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Effects of the Diversity of Flow Velocity on the Upstream Migration Behavior of Grass Carp in the Reaches of Spur Dikes

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Abstract: The construction of spur dikes alters the flow pattern of rivers and affects the upstream migration behavior of fishes. Traditional rock-fill spur dikes and experimental permeable spur dikes with a "Weighted Excess Storage" (WES) profile were evaluated using hydrodynamic experiments and experiments on the upstream migration behavior of juvenile Grass Carp (*Mylopharyngodon idella*). The swimming ability and upstream migration paths of juvenile Grass Carp in the spur dike were analyzed, and the relationship between the upstream migration success rate of Grass Carp and the diversity of flow velocity was studied. The induced velocity and critical velocity of juvenile Grass Carp with a body length of 5 ± 0.5 cm are 0.1 m/s and 0.7 m/s according to the experiment. The flow velocity diversity index increased roughly in a power function trend with the increase in flow discharge, and under the same flow conditions, the flow velocity diversity index of permeable spur dikes was greater than that of rock-fill spur dikes. When the flow velocity was within the preferred velocity range of Grass Carp, the success rate of upstream migration increased linearly with the diversity of flow velocity. When the velocity was greater than 60% of the critical velocity of Grass Carp, the success rate of upstream migration dropped sharply. Compared with rock-fill spur dikes, the experimental permeable spur dikes provide a passage for the upstream migration of fishes and reduce the impact on the upstream migration of fish. The results of this research provide theoretical support for ecologically optimized designs of spur dikes and the ecological management of rivers.

Keywords: spur dike; flow velocity diversity; Grass Carp; upstream migration success rate

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1. Introduction

Inland waterways are important to commercial shipping activities, and spur dikes are important structures that are widely used to direct water flow, protect river banks, and improve the navigation conditions within these waterways [1,2]. The construction of spur dikes alters the characteristics of the original flow of the waterway, creating different flow environments, which have an impact on the habitat of these sections of the local river. In the past, attention was paid to the effects of renovating waterways, while the impact of renovation projects on the river's ecology was ignored. In recent years, the modification of existing structures and the construction of new structures in waterways have placed greater emphasis on ecological performance; therefore, researchers and engineers have begun to study the ecological effects of spur dikes.

Poulet et al. [3–5] showed that spur dikes can alter the characteristics of the habitat in some sections of a river, increase the heterogeneity of river habitats, increase the area of the habitat, and create a favorable living environment for juvenile fish. Biron [6] pointed out that with proper design and construction, the sections of a river with spur dikes have the potential to become a habitat that is suitable for the survival of fish. However, due to the blocking effect of a spur dike, a low-speed area or even a static water area is formed behind the spur dike, which can cause sedimentation, making the environment unstable and not conducive to the survival of benthic species [7].

While taking the regulatory effect of adjusting the flow pattern and scouring of the riverbed into account, a permeable spur dike (a spur dike structure in which the water can flow through the dike's body) has the function of connecting the water flow and enhancing the diversity of the water flow, avoiding excessive deposition of sediment behind the dike, providing a stable habitat for plankton and benthic animals, and ensuring the food supply of fish [8–10]. Furthermore, the shelter formed by the permeable structure can help young fish avoid their natural enemies and predators, forming a good microhabitat [11]. Burch et al. [12], on the basis of a comprehensive analysis of the application of notched spur dikes (dikes with serrated edges) in the Mississippi and Missouri rivers and the results from a relevant ecological survey, found that notched spur dikes could create more heterogeneous habitats, and the density of fish near them was higher than that near rock-fill spur dikes. Lechner [13], through an experiment on the drifting of carp larvae and eggs, found that the larvae and eggs could enter the dam area through the spur dike's gap (the permeable hole of the permeable spur dike) and stay there for a longer time, while a rock-fill spur dike forced the larvae and eggs into the mainstream area and increased their mortality. Many new permeable groins, such as notched spur dikes and W-shaped spur dikes, have been widely used in the ecological restoration of the upper Mississippi River and the Danube River in Austria [14]. The Changjiang River Channel Planning and Design Institute [15] has included permeable frame spur dikes in the "Tiger Beach Head" regulation project that is part of Phase II of the regulation of the Dongliu waterway's channels. After an on-site ecological investigation, it was found that the rate of fish aggregating around the permeable frame spur dikes was about five times that of rock-fill spur dikes.

The studies above mainly focused on the impact of spur dikes on river habitats, and it has been found that the diversity of water flow (which refers to the spatial variability in the flow velocity) is the main factor affecting the ecological effects of spur dikes. Water currents play an important role in the ecology of fish and affect their entire life course [16]. Fish have evolved a wide range of behavioral responses to water currents, among these, the basic reaction of fish to currents is rheotaxis, which has been confirmed in many different fish species [17]. The behavior of rheotaxis is critical for the upstream migration of fish, which is an important ecological indicator used for evaluating rivers [18]. The flow velocity is an important stimulus of the upstream migration of fish and is undoubtedly the most important "director" of upstream migration [19]. Fish that swim upstream in rivers to spawn must navigate complex fields of fluvial velocity to arrive at their ultimate locations. For a fish, an increase in speed must be compensated for by an increase in muscle activity, and the consumption of energy depends on the flow velocity and the size of the fish [20]. The fecundity of spawning fish decreases with an increase in the distance and difficulty of upstream migration, so the energy consumed by fish during the upstream migration process should be minimized [21]. The cost of migration in the study of Kinnison et al. [21] was a function of the total migration distance; McElroy, B. et al. [22] also studied this and argued that the cost of migration should be a function of the total path distance and the speed experienced along the way. DeLonay [23] conducted a real-time survey of the upstream migration path of pallid sturgeon. It was observed that during upstream migration, the fish avoided the relatively high-speed areas, used the relatively slow-speed areas for upstream movement along the curved inner bank of the river, and minimized the sinuosity of their paths to achieve the shortest route from the initial downstream position to the migratory apex.

To meet the requirements of navigation and ensure the safety of the channel, rock-fill spur dikes have been built to reconstruct many large rivers for navigation and embankment stability. Due to the ecological limitations of rock-fill spur dikes, when designing new or rehabilitated river regulation structures, consideration should be given to low-speed migration corridors for fish, which can improve the success rate of the upstream migration of fish that require migration for spawning and improve the overall reproduction of the fish population.

