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Quantifying the Impact of Changes in Sinuosity on River Ecosystems

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Abstract: To quantitatively study the hydrodynamic changes in different river morphologies and clarify the impact of morphological changes on river ecosystems, this study examined a section of the Nansha River near Laoniuwan in the Haidian District, Beijing, and characterized different river morphologies by river sinuosity. The River 2D model was used for simulation and analysis, and the depth and velocity diversity indices were introduced to quantify the distribution of depth and velocity under different sinuosities. *Cyprinus carpio* was selected as the target fish in this study, and its suitability curve was determined using literature and field surveys. Combined with the simulation results, a weighted usable area curve was established to identify its inflection point and maximum value and determine the ecological flow in the river under different sinuosities, that is, to clarify the relationship between sinuosity and ecological flow. The results showed that the lower the sinuosity, the worse the depth and velocity diversity, but a greater sinuosity did not lead to better depth and velocity diversity. The depth and velocity diversity of a sinuosity of 1.5 were better than those of 1.89 in general, except for low flow conditions (Q = 5 m^3/s). For rivers with water use restricted by nature and society and where ecological needs exist, ecological engineering that appropriately changes the planform of rivers can be considered to increase the diversity of river/channel geometry and provide a basis for the ecological restoration of rivers.

Keywords: sinuosity; depth and velocity diversity; ecological flow; habitat

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1. Introduction

Globally, more than two-thirds of rivers are substantially affected by human activity [1]. In recent years, several urban rivers have been channelized and linearized in the planning stages because of the convenience of land use and the safety of flood discharge; thus, their natural form and direction are often drastically changed [2]. For example, only approximately 2% of the rivers and lakes in the United States and Germany are in a natural state [3,4]. Between 1929 and 1942, the U.S. Army Corps of Engineers constructed 14 cut-offs in the Lower Mississippi River between Memphis, Tennessee, and Red River Landing, Louisiana. Engineered cut-offs, in combination with two natural cut-offs, resulted in a net shortening of the river by approximately 235 km [5]. In the mid-to-late 19th century, systematic river channelization engineering was applied in Europe and elsewhere, leading to notable changes in the landscape, from multi-to single-line channel configurations such as the Danube, Rhone, Rhine, Italian rivers, and braided rivers in the French Alps [6]. River channelization in China began in the 1940s, but its rapid development was concentrated from the late 1950s to the mid-1970s. From 1958 to 1962, channelization or segmented channelization projects were conducted nationwide with a total length of approximately 1500 km [7].

Narrowing of the river channel and hardening of its banks accelerate the flow of river water, reducing the ratio of infiltration and interception of runoff during rainfall, increasing the peak volume, advancing it, and reducing the river water quality accordingly [8]. These canalized rivers often have regular and geometric cross sections owing to land occupation and engineering volumes. However, the channelization of curved rivers has not yet been fully demonstrated [9]. When the curved shape of a river changes in its natural state, it also changes its hydrological and hydraulic characteristics [9]. In addition to changes in river scouring and siltation, which have an impact on flood safety, it also leads to the disappearance of geomorphological diversity within the river; that is, it results in changes in the patterns of mainstreams, tributaries, shoals, and jets in natural rivers [10].

In the 1980s, countries such as Germany and Switzerland proposed the concept of "re-naturalization" to restore rivers to a state close to that of nature [11,12]. The United Kingdom has adopted near-natural river management techniques that emphasize the need to give priority to the ecological functions of rivers when restoring and maintaining them [13]. The Netherlands has emphasized the combination of ecological restoration of rivers and flood control and has put forward the concept of "giving space to the river" [14]. Guaranteeing ecological flows is one of the most important initiatives for restoring the naturalization of rivers [9]. With the increasing destruction of ecological and environmental resources, the ecological flow of rivers has received increasing attention. In recent years, research related to the ecological flow of rivers has developed rapidly and has become a major global concern in the 20th century [15–17]. Ecological flow is the amount of water, time, and water quality required to maintain the natural ecosystem of rivers and estuaries and to sustain the ecosystem on which human survival and development depend. The scientific determination of ecological flow is essential for high-quality regional ecological development [18].

After years of research and development, ecological flow calculation methods have been divided into four major categories: hydrological, hydraulic, habitat, and integrated. Both hydraulic and habitat methods determine the ecological flow in a study area by analyzing the relationship between the flow and the type and quantity of habitat provided by the water flowing through a river [19]. Changes in river morphology inevitably cause changes in the diversity of water depths and velocities in a river, affecting the type and quantity of habitats available to certain organisms and causing a considerable change in the ecological flow that maintains that section of the river [9,20,21].

To address the above problems, this study selected a river section near Laoniuwan in the Nansha River Basin of the Haidian District, Beijing, China, as the research object. Based on local historical and field research data, the River 2D model was used to simulate and analyze the results of the simulation, introduce a weighted usable area (WUA) diversity index, and quantitatively analyze the influence of changes in river morphology on WUA diversity. Using *Cyprinus carpio* as the target species, we statistically analyzed the changes in the WUA under different sinuosities and summarized the relationship between sinuosity and ecological flow to provide a basis for the ecological restoration of a river.

2. Materials and Methods

2.1. Study Area and Indicators

Haidian District is located in Northwest Beijing at the junction of the North China Plain and Taihang Mountains remnants (of a mountain range). The total area of Haidian District is 430.73 km^2, lying between latitudes 39°53′–40°09′ north and longitudes 116°03′–116°23′ east.

