. The weirs reduce flow velocity, increase water-retention time, and consequently reduce the water required to satisfy e-flows. In future, the Shiwuli Wetland will be constructed about 2 km upstream of Chao Lake. However, because the wetland has not yet been constructed and this paper focuses on e-flow for

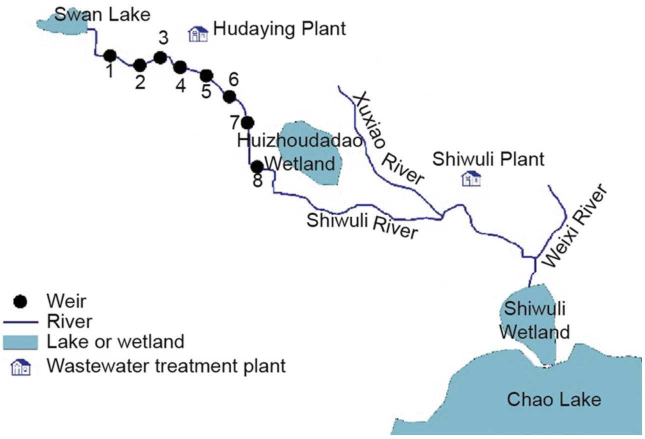

Fig. 1. Weir locations on Shiwuli River.

rivers rather than for wetlands, we have only calculated e-flows for the river above the wetland.

2.2. Method development

Shiwuli River is isolated into segments by weirs. The degree of hydrological connectivity depends on the amount of available water for e-flow supply. When the available e-flow water supply is at the medium level, water connects the isolated segments. When more water is available for e-flows, the river flow velocity increases, offering better hydrological connectivity; and when less water is available for e-flows, the isolated segments are not permanently connected, and the water can be used for intermittent connectivity.

Three e-flow scenarios are proposed in this research, corresponding to high, medium, and low hydrological connectivity. The high and medium connectivity scenarios seek to maintain permanent connectivity, while the low connectivity scenario proposes intermittent connectivity over time. The high hydrological connectivity scenario seeks to maintain flow velocity, which can ensure self-purification in rivers and reduce algal blooms. The medium hydrological connectivity scenario seeks to maintain the longitudinal hydraulic connectivity of river segments isolated by weirs, which can ensure the connectivity of material, energy, and information in rivers. The low hydrological connectivity scenario seeks to offer periodic intermittent connectivity, which can reduce e-flow requirements and avoid serious water quality decline.

2.2.1. E-flow determination under high hydrological connectivity

Flow velocity can significantly influence the self-purification ability of rivers [33]. Flow velocity is positively related to flow volume and the turbulent diffusion coefficient. Pollutant concentrations will decrease under the effects of mixing and diffusion. High flow velocity can significantly increase the oxygen recharge rate, which can maintain high oxidation–reduction potentials in rivers, and thus increase pollutant degradation in an oxidizing environment. In addition, high flow velocity can reduce the possibility of algal blooms. Algal blooms are a serious environmental problem in urban rivers [34]. The mechanism of algal blooming is very complex, and is still being researched. Flow velocity, water temperature, and nutrients are major factors determining algal bloom conditions [35]. For algal blooms, flow velocity must be low [36]. Thus, the first e-flow scenario seeks to ensure that the flow velocity is no less than a specified velocity that can reduce the occurrence of algal blooms.

The flow velocity for each river segment between two weirs is not the same, and the velocity within each segment is not uniform either. The e-flow for a river is determined segment by segment. For each river segment, according to observation, water depth is usually greatest at the upstream side of the downstream weir, and the average flow velocity is usually lowest at that point. To ensure that the velocity within a segment is above a specified v_0, it is only necessary to ensure that the velocity at the upstream side of the downstream weir is above v_0. The required discharge can be determined based on the following formulas:

$$Q = \sigma \varepsilon C_{\mathrm{d}} b (2g)^{1/2} h_0^{3/2} \tag{1}$$

$$h_0 = \Delta h + a_0 v^2/(2g) \tag{2}$$

$$v = Q/[b(h + \Delta h)] \tag{3}$$

where Q is the discharge, σ is the submergence coefficient, ε is the lateral contraction coefficient, C_{d} is the discharge coefficient of weir flow, b is the length of the weir, g is the acceleration of gravity, h_0 is the total head upstream of weir, Δh is the height of the water above the crest of the weir, a_0 is the kinetic energy correction factor, and v is the flow velocity, which is here set at v_0.