The "Four Big Family Fish" are typical potamodromous fish species in China's lakes and rivers, whose entire life cycle often requires alternating between rivers and lakes for spawning, foraging, and overwintering. The most famous of the Four Big Family Fish is the Grass Carp. Juvenile Grass Carp, with body lengths mainly ranging from 5.00 to 15.00 cm, forage and migrate into lakes. The construction of dikes has altered the original characteristics of the flow of rivers and has increased the diversity of the flow in the dike sections. The changes in the flow of water will affect the upstream migratory behavior of juvenile Grass Carp, leading to a modification of their migration path and impacting the overall upstream success of juvenile Grass Carp. However, at present, there are few studies on the impact of constructing spur dikes on the success rate of upstream migration by juvenile Grass Carp. The impact of spur dikes on the diversity of water flow and the law of interaction between a spur dike and the upstream migration behavior of fish are not clear. A hydrodynamic experiment and an experiment on the upstream migration of juvenile Grass Carp were conducted on a traditional rock-fill spur dike and an experimental permeable spur dike to measure the velocity, flow patterns, and success rate of upstream migration by juvenile Grass Carp around the spur dike, and a method of calculating the flow velocity diversity index was proposed for analyzing the relationship between the diversity of flow velocity and success rate of upstream migration. The results of this research can provide theoretical support for ecologically optimized designs of spur dikes and reduce the cost of the ecological restoration of rivers.

2. Materials and Methods

The entire experiment was divided into three parts. The first part was the measurement of Grass Carp swimming ability, the second part was the observation of the flow field near the spur dike, and the third part was the experiment on the upstream migratory behavior of Grass Carp near the spur dike.

2.1. Experimental Design

The swimming ability of Grass Carp was tested in a rectangular glass tank with a length of 25 m, a width of 0.5 m, and a height of 0.5 m. The bottom slope of the flume was zero, and the water flowed into the flume from an underground reservoir through a pipeline. The experiment's inlet flow was controlled by a flow control system jointly developed by Tsinghua University and Beijing Shangshui Information Technology Co., Ltd. The flow inlet was equipped with energy dissipation grids to ensure the stability of the flow. The water depth was controlled by the tailgate. The experimental observation section located at two-thirds of the length of the flume was selected to obtain a uniform and stable flow field. A schematic of the flume system can be seen in Figure 1.

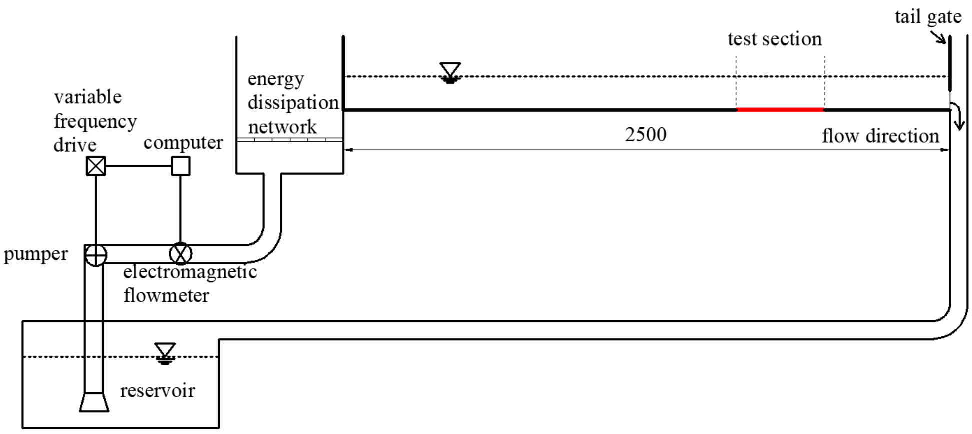

Figure 1. Fish swimming ability experiment flume system (unit: cm; 1 cm = 0.01 m).

The swimming ability of Grass Carp was primarily observed using a high-speed camera system. This system included 14 image sensors and 1 networked hard disk recorder, all of which were produced by Zhejiang Dahua Technology Co., Ltd. (Hangzhou, China). The image sensor was a high-performance image sensor with a good low-illumination effect and high image definition. The maximum infrared monitoring distance was 30 m, and the infrared far and near light compensation and the uniformity of the pictures were automatically adjusted.

The experimental section in the experiment on the swimming ability of Grass Carp had a length of 3 m, and steel wire fences were placed upstream and downstream from the section to ensure that the experimental fish always swam in the designated area. The wall of the sink was clean, and the water body was clear, providing a clear view for observing the swimming behavior of the fish. Eight high-speed cameras were installed directly above the experimental section at a spacing of 0.4 m, and three high-speed cameras were installed on the side at a spacing of 1.0 m to record all the swimming behavior of the fish. The flow velocity was recorded using a Nortek ADV (Vectrino+, Rijeka, Croatia) equipped with a side-looking head. For the experiment, the velocity rate was set to 1.0 m/s, the sampling rate was maintained at 100 Hz, and the data had an accuracy of 0.001 m/s. The accuracy of the data was positively correlated with the signal's correlation coefficient (COR) and the signal-to-noise ratio (SNR). The measured data displayed COR and SNR values greater than 90% and 18 dB, respectively. A schematic of the experimental set-up can be seen in Figure 2.

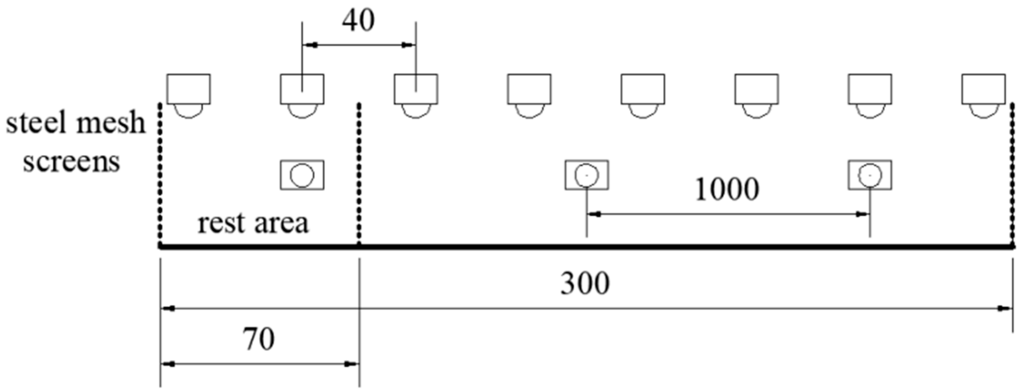

Figure 2. Arrangement of swimming ability experiment of Grass Carp (unit: cm; 1 cm = 0.01 m).