The Nansha River is located in the northwestern part of Haidian District, in a floodplain behind mountains. The total length of the main channel and the river basin is approximately 30.6 km and 263 km^2, respectively (Figure 1). The basin belongs to the warm belt of semi-humid monsoon continental climate, with average precipitation and surface evaporation for many years of up to 619 and 1883 mm, respectively. The river depth, upper mouth width, and bottom of the river longitudinal slope of the basin are approximately

4.0–5.0 m, 80.0–130.0 m, and 1–2.6‰, respectively, belonging to the Wenyu river system. A U-shaped bend is present on the west side of the Beijing–Bao Expressway near Laoniuwan, with a small turning radius and poor flow conditions, which are not conducive to flooding and regional drainage safety. The original Nansha River was scheduled to be straightened in the local comprehensive improvement plan of 2008; however, this plan has not yet been implemented. Moreover, there has always been controversy over whether the reach should remain in its current state or transform into a straight state. In recent years, as the concept of river management has advanced, the importance of maintaining the river's existing form in terms of flood control and ecology has been recognized. However, there has been no quantitative comparison of the impact on river ecology between the two maintenance cases of the existing planar meander form and its planned straightening. In this context, discussions and analyses in this area have practical importance for the development of locally related work.

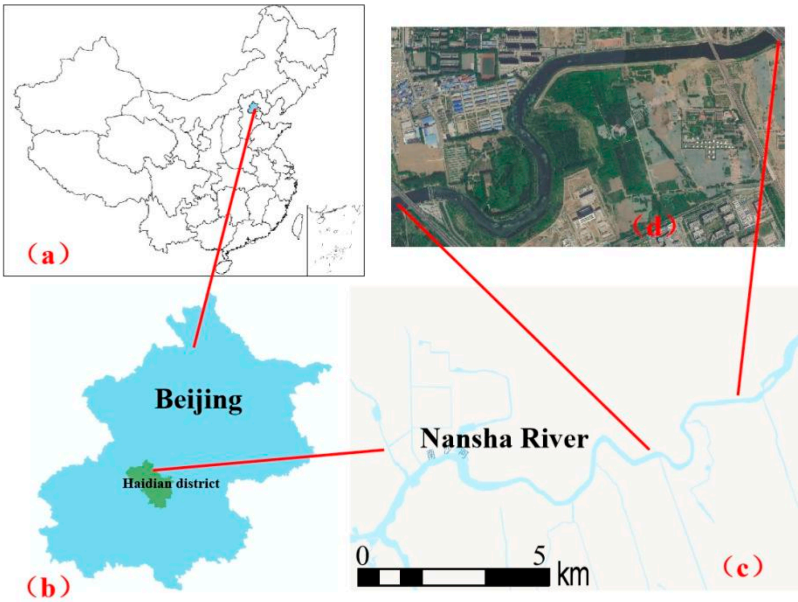


Figure 1. Study area. (**a**) Map of China; (**b**) scope of Beijing; (**c**) the main stream of the Nansha River and some of its tributaries; and (**d**) schematic of the study reach.

Fish are the top predators in river ecosystems, play an important role in the energy flow and material cycle of the entire ecosystem, and are important indicators of regional water conservation and environmental safety [22]. Based on the principles of representation, accessibility, and feasibility, a species with rich historical research data and a definitive research foundation that fully reflects the changes in habitat, that is, the changes in habitat suitability caused by changes in different planar forms, was selected. In addition, *C. carpio* is the dominant species in this area owing to its large population. Based on these factors, *C. carpio* was selected as the indicator species through a combination of field research and data mining.

Fish are the top predators in river ecosystems and play an important role in the energy flow and material cycle of the whole ecosystem, as well as being an important indicator of regional water conservation and environmental safety [22]. Based on the principles of representation, accessibility, and feasibility, species with rich historical research data and a definitive research foundation were selected, fully reflecting the changes in habitat—that is, the changes in habitat suitability caused by changes in different planar forms. In addition, *Cyprinus carpio* is the dominant species in this area, with a large number. Based on the above factors, *Cyprinus carpio* was selected as the indicator species through a combination of field research and data mining.

2.2. Hydraulic Model and WUA

In this paper, the ecological flow was determined using a habitat simulation method based on the principle of the in-channel flow increase method (IFIM)—which is the earliest and most widely used method in habitat simulation [23]—to establish the relationship between the quantity and quality of a suitable fish habitat and flow through a hydraulic ecological model, evaluate the impact of flow changes on the fish habitat, and adjust the flow to improve the ecological environment. The model used was River 2D, which is an unsteady two-dimensional depth-averaged finite element hydrodynamic model written by Professor Peter Steffler of the University of Alberta [24]. Its hydrodynamic simulation is based on a two-dimensional Saint-Venant set of equations consisting of mass conservation and momentum conservation equations in the x- and y-directions [25,26].

The weighted usable area of the selected target species is abbreviated as *WUA*:

$$WUA = \sum_{i=1}^{n} CSF(V_i, C_i, D_i) \times A_i \tag{1}$$

In Equation (1), *WUA* represents the WUA of the selected study reach. $CSF(V_i, D_i, C_i)$ is the overall suitability value of each cell. Among them, i represents the number of cells; V, C, and D represent the flow velocity, bed substrate, and depth suitability index, respectively; and A_i represents the area of each cell level. After the field survey, the substrate in the study section is known to be more uniform, so its suitability index can be considered to be 1.

2.3. Data Processing

Sinuosity is defined as the ratio of the length of the curved arc along the river channel between the two endpoints of a river segment to the length of a straight line between the two endpoints [27]. According to the river classification and the actual situation of the studied river section, based on the current elevation data of the Nansha River, six planar meander forms were constructed using the replication and interpolation methods as follows.

First, based on the actual situation and the reasons for the selection of the above-mentioned study river section, the range of sinuosities was determined to be 1.0 (planning) to 1.89 (current situation).

Second, based on the current situation, we identified and analyzed the elevation data of the meander section; the elevation data of the river section without the sinuosity changing was guaranteed to be consistent, and the data of the changed river section was replicated based on the location correspondence.

Thirdly, when the sinuosity changed, the length of the river section would change. Based on the replication method, the River 2D model was used to perform model interpolation during data preprocessing. Finally, the six determined planar meander morphology maps are shown below in Figure 2.

2.4. Determination of the Suitability Curve

A key factor that determines the accuracy of habitat simulation results is the habitat suitability index (HSI), which is used to quantitatively describe the suitability of a species to a habitat, with values ranging from 0 to 1, with 0 being completely unsuitable and 1 being completely suitable; the larger the value, the better the suitability [28].