2.2.2. E-flow determination under medium hydrological connectivity

For channelized urban rivers isolated by weirs, longitudinal connectivity is a key issue. The second e-flow scenario seeks to maintain longitudinal connectivity by ensuring that ① the water level at the upstream side of the downstream weir is greater than the height of the weir, and ② the lowest water depth is no less than 0.2 m within a river segment in order to avoid a bare channel bed [24]. Once the water level is above the weir, any amount of continual water input into a river segment will ensure that the water level remains above the weir. Thus, to maintain longitudinal connectivity, it is only necessary to ensure that the lowest river water level is no less than 0.2 m. For some rivers, the required water level may be different, and the value can be set accordingly.

Manning's equation is commonly used for open channel flow. This empirical equation applies to uniform flow in open channels and is a function of channel velocity, flow area, and channel slope [37]. It is used to determine the required flow to ensure that the lowest water level is no less than a specified value—that is, 0.2 m in this research. Within a river segment, the water depth in the upstream river section is usually the lowest; thus, the flow required in this river section is determined as the required e-flow.

$$Q = AR^{2/3} S^{1/2}/n \tag{4}$$

$$A = (a + hm) \cdot h \tag{5}$$

where n is the Manning roughness coefficient, A is the area of water in a channel cross-section, R is the hydraulic radius, S is the channel slope, m is the side slope coefficient, h is the water depth, and a is the channel bottom width.

2.2.3. E-flow determination under low hydrological connectivity

In the previous two methods, river connectivity is permanently maintained. However, if the available water volume for e-flow is low, the water cannot maintain permanent longitudinal river connectivity, and the river will be isolated into several impoundments with still water surfaces. The water quality will gradually decline due to continual pollution input and oxygen consumption. Under these conditions, the impounded water needs to be replaced every few days. This third e-flow scenario seeks to provide sufficient water to replace the impounded water within a given periodicity, in order to ensure that the water quality does not decrease below an acceptable level.

The flow management cycle for this scenario is divided into a flow-retention phase and a flow-release phase. With the decline of water quality in the isolated segments, water must be replaced within a given periodicity. We propose that water be stored in the river for a number of specified days, T_0, and then be released with a specified velocity, v_1.

$$Q = E/(T_0 + T_1) \tag{6}$$

$$T_1 = E/(Av_1) \tag{7}$$

where E is the water volume within a river segment when the water does not flow, and when the water depth at the upstream side of the downstream weir is equal to the height of the weir; T_1 is the time required to release all the water in a river segment; and v_1 is the specified velocity for the release of stored water, which here is set at 0.2 $\text{m}\cdot\text{s}^{-1}$ in order to reduce algal blooms [38–41]. For different rivers, the required flow velocity may be different, and the velocity value can be set accordingly.

2.2.4. Overall e-flow determination

Dilution or seepage and evaporation water need to be considered in addition to the water required for connectivity. The dilution water requirement can be determined by the mass-balance equation [24], as follows:

$$Q_\text{d} = [Q_\text{p}(C_\text{p} - C_\text{max}) - M]/(C_\text{max} - C_0) \tag{8}$$

where Q_d is the water required to dilute pollutants to the permitted quality, Q_p is the volume of polluted water, C_p is the concentration of pollutants discharged into the urban river, C_max is the water quality permitted by the government, M is the reduction of pollutants through degradation, and C_0 is the concentration of pollutants in the water used for pollutant dilution.

The water required for seepage and evaporation is determined as follows:

$$Q_\text{se} = I \cdot H_\text{se} \tag{9}$$

where Q_se is the water requirement for seepage and evaporation, I is the channel area covered by water, and H_se is the depth of water from seepage and evaporation per unit time.