Experiments to observe the flow field and the upstream migration path of Grass Carp were conducted in a straight open-channel flume that was 30 m long, 3 m wide, and 0.8 m high with a bed slope of zero and concrete sidewalls and bottom. The water was piped into the flume from an underground reservoir. The inlet flow was controlled by an electromagnetic flowmeter, and an energy dissipation grid was arranged in front of the experimental tank to ensure the stability of the water flow. The water's depth and drops in the water's surface were controlled by the tailgate. A spur dike was installed in the middle of the flume, and the dike's axis was 14 m away from the water inlet. A schematic of the flume system can be seen in Figure 3.

The experimental spur dikes included the most common rock-fill spur dike and the experimental permeable spur dike found on the Changjiang River. The height of the experimental rock-fill spur dike model was 0.15 m, the width of the dike's crest was 0.075 m, and the length of the dike was 1.35 m. The sectional structure of the rock-fill spur dike is shown in Figure 4.

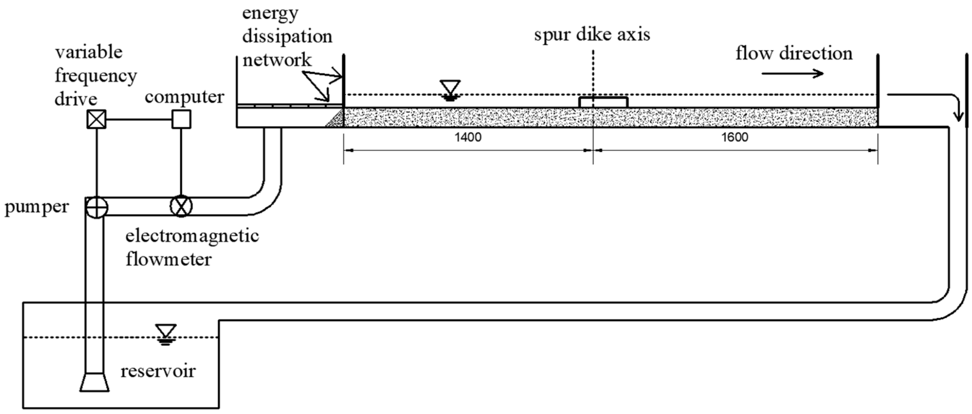

Figure 3. Experiment flume system (unit: cm; 1 cm = 0.01 m).

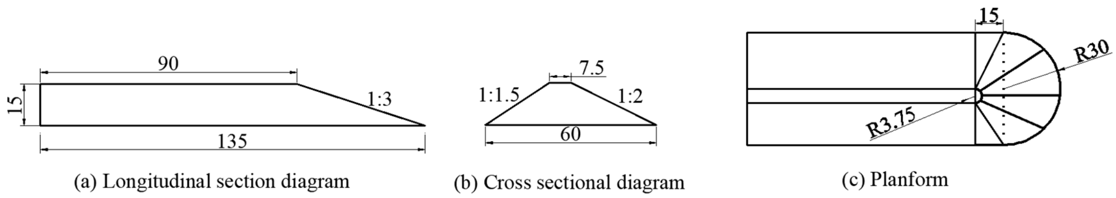

Figure 4. Structure diagram of rock-fill spur dike (unit: cm; 1 cm = 0.01 m).

The independently designed permeable spur dike used the WES curve of an overflow weir as a reference for designing the spur dike's body curve. The back slope curve of the spur dike consisted of a top curve section, a middle line section, and a return arc section. The upstream slope curve of the spur dike consisted of a top curve section and a return arc section. The top curve section was further optimized on the basis of the WES curve. The arc return section was an arc curve, and the middle line section was at a tangent to the top curve section and the lower arc return section. The dike body's curve is shown in Figure 5. The spur dike was an assembled structure composed of a dike head, a permeable dike body, and a dike root. The permeability of the dike body was 17.6%, and the equation used to calculate the permeability is shown in Formula (1).

$$\alpha = \frac{S_1}{S} \times 100\% \quad (1)$$

where S_1 is the projected area of the water permeable hole and S is the projected area of the impermeable dike body.

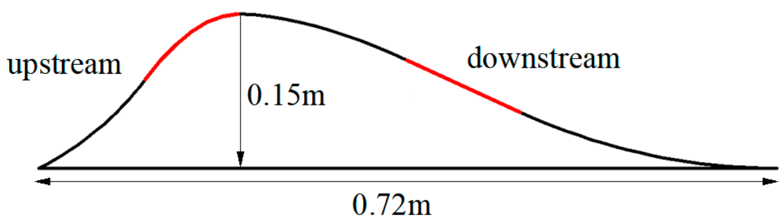

Figure 5. Side view of permeable spur dike. The two red lines are the connecting sections connecting the upstream and downstream curves.

The experiment permeable spur dike was 0.15 m high, 0.72 m wide, and 1.35 m long. The structure of the permeable spur dike is shown in Figure 6.

The XKVMS-02 large-area surface flow field observation system, produced by Chongqing Jiaotong University, was used to observe the impact of the spur dike on the local flow field of the river. This system collected images of plastic tracer particles moving on the water's surface through high-definition cameras and calculated the distribution of fringes through software processing. The high-definition camera of the observation system had a shooting range of 3 m × 7 m, with two cameras arranged on the right bank of the flume, as shown in Figure 7.

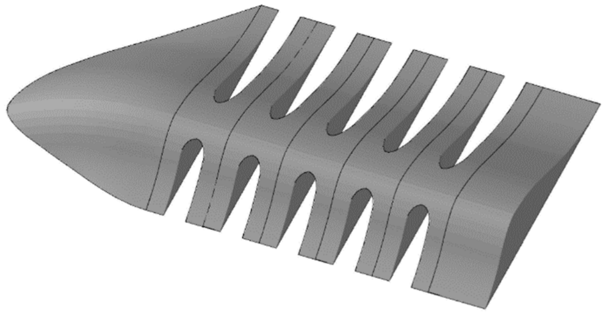

Figure 6. Three-dimensional view of permeable spur dike from above.

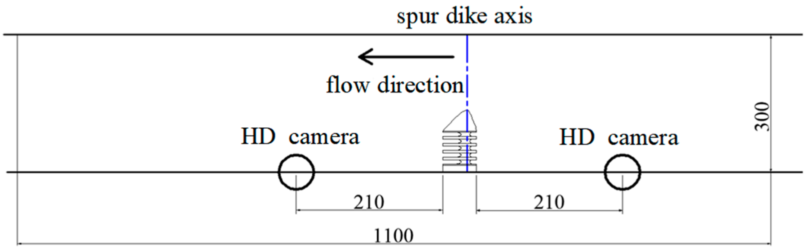

Figure 7. Plan view of experiment flume with permeable spur dike (unit: cm; 1 cm = 0.01 m). The blue line is the spur dike axis.