Currently, there is a lack of information on the suitability of the hydraulic characteristics for fish distributed in the Nansha River. In this study, we refer to the existing literature [29] and actual local information to obtain a preliminary suitable flow and water depth for the target fish and derive the suitability curve for *C. carpio*. The substrate size and water quality in the study area were homogeneous and were ignored during this estimation. The suitable and optimal flow velocities for *C. carpio* were 0.1–1.1 m/s and 0.2–0.6 m/s, respectively. The suitable water depths for *C. carpio* were 0.2–2.5 m, and the optimum water depths were 1.0–1.5 m (Figure 3).

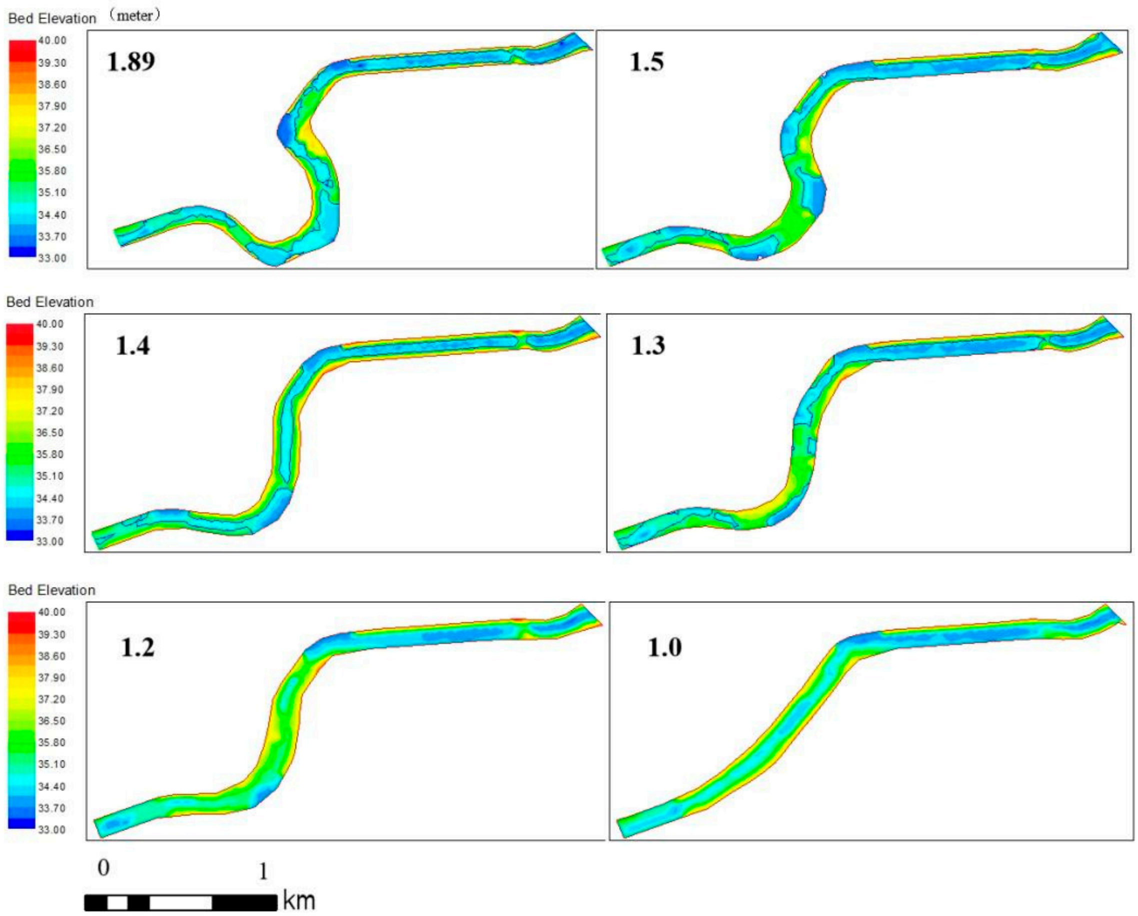


Figure 2. Different sinuosities (1.89–1.0).

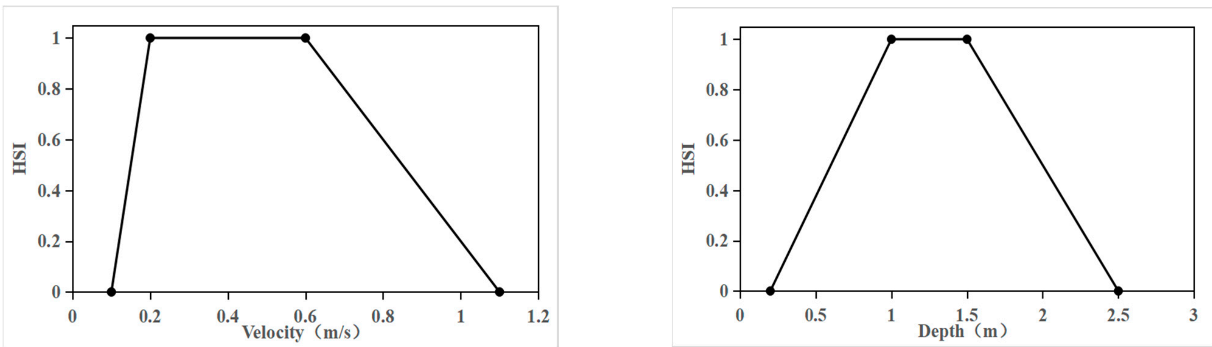


Figure 3. Velocity and depth suitability curves for *Cyprinus carpio*. (Drawings based on the research of Yang et al. [29]).