The overall e-flow, Q_e, is then calculated as follows:

$$Q_\text{e} = \max(Q, Q_\text{d}) + Q_\text{se} \tag{10}$$

3. Results and discussion

3.1. E-flows under different hydrological connectivity scenarios

After the construction of the planned wastewater control projects, the quality of water entering the river is expected to reach a level IV standard, which is better than the allowed water quality standard, level V. Thus, pollutant dilution water does not need to be considered in the e-flow assessment in this case. Therefore, the water requirements for hydrological connectivity and for seepage and evaporation are the major components of the e-flows. It is realistic to assume that pollutants may be released into the river due to occasional accidents at the wastewater control project. The influence on e-flows of pollutant input into the rivers will be further discussed in Section 3.2. In this section, the e-flows under discussion consist of water requirements for hydrological connectivity and for seepage and evaporation.

Previous research on algal blooms has indicated that when the flow velocity is greater than 0.1–0.2 $\text{m}\cdot\text{s}^{-1}$, algal blooms seldom occur [38–41]. Thus, for the high hydrological connectivity scenario, the minimum flow velocity was set at 0.1 and 0.2 $\text{m}\cdot\text{s}^{-1}$, respectively; the e-flow results are shown in Table 1. The e-flow results under the medium hydrological connectivity scenario are shown in Table 2. In the low hydrological connectivity scenario, we set the water-retention times from 1 to 10 d, with increments of 1 d, in order to reveal the influence of retention time on water requirements. The results are shown in Table 3.

Table 1
E-flows under high hydrological connectivity.

	Segment e-flows ($\text{m}^3\cdot\text{s}^{-1}$)								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
v_0 = 0.1 $\text{m}\cdot\text{s}^{-1}$	2.63	2.51	1.61	3.11	2.32	1.02	6.02	5.03	4.75
v_0 = 0.2 $\text{m}\cdot\text{s}^{-1}$	5.23	5.11	3.21	6.21	4.62	2.02	13.02	11.83	10.35

S: segment.

Table 2
E-flows under medium hydrological connectivity.

	S1	S2	S3	S4	S5	S6	S7	S8	S9
E-flow ($\text{m}^3\cdot\text{s}^{-1}$)	0.67	1.34	1.01	1.34	1.12	0.52	1.14	1.00	1.58

Table 3
E-flows under low hydrological connectivity.

Retention days (d)	Segment e-flows ($\text{m}^3\cdot\text{s}^{-1}$)								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
1	1.73	0.22	0.15	0.29	0.40	0.23	0.82	1.07	2.95
2	1.29	0.16	0.11	0.22	0.30	0.17	0.61	0.80	2.26
3	1.03	0.13	0.09	0.17	0.24	0.14	0.49	0.64	1.85
4	0.86	0.11	0.08	0.15	0.21	0.12	0.41	0.54	1.57
5	0.74	0.10	0.07	0.13	0.18	0.11	0.35	0.47	1.38
6	0.65	0.09	0.06	0.11	0.16	0.10	0.31	0.41	1.24
7	0.58	0.08	0.05	0.10	0.14	0.09	0.28	0.37	1.13
8	0.53	0.07	0.05	0.09	0.13	0.08	0.25	0.33	1.04
9	0.48	0.07	0.05	0.08	0.12	0.08	0.23	0.31	0.97
10	0.44	0.06	0.04	0.08	0.11	0.07	0.21	0.28	0.91

The segments with the maximum or minimum e-flows are not the same under different e-flow scenarios. (Note that river segment 1 is located between Swan Lake and the most upstream weir, river segment 2 is between the most upstream weir and the second-most upstream weir, and so forth, ending with river segment 9, which is between the Shiwuli wetland and the most downstream weir.) In the high connectivity scenario (Table 1), the maximum e-flow is in segment 7, at 6.02 $m^3 \cdot s^{-1}$ under a flow velocity of 0.1 $m \cdot s^{-1}$, and at 13.02 $m^3 \cdot s^{-1}$ under a flow velocity of 0.2 $m \cdot s^{-1}$. The minimum e-flow in this scenario is in segment 6, at 1.02 $m^3 \cdot s^{-1}$ under a flow velocity of 0.1 $m \cdot s^{-1}$, and at 2.02 $m^3 \cdot s^{-1}$ under a flow velocity of 0.2 $m \cdot s^{-1}$. In the medium connectivity scenario, the maximum e-flow is in segments 2 and 4, at 1.34 $m^3 \cdot s^{-1}$, while the minimum e-flow is in segment 6, at 0.52 $m^3 \cdot s^{-1}$ (Table 2). In the low connectivity scenario, the maximum e-flow is in segment 9, while the minimum e-flow is in segment 3 (Table 3). Having different segments with maximum (or minimum) e-flows under different e-flow scenarios results from different major influencing factors determining the e-flow requirement. In the high connectivity scenario, weir height and width are the major influences on e-flow requirements; in the medium connectivity scenario, the shape of the river cross-section and the channel slope are the major influencing factors; and in the low connectivity scenario, the length of the river segment is the major influencing factor. In comparison with the physical characteristics of the river channel—that is, the channel cross-section shape, channel slope, and channel length—the heights of the weirs are relatively easy to modify. In the high hydrological connectivity scenario, if the river managers plan to reduce the e-flow requirements, low weir heights are preferred.