The section for observing the upstream migration of Grass Carp in this experiment was 11 m long, and fences were installed at the tailgate and water inlet of the flume. The experimental water was clean, which made it convenient to observe the swimming behavior of the fish. Fourteen high-speed cameras were installed 1.0 m above the experimental section to ensure that the video covered the entire section and recorded the entire swimming process of the fish during the experiment. The experimental arrangement is shown in Figure 8.

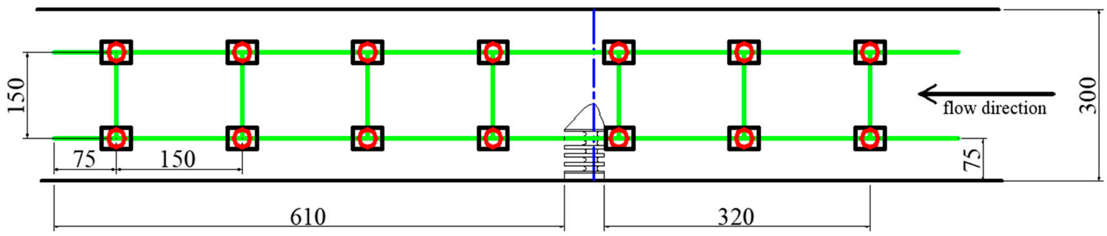

Figure 8. Observation section arrangement of Grass Carp upstream migration experiment (unit: cm; 1 cm = 0.01 m). The blue line is the spur dike axis, the green lines are the camera mounting, the black box and ref circle are the camera identification.

2.2. Experimental Procedure

Inflows of 27.3 L/s, 59.5 L/s, 89.5 L/s, 119.1 L/s, 142 L/s, 156.4 L/s, and 198 L/s were selected for the model to simulate the flow of the middle reaches of the Changjiang River in different periods, such as the dry season, the normal flow season, and the flood season. The influence of the traditional rock-fill spur dike and the experimental permeable spur dike on the river flow patterns and upstream migration path of Grass Carp was studied under those flow discharge rates.

The Grass Carp used in the experiment were taken from the Yongchuan Fishing Ground in Chongqing. The juvenile Grass Carp had a length of 2.0–8.0 cm, a weight of

0.1–7 g, and a body condition ratio of 1.0 ± 0.2. The growth and health of the juvenile Grass Carp in this length range were good. Body condition is the ratio of a fish's weight to the cube of its body length, which can be calculated using the formula

$$K = (W/L^3) \times 100 \quad (2)$$

where K is the body condition, W is the weight (g), and L is the body length (cm).

Body condition is a reflection of the degree of obesity and the fish's growth status. All juvenile Grass Carp were fed according to standard fish care methods.

During the experiment on the upstream migration of fish, the juvenile Grass Carp were raised temporarily in the fish tank and then placed in a marked container for standby, and the experimental current was adjusted to be stable according to the water flow conditions in the dry season (27.3 L/s). The juvenile Grass Carp were placed in the rest area of the experimental tank to adapt to the water flow. After the experimental fish had adapted to the current for 1 h, the flow discharge was adjusted according to the flow conditions set in the experiment, and then the block was removed and the fish swimming in the experimental tank were observed. After the experimental fish entered the area observed by the camera, videos captured the path of movement of the experimental fish. When the experimental fish stayed still or hovered in a small zone for a long time, or swam out of the experiment observation area and did not return in a short time, the experiment was considered to be over. After each experiment was completed, the experimental fish were allowed to recover, and the recovered experimental fish did not participate in the next experiment. Personnel were not allowed to enter the experimental area during each run of the experiment.

3. Results

3.1. Analysis of the Swimming Ability of Juvenile Grass Carp

The swimming ability of fish refers to the duration and intensity of swimming, which is the basis for whether fish can pass obstacles of water velocity [24]. Generally, the induced velocity, preferred velocity, and critical velocity are used as indicators. By measuring the swimming ability of juvenile Grass Carp, the foundation was laid for studying the influence of river flow on the upstream migration behavior of Grass Carp. The tests of the swimming ability of juvenile Grass Carp included tests of the induced velocity and critical velocity. Each test was repeated 20 times for juveniles with the same body length.

3.1.1. Induced Velocity

Fish sense the direction through the water flow when they are moving, thereby producing a flow response. The minimum flow velocity that can cause a fish to have a flow response is called the fish's induced velocity. During the experiment, three groups of juvenile Grass Carp were used, with 10 in each group. These were placed in the resting area of the test section of the experimental tank. After acclimatization in still water for 1 h, the experimental flow velocity was gradually increased in increments of 0.5 BL/s, where BL was equal to the length of the experimental fish. At the same time, the swimming behavior of the fish was observed. When 90% of the experimental fish were observed to swim against the current, the flow velocity was taken as the induced velocity of the experimental fish. The movement status of the juvenile Grass Carp is shown in Figures 9 and 10. The percentage of error of the experiment was 5%, and the standard deviation was 1.4%.

It can be observed from the figure that when the flow velocity was 0, the juvenile Grass Carp concentrated at the tail of the experiment section and swam freely. As the flow velocity increased, the juvenile Grass Carp gradually adjusted their swimming direction and swam towards the incoming direction. At this point, the flow velocity was determined as the induced velocity.

Induced velocity tests were conducted on juvenile Grass Carp with body lengths ranging from 2 cm to 8 cm. The relationship between induced velocity and the body length of the juvenile Grass Carp is shown in Figure 11.

Figure 9. Grass Carp state in still water.

Figure 10. State of Grass Carp at induced velocity.

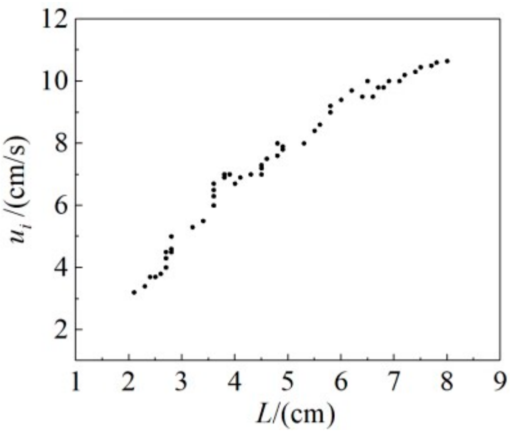

Figure 11. Relationship between induced velocity and body length of juvenile Grass Carp.