2.5. Model Building and Validation

Based on the local hydrological data, six flow conditions were simulated—5, 10, 15, 20, 25, and 30 m^3/s—and the roughness was taken as 0.035. River sections 1–6 were selected (see Figure 4). Comparing the simulated water level of the model—with an initial flow of 520 m^3/s—to the design water level of the "Haidian District Nansha River (Shangzhuang gate district boundary) Desilting Control Project" (the planning report of which has been approved and is being implemented) in 2016, it can be seen that the simulated value of the water level of the constructed model matched well with the design water level value of the desilting control project being implemented. The relative error was small (see Table 1), and the model established in this study exhibited good simulation ability for the hydrodynamic conditions of the Nansha River, where the spacing between 1 and 6 in each section is 300 m.

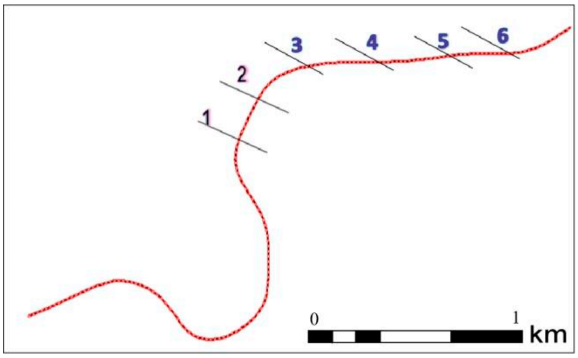


Figure 4. Schematic diagram of the cross section.

Table 1. Sections 1–6 simulation and water level design.

Section Name	1	2	3	4	5	6
Simulated water level (m)	38.55	38.43	38.20	38.08	37.96	37.92
Design water level (approved dredging project) (m)	38.45	38.40	38.40	38.39	38.36	38.28
Relative error (%)	0.26	0.08	0.52	0.80	1.05	0.98

2.6. Depth and Velocity Diversity Index

Diversity indices originated from the quantitative characterization of species diversity, Fisher proposed the concept of the species diversity index in 1943 [30]. Later, it was developed and gradually applied in the fields of environmental science, physical geography, and basic agricultural science—Fatch Paul et al. [31] proposed the overall agricultural diversity index for measuring agricultural diversity. Li Changchao et al. proposed a comprehensive index of microplastic diversity by clarifying the differences between microplastics in different environments and analyzing them retrospectively [32]. Currently, the indices for quantifying depth and velocity diversity are not yet clear. Combining the generalization and application of diversity indices from previous authors, this paper constructs a depth and velocity diversity index based on Shannon's index to better characterize depth and velocity diversity quantitatively.

The Shannon (H) diversity index can be used to reflect the degree of depth and velocity heterogeneity [33]. The higher its value, the better the degree of depth and velocity flow heterogeneity, and the more stable the survival of organisms in the region.

$$H = -\sum_{i=1}^{m} (P_i) \times \log_2(P_i) \tag{2}$$

In Equation (2), H denotes the diversity index; m denotes the number of different types of areas; and P_i denotes the proportion of the study area occupied by the ith type.

In order to consider the heterogeneous results of the combination of water depth and velocity, this paper introduces the depth and velocity diversity index based on the above analysis, referring to the research of related experts and scholars. We use H_e to express it, which is calculated as follows:

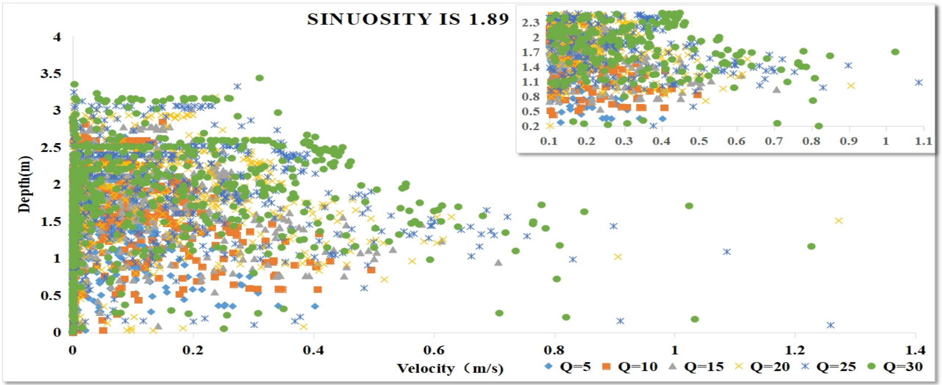
$$H_e = \sum_{i=1}^{m} (P_i) \times \log_2(P_i) \sum_{j=1}^{n} (P_j) \times \log_2(P_j) \tag{3}$$

In Equation (3), H_e represents the depth and velocity diversity index; m represents the number of different depth regions, n is the number of different velocity regions; P_i is the proportion of the study area occupied by the ith depth interval, and P_j is the proportion of the study area occupied by the jth velocity interval.