The e-flows are the highest in the high connectivity scenario; however, the e-flows in the low connectivity scenario are not always the lowest, even though the flows are intermittently released. The e-flows in the low connectivity scenario are greater than those in the medium connectivity scenario for segment 1, when the flow retention is less than 6 d; for segment 8, when the flow retention is 1 d; and for segment 9, when the flow retention is less than 4 d. In the low connectivity scenario, the e-flow is closely related to the water storage capacity of a river segment. Greater flow velocity is required to fill a river segment with a larger storage capacity for a specified number of water-retention days; this can result in greater average flow velocities in the low connectivity scenario than in the medium connectivity scenario.

3.2. Influence of pollution control on e-flows

In the Shiwuli River Basin, wastewater and rainwater pipes are being reconstructed or repaired to deliver water to the two treatment plants. Point-source and non-point-source pollutions are controlled through the wastewater treatment plants to ensure that no untreated pollutants are discharged into the river. However, after water collection and treatment, it is still possible for some rainwater or domestic and industrial wastewater to be discharged into the river. Table 4 shows the chemical oxygen demand (COD) concentrations and daily inputs (under prior conditions) for each segment before the launch of these projects. Due to the difficulty in precisely predicting untreated pollutant inputs, we set the future untreated wastewater input for each river segment as 10%–50% of the old wastewater input into each segment, in incremental steps of 10%. The influence of untreated pollutants on the e-flows was analyzed.

The permitted water quality for the river is standard level V, which has a corresponding COD value of 40 $mg \cdot L^{-1}$ [42]. The water released from the wastewater plant is at standard level IV, with a corresponding COD value of 30 $mg \cdot L^{-1}$. The water amounts required from the wastewater treatment plants to dilute untreated pollutants in order to reach standard level V are shown in Table 5. Only segment 7 does not need water to dilute pollutants, because the untreated pollutant concentration for that segment is less than what is permitted by standard level V. The other segments require dilution water to meet the required water quality. The dilution water requirements for segments 1 and 9 are the largest, as these segments have the largest pollutant inputs.

Because the flow used for hydrological connectivity can also serve as dilution water, the water required for pollutant dilution may not increase the original e-flow requirements for hydrological connectivity, seepage, and evaporation. Therefore, we further compared the dilution water requirements with the e-flows determined in Section 3.2 in order to determine whether additional water inputs are required. Table 6 shows the ratios of the new e-flow requirements (where the e-flows consist of the water required for pollutant dilution, hydrological connectivity, seepage, and evaporation) to the original e-flow requirements (where the e-flows consist of the water required for hydrological connectivity, seepage, and evaporation). Except for segments 6, 7, and 8, the e-flows will increase to some extent. The ratio is significantly influenced by the amount of pollutants inputted into the segment. Segments 6, 7 and 8 have the lowest levels of untreated pollutants compared with the other segments. The e-flows for segments 1, 2, and 9 are significantly influenced by large untreated pollutant inputs, especially segment 1. From the perspective of e-flow allocation, pollutant input reductions in segments 1, 2, and 9 are critically important in order to reduce the e-flow requirement of the river.

Table 4
Wastewater input into each river segment under prior conditions.

Segment	Concentration ($mg \cdot L^{-1}$)	Flow ($t \cdot d^{-1}$)	Pollutants ($t \cdot d^{-1}$)
S1	173.54	19 756	3.428
S2	54.85	9 115	0.500
S3	121.10	200	0.024
S4	67.96	1 804	0.123
S5	121.05	832	0.101
S6	136.99	116	0.016
S7	22.83	48	0.001
S8	86.45	90	0.008
S9	200.65	7 773	1.560

Table 5
Dilution water requirements under different untreated pollutant inputs.