From the graph, it can be seen that the induced velocity of juvenile Grass Carp with body lengths ranging from 2 cm to 8 cm increased with an increase in body length, but the rate of the increase in velocity gradually slowed down and eventually stabilized around 0.1 m/s.

3.1.2. Critical Velocity

Critical velocity refers to the maximum velocity that fish can adapt to, and it is an important evaluation index used to measure swimming ability. The critical velocity of juvenile Grass Carp was measured by increasing the flow velocity. In the first step, three preliminary experiments were conducted to estimate the critical velocity of Grass Carp, with one juvenile Grass Carp selected for each preliminary experiment. Before the start of the experiment, the experimental fish were acclimated for 1 h at a flow velocity of 1 BL/s, and then the velocity was increased by 0.4 BL/s every 2 min until the fish became tired, which was defined as when the experimental fish was washed by the current to the steel wire mesh downstream from the experiment section, the fish's whole body was in contact with the steel wire mesh, and the fish could not swim for more than 20 s. The flow velocity at this time was recorded, and the average flow velocity obtained from the preliminary experiments was taken as an estimate of the critical velocity.

During the formal experiment, the experimental fish were placed in the resting area of the experimental flume, and the flow velocity was adjusted to 1 BL/s. The experimental fish adapted to this water flow for 1 h to eliminate the fear produced by the transfer process. When the formal experiment began, the automatic flow control system was adjusted to increase the water's flow velocity by 0.5 BL/s every 5 min until it reached 60% of the estimated critical velocity, and then the water's flow velocity continued to increase. The flow velocity was increased by 15% of the estimated critical velocity every 20 min. At the same time, the swimming behavior of the fish was observed and recorded through video monitoring. When the experimental fish were caught against the wire mesh and could not swim for more than 20 s, the experiment was declared to be over, and the water velocity and swimming time of the experimental fish were recorded. During the experiment, to avoid frightening the experimental fish, no one was allowed to walk around the flume. After the experiment, the experimental fish were fed in other tanks and did not participate in the subsequent experiment.

The formula used for calculating the critical velocity is shown in Formula (3) [25].

$$U_{crit} = U + \Delta U \times t/\Delta t \quad (3)$$

where U_{crit} is the critical velocity (cm/s); U is the maximum flow velocity that induced fatigue in the experimental fish (cm/s); ΔU is the increase in velocity, which was 15% of the estimated critical velocity (cm/s); t is the time taken from the start of the experiment to when the fish became fatigued (min); and Δt is the time interval (20 min).

Critical velocity tests were conducted on juvenile Grass Carp with body lengths ranging from 2 cm to 8 cm. The relationship between the critical velocity and the body length of the juvenile Grass Carp is shown in Figure 12. The percentage of error of the experiment was 5%, and the standard deviation was 1.8%.

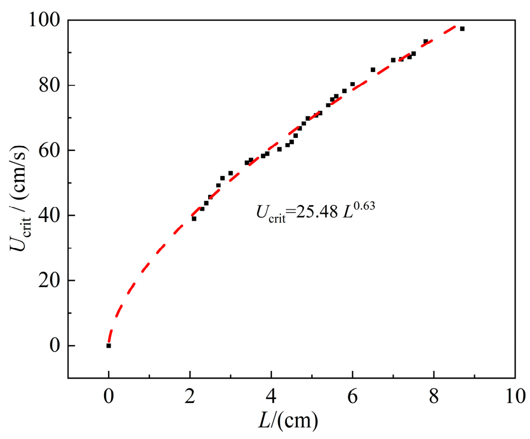

Figure 12. Relationship between critical velocity and body length of juvenile Grass Carp.

It can be seen from the figure that the critical velocity of juvenile Grass Carp increased with an increase in body length, essentially in the form of a power function.

3.1.3. Preferred Velocity

Preferred velocity refers to the most suitable range of velocity among the various velocities that fish can adapt to. Through an investigation of the swimming behavior of juvenile Grass Carp, the preferred velocity of juvenile Grass Carp was analyzed and the curve of suitable velocity for Grass Carp was drawn. Under natural conditions, the swimming behavior of fish is not fixed, and the motion behavior of fish generally changes with changes in the flow velocity. The swimming behavior of juvenile Grass Carp under different flow velocities was explored by analyzing the experimental videos.

When the water velocity was low ($u < 0.1$ m/s), the flow velocity did not reach the induced velocity of the experimental fish, and the experimental fish swam freely in the test section.

When the water velocity was greater than the induced velocity and less than 60% of the critical velocity, the fish could sense the direction of the current, and the current did not impose stress on the fish. The experimental fish basically kept moving against the current.

When the water velocity was greater than 60% of the critical velocity, the number of fish swimming countercurrent backward increased significantly, but this was also accompanied by occasional countercurrent sprinting behavior. With an increase in the flow velocity, the swimming behavior of the experimental fish, including countercurrent retreats and countercurrent sprints, became more frequent. In this stage, the swimming state of the experimental fish was mainly manifested as countercurrent retreats and countercurrent sprints.

When the water velocity continued to increase beyond 80% of the critical velocity, the experimental fish continuously retreated to the front of the block, and the tail fins of the experimental fish touched the downstream block of the test section. They occasionally sprinted forward, but the distance was very small, generally not more than 1× the body length. At this time, the experimental fish began to be exhausted and finally became stuck in the downstream block, no longer moving.

The observations of the moving behavior of Grass Carp reflected the reaction of the Grass Carp to the current. When the current was not fast enough to reach the induced velocity, the fish's movement was free. Therefore, when the velocity in a certain zone of the river was too slow, the migratory fish in this zone were unable to identify the direction of the current, resulting in a failure to migrate upstream. When the current reached the induced velocity but did not exceed 60% of the critical velocity, the fish could easily swim against the current. This range of velocity was the preferred velocity for the fish, at which the fish could efficiently complete upstream migration. When the water velocity exceeded 60% of the critical velocity, the fish would feel stress, the muscles of the fish would tense, the frequency of fin movement would increase, and the fish started to continuously sway to complete their upstream migration. With an increase in the velocity and the time of movement, the juvenile Grass Carp began to show countercurrent retreating behavior, failed to complete upstream migration, and even floated with the current when exhausted. At this time, if the fish was injured, even after the water velocity decreased, it would gradually die after a period of time.