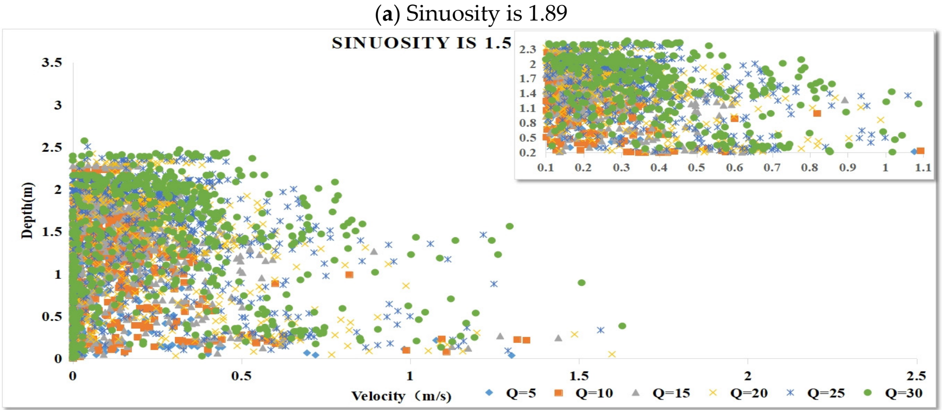
3. Results

3.1. Analysis of Water Depth and Flow Velocity Diversity at Each Sinuosity

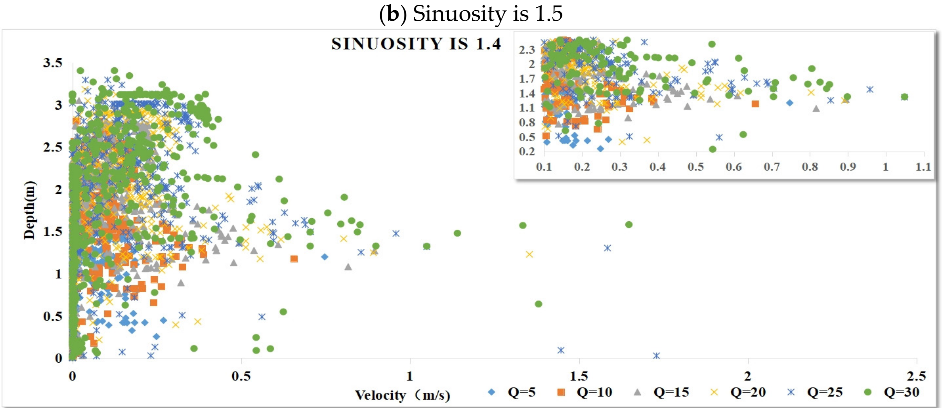
The simulation results were processed and analyzed, and the water depth and velocity distribution of each sinuosity at different flows were calculated. The water depth and flow velocity scatter distribution maps and box plots are shown in Figures 5 and 6. Notably, most scatter points fall in an area with a water depth of 0.5–2.5 m and a flow velocity of 0–0.5 m/s. The studied river section was suitable for the survival of the target fish. Under the same sinuosity, the scattering points showed a more dispersed trend with increasing flow, and the maximum depth and velocity diversity values gradually increased. That is, depth and velocity diversity exhibited better trends, and the distribution of depth and velocity was more dispersed for sinuosities 1.3, 1.5, and 1.89. Under the same flow, as the sinuosity increased, the water depth exhibited a steady upward trend, and the flow velocity initially increased before falling.



(**a**) Sinuosity is 1.89



(**b**) Sinuosity is 1.5



(**c**) Sinuosity is 1.4

Figure 5. *Cont.*

(**d**) Sinuosity is 1.3

(**e**) Sinuosity is 1.2

(**f**) Sinuosity is 1.0

Figure 5. Scatter diagrams of depth and velocity distribution under different sinuosities with different flows.

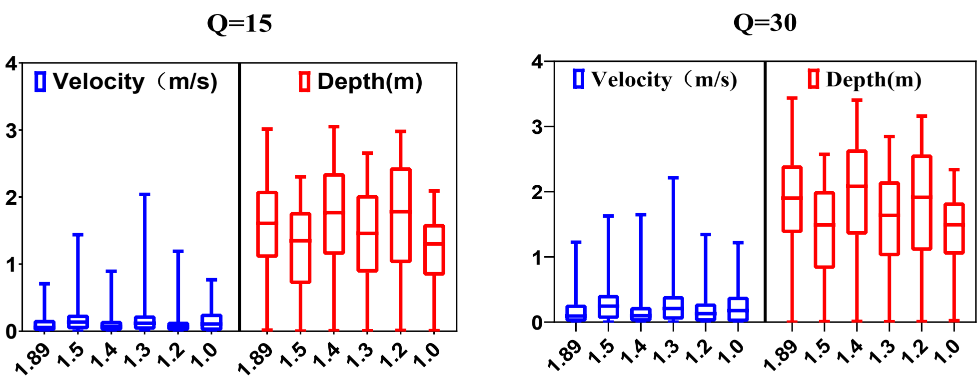


Figure 6. Velocity and depth distribution under different sinuosities.

To quantify the relationship between sinuosity and diversity of water depth and velocity, the velocity was divided into nine intervals, 0–0.1, 0.1–0.2, 0.2–0.4, 0.4–0.6, 0.6–0.8, 0.8–1.0, 1.0–1.2, 1.2–1.5, and 1.5 m/s or more, based on the actual conditions of the studied river and the suitable survival threshold of the target fish. The water depth was divided into six intervals: 0.5–1.0, 1.0–1.5, 1.5–2.0, 2.0–2.5, 2.5–3.0, and 3.0 m or more. Based on the simulation results, the percentage of each interval in the water area of the river section was derived and used as the P_{ij} quantity to calculate the water depth flow diversity index and quantitatively describe the relationship between sinuosity, depth, and velocity diversity under different flows (Figure 7 and Table 2).