RA	Water amounts ($m^3 \cdot s^{-1}$)								
	S1	S2	S3	S4	S5	S6	S7	S8	S9
10%	2.64	0.14	0.02	0.05	0.07	0.01	0	0.00	1.25
20%	5.28	0.27	0.03	0.10	0.13	0.02	0	0.01	2.50
30%	7.91	0.41	0.05	0.15	0.20	0.03	0	0.01	3.75
40%	10.55	0.54	0.06	0.20	0.27	0.05	0	0.02	4.99
50%	13.19	0.68	0.08	0.25	0.34	0.06	0	0.02	6.24

RA: the ratio of the untreated wastewater input into each river segment to the current wastewater input into each segment.

Table 6
Ratio of e-flows considering pollution (Q_{ep}) to e-flows not considering pollution (Q_{e0}).

RA	E-flow scenario	Q_{ep}/Q_{e0}								
		S1	S2	S3	S4	S5	S6	S7	S8	S9
10%	E-flow1-1	1	1	1	1	1	1	1	1	1
	E-flow1-2	1	1	1	1	1	1	1	1	1
	E-flow2	3.94	1	1	1	1	1	1	1	1
	E-flow3-1	1.52	1	1	1	1	1	1	1	1
	E-flow3-2	2.05	1	1	1	1	1	1	1	1
	E-flow3-3	2.56	1.04	1	1	1	1	1	1	1
	E-flow3-4	3.07	1.23	1	1	1	1	1	1	1
	E-flow3-5	3.57	1.35	1	1	1	1	1	1	1
	E-flow3-6	4.06	1.50	1	1	1	1	1	1	1.01
	E-flow3-7	4.55	1.69	1	1	1	1	1	1	1.11
	E-flow3-8	4.98	1.93	1	1	1	1	1	1	1.20
	E-flow3-9	5.50	1.93	1	1	1	1	1	1	1.29
	E-flow3-10	6.00	2.26	1	1	1	1	1	1	1.37
20%	E-flow1-1	2.01	1	1	1	1	1	1	1	1
	E-flow1-2	1.01	1	1	1	1	1	1	1	1
	E-flow2	7.88	1	1	1	1	1	1	1	1.58
	E-flow3-1	3.05	1.23	1	1	1	1	1	1	1
	E-flow3-2	4.09	1.69	1	1	1	1	1	1	1.11
	E-flow3-3	5.12	2.08	1	1	1	1	1	1	1.35
	E-flow3-4	6.14	2.46	1	1	1	1	1	1	1.59
	E-flow3-5	7.13	2.71	1	1	1	1	1	1	1.81
	E-flow3-6	8.12	3.01	1	1	1	1	1	1	2.01
	E-flow3-7	9.10	3.38	1	1.01	1	1	1	1	2.21
	E-flow3-8	9.96	3.87	1	1.12	1.04	1	1	1	2.40
	E-flow3-9	10.99	3.87	1	1.26	1.12	1	1	1	2.57
	E-flow3-10	11.99	4.51	1	1.26	1.23	1	1	1	2.74
30%	E-flow1-1	3.01	1	1	1	1	1	1	1	1
	E-flow1-2	1.51	1	1	1	1	1	1	1	1
	E-flow2	11.81	1	1	1	1	1	1	1	2.37
	E-flow3-1	4.57	1.85	1	1	1	1	1	1	1.27
	E-flow3-2	6.14	2.54	1	1	1	1	1	1	1.66
	E-flow3-3	7.68	3.12	1	1	1	1	1	1	2.02
	E-flow3-4	9.20	3.69	1	1.01	1	1	1	1	2.39
	E-flow3-5	10.70	4.06	1	1.16	1.12	1	1	1	2.71
	E-flow3-6	12.18	4.51	1	1.38	1.26	1	1	1	3.02
	E-flow3-7	13.65	5.08	1	1.51	1.45	1	1	1	3.32
	E-flow3-8	14.93	5.80	1	1.68	1.56	1	1	1	3.60
	E-flow3-9	16.49	5.80	1	1.89	1.69	1	1	1	3.86
	E-flow3-10	17.99	6.77	1.22	1.89	1.84	1	1	1	4.12
40%	E-flow1-1	4.01	1	1	1	1	1	1	1	1.05
	E-flow1-2	2.02	1	1	1	1	1	1	1	1
	E-flow2	15.75	1	1	1	1	1	1	1	3.16
	E-flow3-1	6.10	2.46	1	1	1	1	1	1	1.69
	E-flow3-2	8.18	3.38	1	1	1	1	1	1	2.21
	E-flow3-3	10.25	4.16	1	1.19	1.12	1	1	1	2.70
	E-flow3-4	12.27	4.92	1	1.35	1.28	1	1	1	3.18
	E-flow3-5	14.26	5.41	1	1.55	1.50	1	1	1	3.62
	E-flow3-6	16.24	6.02	1.08	1.83	1.69	1	1	1	4.03
	E-flow3-7	18.19	6.77	1.30	2.02	1.93	1	1	1	4.42
	E-flow3-8	19.91	7.73	1.30	2.24	2.07	1	1	1	4.80
	E-flow3-9	21.99	7.73	1.30	2.52	2.25	1	1	1	5.15
	E-flow3-10	23.98	9.02	1.62	2.52	2.45	1	1	1	5.49
50%	E-flow1-1	5.02	1	1	1	1	1	1	1	1.31
	E-flow1-2	2.52	1	1	1	1	1	1	1	1
	E-flow2	19.69	1	1	1	1	1	1	1	3.95
	E-flow3-1	7.62	3.08	1	1	1	1	1	1	2.12
	E-flow3-2	10.23	4.23	1	1.15	1.12	1	1	1	2.76
	E-flow3-3	12.81	5.21	1	1.48	1.40	1	1	1	3.37
	E-flow3-4	15.34	6.15	1.01	1.68	1.61	1	1	1	3.98
	E-flow3-5	17.83	6.77	1.16	1.94	1.87	1	1	1	4.52
	E-flow3-6	20.29	7.52	1.35	2.29	2.11	1	1	1	5.04
	E-flow3-7	22.74	8.46	1.62	2.52	2.41	1	1	1	5.53
	E-flow3-8	24.89	9.67	1.62	2.80	2.59	1	1	1	6.00
	E-flow3-9	27.48	9.67	1.62	3.15	2.81	1	1	1	6.44
	E-flow3-10	29.98	11.28	2.03	3.15	3.07	1	1	1	6.86