On the basis of the comprehensive experimental data and the movement of juvenile Grass Carp, it was found that the induced velocity of juvenile Grass Carp with a body length of 5 ± 0.5 cm was 0.10 m/s, the critical velocity was 0.70 m/s, and the preferred velocity range was between 0.10 m/s and 0.42 m/s. The suitability curve of flow velocity for juvenile Grass Carp is shown in Figure 13.

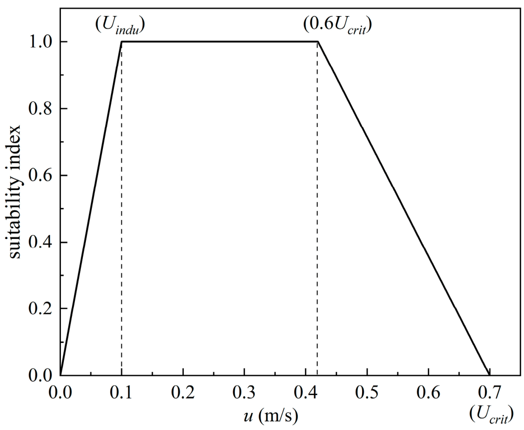

Figure 13. Velocity suitability curve for juvenile Grass Carp.

3.2. Flow Field in the Reaches of Spur Dikes

A river's flow will have an important impact on the behavior of fish. Therefore, a study of the impact of spur dikes on the local flow patterns of the river in this section was the basis for exploring the impact of spur dikes on the upstream migration behavior of fish.

The distribution of the flow patterns near the spur dike was relatively complex. According to previous studies and combined with the observed experimental flow field, the flow field near the spur dike was divided into zones, as shown in Figure 14 [26], and the flow structure of each zone was analyzed.

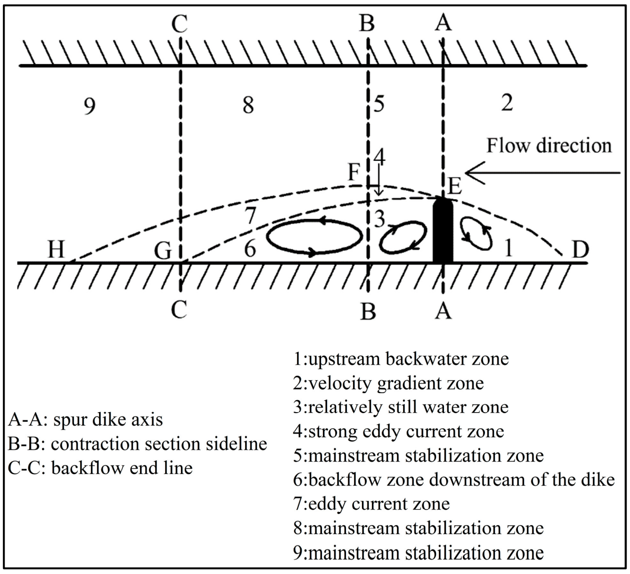

Figure 14. Schematic plan-view diagram of flow regime zone of spur dike. D–H mean Backflow zone and mainstream transition zone.

According to the characteristic distribution of the flow patterns near the spur dike, there were three characteristic lines, namely, the spur dike's axis (A-A), the contraction section's sideline (B-B), and the backflow end's line (C-C). These three characteristic lines divided the flow area near the spur dike into four sections in the longitudinal direction, as shown in Table 1.

Table 1. Flow area in longitudinal direction.

Flow Area	Location
upstream backwater section	upstream of line A-A
downstream contraction section	between A-A and B-B
downstream backflow section	between B-B and C-C
downstream recovery section	downstream of C-C

After backflow occurred and stabilized, there was a curve DEG in which there was positive flow and reverse flow, and these flows were equivalent. In the same discharge section, passing through the curve DEG, the velocity gradually increased to the maximum velocity of the section, and the maximum velocity of the section made up the curve EFH. In this way, the flow area near the spur dike could be horizontally divided into three zones according to the curves DEG and EFH, as shown in Table 2.

The spur dike could be further divided into nine refined flow zones according to the different characteristics of water flow in different regions, as shown in Table 3.

Table 2. Flow area in horizontal direction.

Flow Area	Location
backflow zone	within the arc DEG
mainstream transition zone	between DEG and EFH
mainstream stabilization zone	outside the arc EFH

Table 3. Flow area division.

Flow Zone Number	Flow Zone Name
1	upstream backwater zone
2	velocity gradient zone
3	relatively still water zone
4	strong eddy current zone
5	mainstream stabilization zone
6	backflow zone downstream of the dike
7	eddy current zone
8	mainstream stabilization zone
9	mainstream stabilization zone

With a change in the flow, the spur dike gradually changed from the unsubmerged state in the dry season to the submerged state, and the flow fields of spur dikes in different submerged states were different. In order to study the distribution of the flow field of spur dikes under different flow conditions, the distribution of the flow field on the water surface of the traditional rock-fill spur dike and the spur dike with a permeability of 17.6% under flows of 27.3 L/s, 59.5 L/s, 89.5 L/s, 119.1 L/s, 142 L/s, 156.4 L/s, and 198 L/s was measured. The dike's axis position was set as the origin of the X axis, with the downstream direction being negative and the upstream direction being positive. The root of the spur dike was set as the origin of the Y axis, with the direction towards the opposite bank being positive. The flow field is shown in Figure 15.

For simulating the dry season's flows (Q = 27.3 L/s, Q = 59.5 L/s), the flow discharge was small, the water level was low, the spur dike was not submerged, the velocity in each zone of the spur dike was small, the velocity in the backflow zone was less than 0.1 m/s, and the velocity in the mainstream stabilization zone was 0.2–0.45 m/s. For simulating the normal flow (Q = 89.6 L/s, Q = 119.1 L/s), the spur dike was submerged, the flow velocity in the backflow zone was less than 0.15 m/s, and the velocity in the mainstream transition zone was 0.2–0.45 m/s. The flow velocity in the mainstream stabilization zone was 0.5–0.7 m/s. For simulating the flow in the flood season (Q = 142 L/s, Q = 156.4 L/s, 198 L/s), the flow velocity was relatively high, the flow velocity near the spur dike changed greatly, the flow velocity in the backflow zone was less than 0.25 m/s, the flow velocity in the mainstream transition zone was 0.5–0.7 m/s, and the flow velocity in the mainstream stabilization zone was 0.7–1.0 m/s.