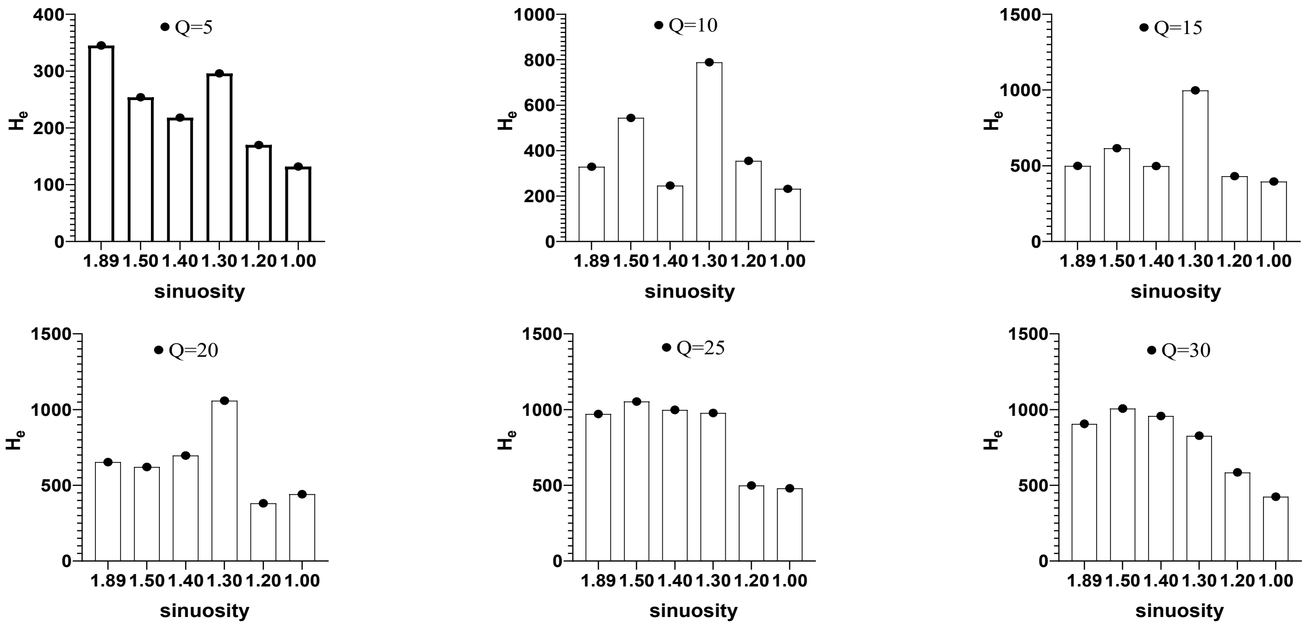


Figure 7. Diversity index of water depth and rate at different flows.

Table 2. Diversity index values of depth and velocity at different sinuosities.

Q (m^3/s) \ S	1.89	1.5	1.4	1.3	1.2	1.0
5	345	254	218	296	170	132
10	329	544	246	789	355	232
15	499	616	498	998	431	396
20	653	621	697	1059	381	441
25	971	1053	998	978	499	480
30	906	1007	958	827	585	425

The overall trends in depth and velocity diversity increased with increasing sinuosity. This does not necessarily imply that greater sinuosity results in better depth and velocity diversity. For the index calculation results, the maximum value of the index was 1059 for the river form with a sinuosity of 1.3. However, lower sinuosity resulted in worse depth and velocity diversity. The sinuosities of 1.2 and 1.01 exhibited a substantially lower depth and velocity diversity index than the other forms under all flow conditions (Figure 8).

With increasing flow, most plane forms with different sinuosities showed an increasing trend, but this did not imply that greater flow resulted in better depth and velocity diversity. Furthermore, the maximum value of the index of sinuosity of 1.89–1.0 is obtained in the following order: Q = 25, 25, 25, 20, 30, and 25 m^3/s. In the case of a low flow of Q = 5 m^3/s, the greater the sinuosity, the better the depth and velocity diversity within a certain range (Figure 9).

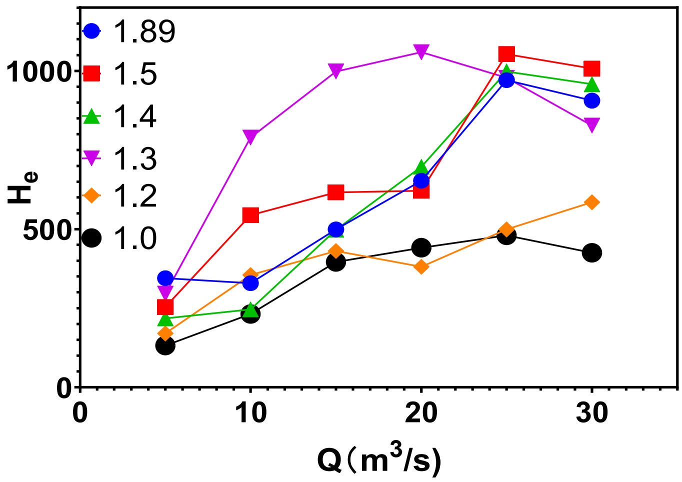


Figure 8. Trend of depth and velocity diversity index.

3.2. Sinuosity and Ecological Flow

Based on the suitability curve of *C. carpio*, the WUA distribution of the species at six sinuosities under different flow conditions was determined by simulation analysis (Figure 10). With an increasing flow rate, the WUA exhibited an overall increasing trend. At the same flow, river sections with greater sinuosity were relatively better; these more suitable areas were mostly at river bends, and the areas more suitable for *C. carpio* in the straight section were substantially smaller. The WUA distribution was organized, and the Q-WUA relationship curves were plotted.

As seen from the curves, a peak sinuosity of 1.5 was the largest, and that of 1.4 was the smallest. Under low flow, the suitable survival area of the river section with high sinuosity was substantially better than that of the river section with low sinuosity. At higher flows, the meanders were also better; however, there were more suitable areas for smaller meanders. Combined with the habitat simulation method, the highest point of the curve was the ecological flow of the river, and we could identify the ecological flow of meanders from 1.0–1.89 as being 20, 25, 20, 15, 22.5, and 15 m^3/s. When determining the ecological flow of meanders at a sinuosity of 1.5, the flows of 20 and 25 m^3/s did not exhibit monotonic increasing or decreasing trends. Thus, using a trial calculation of 22.5 m^3/s WUA, we found that the WUA corresponding to Q = 22.5 was the maximum value on the curve.

With increasing sinuosity, the overall ecological flow required by the target fish in the studied river section exhibited a decreasing trend, and sinuosity and ecological flow exhibited a negative correlation (Figure 11). Meanders with high sinuosity have a greater diversity of water depths and velocities, more geomorphological unit variety, and a strong regulation ability, which makes the rivers more suitable for the survival and reproduction of fish at lower flows. The smallest ecological flow of 15 m^3/s was required with sinuosities of 1.89 and 1.4. Comparing the WUA under the two morphologies, 1.89 was much larger than that of 1.4. In this study, considering the relationship between the social economy and ecology, a sinuosity of 1.89 was considered the appropriate morphology.