Scenario e-flow1-1 and e-flow1-2 are the e-flows under high hydrological connectivity, where the flow velocity is equal to 0.1 and 0.2 $m·s^{-1}$, respectively. Scenario e-flow2 is the e-flow under medium hydrological connectivity. Scenario e-flow3-1, e-flow3-2, and so forth up till e-flow3-10 are the e-flows under low hydrological connectivity, where the retention time is equal to 1 d, 2 d, and so forth up till 10 d, respectively.

4. Conclusions

Many urban rivers have been channelized for flood control. With the increasing construction of water pollution-control projects, water pollution problems will not be obvious for urban rivers. For these urban rivers, typical e-flow assessment methods, which mainly highlight requirements for habitat provision and pollutant dilution, are not suitable. In this paper, we took the requirement for hydrological connectivity into account in e-flow assessment, and proposed three degrees of e-flows according to the degree of longitudinal hydrological connectivity (high, medium, and low). The proposed method was applied to Shiwuli River to test its effectiveness. The new method may offer more precise and realistic e-flow results in order to effectively direct the construction and management of e-flow supply projects, thus avoiding long-distance water transfer and reducing the costs of project construction and daily operation.

To simplify the analysis in this research, e-flows for the planned Shiwuli Wetland in the downstream reaches of the river were not taken into account. The wetland's e-flows could influence the river's e-flows, so the e-flow integration of rivers and wetlands should be examined in future research. In addition, future research could further analyze how factors such as weir height and width, the river cross-section, and the channel slope influence e-flows. Such information would be useful for river structure modification and management.

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Compliance with ethics guidelines

Xin-An Yin, Zhifeng Yang, Enze Zhang, Zhihao Xu, Yanpeng Cai, and Wei Yang declare that they have no conflict of interest or financial conflicts to disclose.

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