With a change in the flow discharge, the flow pattern of the rock-fill spur dikes and the experimental permeable spur dikes was roughly the same in each zone. According to the zones of the spur dike, the flow velocity in the backflow zone was the lowest, and the area of the backflow zone decreased as the flow increased. The flow velocity in the mainstream stabilization zone downstream from the dike was the largest, and the maximum flow velocity increased as the flow discharge increased. Meanwhile, the area increased as the flow discharge increased. The mainstream transition zone was between the backflow zone and the mainstream stabilization zone, and the area was small, accounting for about one-third of the backflow zone's area, and the area remained basically unchanged. The velocity in the backflow zone upstream from the dike was basically the same as that in the backflow zone downstream from the dike, but the area of the upstream backflow zone was smaller than that of the downstream backflow zone and decreased as the flow discharge increased. The flow upstream from the spur dike was less affected by the dike, and the range of influence of the spur dike was about 2 m.

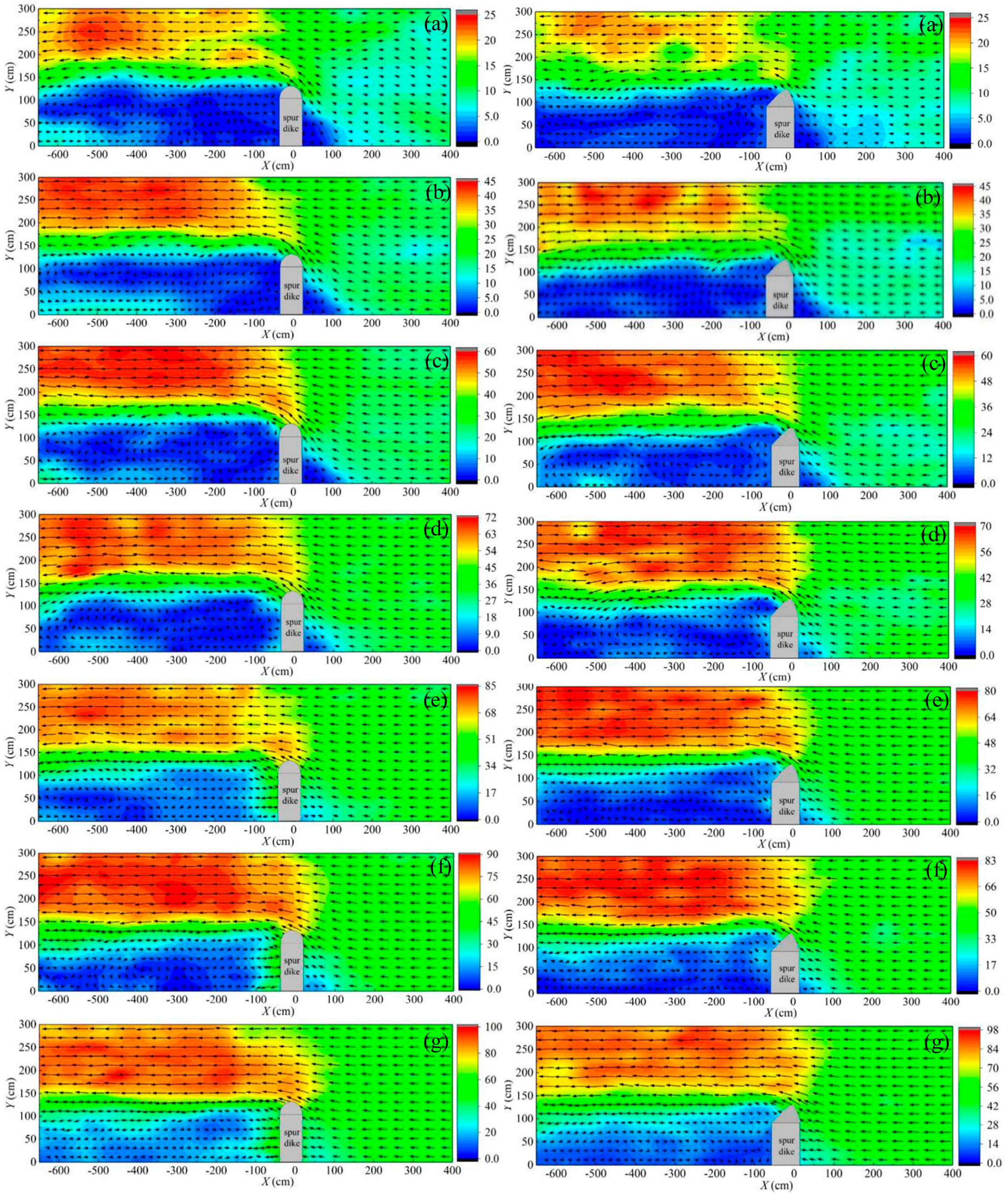

Figure 15. Flow field distribution on the surface of spur dikes under different flows: (**a**) Q = 27.3 L/s; (**b**) Q = 59.5 L/s; (**c**) Q = 89.6 L/s; (**d**) Q = 119.1 L/s; (**e**) Q = 142 L/s; (**f**) Q = 156.4 L/s; (**g**) Q = 198 L/s; the left-hand graphs are for a rock-fill spur dike, and the right-hand graphs are for a permeable spur dike (unit: cm/s).

There were also some differences in the flow patterns between the rock-fill spur dike and the experimental permeable spur dike.

At the same flow discharge, compared with the permeable spur dike, the water resistance coefficient of the rock-fill spur dike was relatively high, resulting in a larger unit flow in the mainstream stabilization zone. Therefore, the flow velocity in the mainstream stabilization zone of the rock-fill spur dike was greater than that of the permeable spur dike.

There was little difference in the velocity and area of the backflow zone between the rock-fill spur dike and the permeable spur dikes in the dry season. However, in the flood season, when the flow discharge exceeded 142 L/s, the backflow zone upstream from the rock-fill spur dike and the relatively still water zone downstream from the dike basically disappeared, and there was a zone of high-velocity flow downstream from the dike, with the flow velocity increasing with the increase in flow discharge. When the flow reached 198 L/s, due to the high water level in the flood season, the overtopping flow formed a waterfall, greatly increasing the velocity downstream from the dike, leading to the disappearance of the backflow zone.

As the water resistance coefficient of a permeable spur dike is relatively small compared with that of rock-fill spur dikes, the water upstream from the dike flows downstream through the permeable holes, reducing the overtopping flow discharge; moreover, the WES-like profile slows down the overtopping current. Therefore, in the flood season, the area of the backflow zone of the permeable spur dike was larger than that of the rock-fill spur dike, and the flow velocity in the backflow zone was smaller than that of the rock-fill spur dike, with no zone of high-velocity flow in the backflow zone of the permeable spur dike.