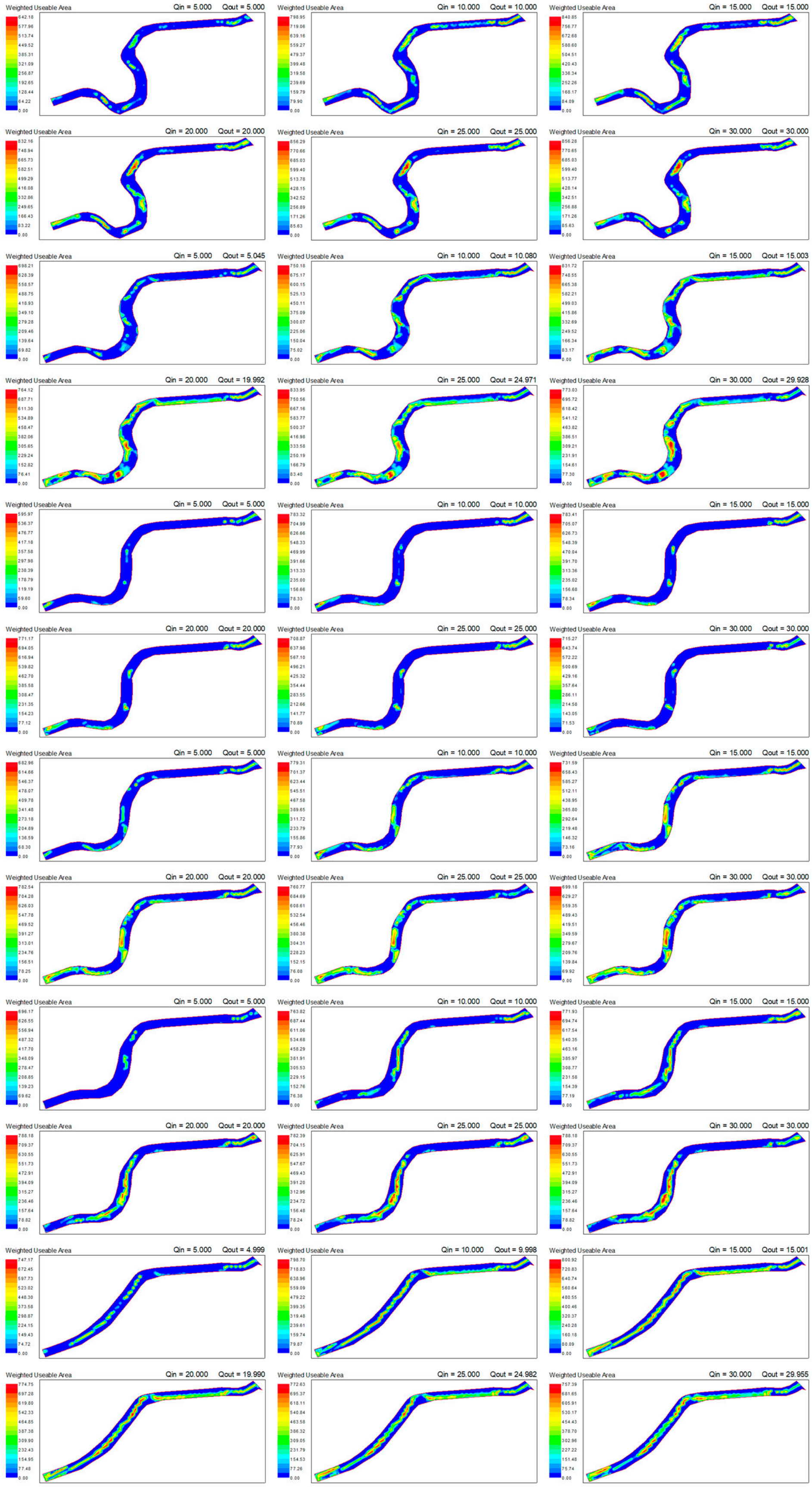


Figure 9. Distribution of WUA at different flows (with sinuosities of 1.89–1.0).

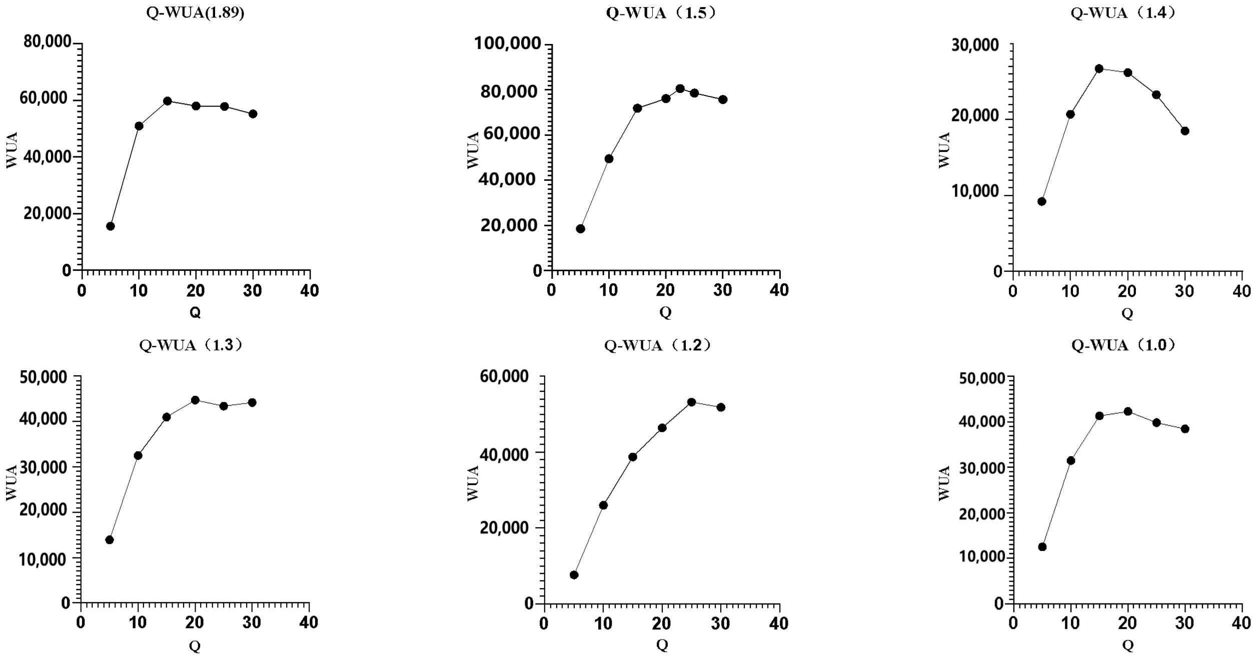


Figure 10. Q-WUA curves at different sinuosities.

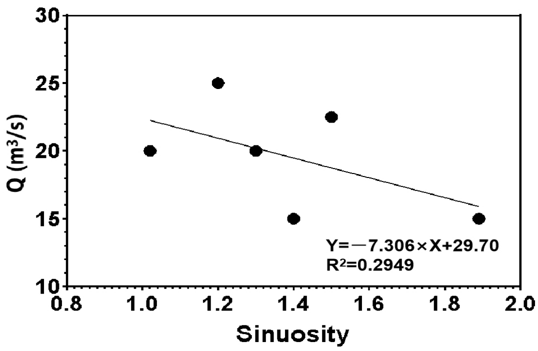


Figure 11. Relationship between sinuosity and ecological flow.

4. Discussion

4.1. Quantification of River Depth and Velocity Diversity

Many experts and scholars have conducted studies on the depth and velocity diversity. Scholars have introduced the habitat depth and velocity diversity index to quantitatively analyze the effects of artificial step-deep pool systems on aquatic habitats and river ecology [34]. Stähly et al. quantified the spatial variation in aquatic habitats in river segments using the hydroform diversity index [35]. The establishment of related indices allows a more intuitive quantitative study of the relationship between geomorphology, hydrology, and river ecosystems, and the use of hydrodynamic models to quantitatively simulate and analyze the spatial distribution and trend changes in water depth and flow velocity can provide technical support for the layout of river ecological restoration measures and the assessment of restoration effects [36–38].

4.2. Habitat Modeling Methodology and Ecological Flows

The habitat simulation method is used to determine the ecological water demand of rivers according to the physical habitat conditions required by the indicator species through field monitoring or water environment modeling to obtain the spatial and temporal distribution of habitat factors and habitat suitability evaluation indexes. Simulation of the quantitative relationship between the flow and distribution of suitable habitats is performed to obtain the ecological flow of aquatic organisms for the protection of the indicator species, mostly fish, and to provide a basis for the rational development and utilization of water resources [39–41]. Habitat simulation methods more adequately consider a single or multiple species, such as this study, which considers the dominant species in the study area, *C. carpio*, which reflects specific ecological needs, although the entire river ecosystem is ignored. Our results show that, as the flow changed, the inflection point of the Q-He curve did not coincide with the maximum value and Q-WUA curve, which initially showed the limitations of the ecological flow calculated by habitat simulation methods alone. In general, the better the diversity of the habitat, the better the biodiversity and the healthier the river ecosystem [42,43]. Further research is needed to determine if the flow required to maintain the stability of the entire river ecosystem should be considered.

4.3. Relationships between Changes in Sinuosity, River Ecology, and Socioeconomics

Changes in river morphology affect not only the physical form and dynamic river processes of individual reaches but also longer reaches and even entire river systems, including some tributaries [44]. Human intervention in river environments always needs to consider the unintended side effects and potential long-term legacies that may create new problems upstream or downstream [45], thereby affecting habitat availability and ecological status in longer reaches [9]. Furthermore, it is particularly important to clarify the relationship between sinuosity and the ecological and regional socioeconomic needs of rivers when carrying out comprehensive river sinuosity adjustment-oriented improvement projects.

Scholars have studied the mechanism of sinuosity in the self-purification of water bodies and proposed increasing the sinuosity to improve the ability of rivers to remove pollutants from water, which was thought to increase the growth rate of dissolved oxygen. However, the excessive meandering of rivers can affect flooding, sand drainage, and the safety of riverbanks [46]. Changes in the meandering of rivers must be justified, as there is a corresponding relationship between the meandering of rivers, society, and ecology; that is, no blind remediation is possible. Moreover, meanders of rivers that do not require remediation and whose meanders have remained unchanged for a long time should be left unchanged [47]. Meandering river ecosystems are sensitive and have difficulty recovering from damage [48]. Consequently, unnecessary human interference should be reduced to prevent the destruction of river habitats, which affect the stability of river ecosystems [49]. River morphology characterized by sinuosity is linked to the abundance, evenness, and diversity of organisms in the structure of river ecosystems, and there are large differences in organisms living at different geomorphic units of rivers [50,51]. In general, the complex sinuosity of water supports the diversity of river organisms [52,53]. Against the risk of riparian soil erosion along dammed rivers, the configuration of river morphology should be considered as one of the potential management strategies for offsetting the negative impacts of damming [54]. Moreover, after changing the sinuosity of rivers, monitoring of river habitat types and the corresponding biological changes should continue [55]. In this study, we quantified the relationship between sinuosity, depth, velocity diversity, and ecological flow and argued for an appropriate sinuosity, which has practical implications for the multi-objective ecological restoration of rivers.

For some water-scarce rivers affected by the natural environment, geographic location, socioeconomic factors, and human factors, there may be much less in-channel runoff than the ecological flow calculated through hydraulics and habitat simulation. In such cases where water diversion and replenishment cannot be guaranteed, research such as this study should be considered to determine the appropriate sinuosity through quantitative methods to maintain the stability of river ecosystems at relatively low flow rates through ecological engineering to adjust the river sinuosity.

5. Conclusions

In this study, a River 2D model was used to simulate the hydrodynamics and habitats of six morphologies of the studied river, which, combined with the depth and velocity diversity index and the Q-WUA curve, were used to determine the relationship between sinuosity, depth and velocity diversity, and the ecological flow required by the target species. Quantitative research showed that, as the sinuosity increased, the depth and velocity diversity of the water increased, and the two were positively correlated; however, this did not imply that the greater the sinuosity, the better the depth and velocity diversity, except under low flow conditions. Our results showed that the ecological flow required for the target species in the reach exhibited a downward trend and was negatively correlated with sinuosity.

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