3.3. Upstream Migration of Grass Carp in Sections of the Spur Dike

Migration has a significant impact on some fish species, and this behavior is very sensitive to variations in flow. The establishment of spur dikes will partially block the river channel, affecting the local distribution of flow velocity in the river channel, which will affect the upstream migration route of the fish and the success rate of upstream migration. Therefore, it is important to quantify the relationship between the diversity of flow velocity in a channel under the influence of spur dikes and the success rate of upstream migration by fish.

3.3.1. The Diversity of Flow Velocity

In landscape ecology, a landscape's heterogeneity refers to the spatial variability of the resources that play a decisive role in the existence of a species in the landscape. Spatial heterogeneity is the main focus of research into a landscape's heterogeneity. The number and size of different types of patches are often used to measure the intensity of spatial heterogeneity [27]. The method of analyzing spatial heterogeneity was used to analyze the diversity of the river's flow under the influence of a spur dike, and the flow velocity factor was divided into different patches to measure the diversity in the flow velocity in local river sections.

The flow velocity factor was divided into patches according to the suitability of the flow velocity for fish. The species of fish in this study was Grass Carp, and the length of the experimental fish was 5 cm. According to the results in Section 3.1, the induced velocity of the juvenile Grass Carp was 0.1 m/s and the critical velocity was 0.7 m/s. We divided the flow velocities between 0 and the critical velocity (0.7 m/s) into 0.1 m/s intervals.

Shannon [28] introduced the concept of entropy into information theory to represent the average amount of information sent by a signal source. Information entropy is a measure of the uncertainty of discrete random variables. The formula for its calculation is as follows:

$$\mathrm{H(X)} = \mathrm{E(I(x_i))} = \sum_{i=1}^{n} \mathrm{p(x_i)} \log \frac{1}{\mathrm{p(x_i)}} = -\sum_{i=1}^{n} \mathrm{p(x_i)} \log(\mathrm{x_i}) \tag{4}$$

where p (x_i) is the probability of event xi occurring in the probability system and $I(x_i)$ is the amount of information contained in the event, $I(x_i) = \log\left(1/\mathrm{p}\left((x_i)\right)\right)$. In actual calculations, the natural logarithm with the constant e as the base was used in Equation (3). The more uncertain and complex a random event is, the greater the information entropy will be.

Information entropy is also called the Shannon diversity index. Because the Shannon diversity index can represent a system's complexity and diversity, it is widely used in ecology, landscape ecology, and other fields to reflect biodiversity and a landscape's heterogeneity.

In this study, the Shannon diversity index was selected to measure the degree of differentiation of flow velocity patches in the reaches of a spur dike. Based on the results of calculating this index, the river's flow velocity diversity index H_v was obtained.

$$H_v = -\sum_{i=1}^{n} P_{vi} \ln(P_{vi}) \quad (5)$$

where H_v is the diversity index of flow velocity; i is 1, 2, 3, 4, 5, 6, 7, or 8; n is the number of patch types of the flow velocity factor; and P_{vi} is the ratio of the area of the ith flow velocity patch to the total area of the calculation zone. The larger the diversity index H_v of the river's flow velocity, the more diverse the flow in the spur dike's reach will be.

On the basis of the experimental results of the hydraulic characteristics of spur dikes in Section 3.2, the percentages of each velocity patch area in the total area of the traditional rock-fill spur dike and the experimental permeable spur dike under different discharge rates were calculated, and the law of the variation in the flow velocity diversity index H_v with flow discharge was analyzed. The percentage of each patch area at different flow discharge rates (Q) is shown in Figure 16.

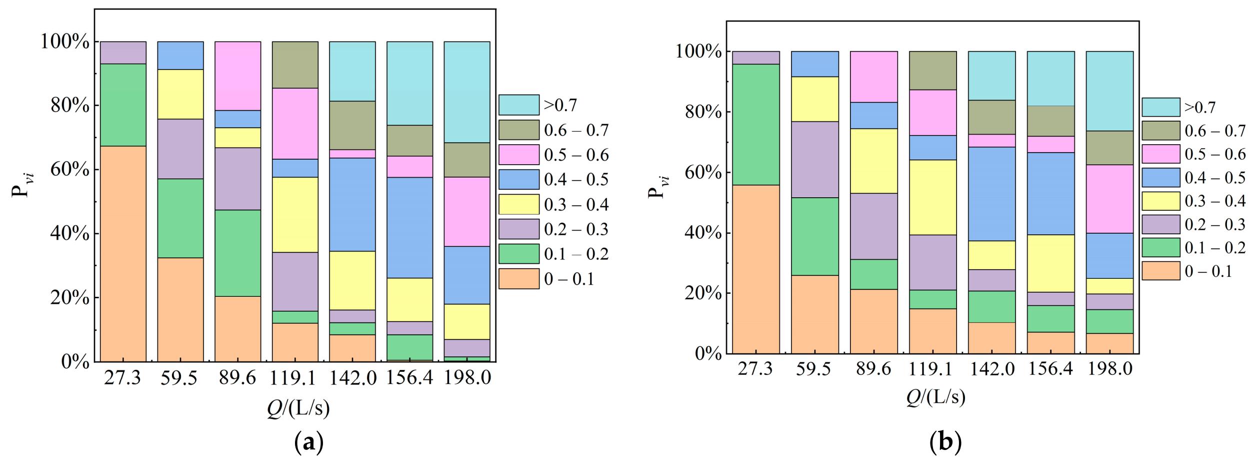

Figure 16. Proportional diagram of flow velocity at all levels under (**a**) rock-fill spur dike and (**b**) experimental permeable spur dike ("P" represents the ratio of the area of flow velocity patch to the total area of calculation zone; "Q" represents the flow discharge different flow discharges).

The velocity diversity index (H_v) under different flow discharges rates ($Q_{L/s}$) was calculated according to the proportion of the area with different velocities at different levels of flow, as shown in Table 4.

Table 4. Velocity diversity index under different flow discharge rates.

Q (L/s)	Experimental Permeable Spur Dike	Rock-Fill Spur Dike
27.3	0.828	0.801
59.5	1.537	1.526
89.6	1.734	1.657
119.1	1.862	1.808
142.0	1.917	1.823
156.4	1.907	1.753
198.0	1.885	1.718

The influence of flow discharge on the velocity diversity index is shown in Figure 17.

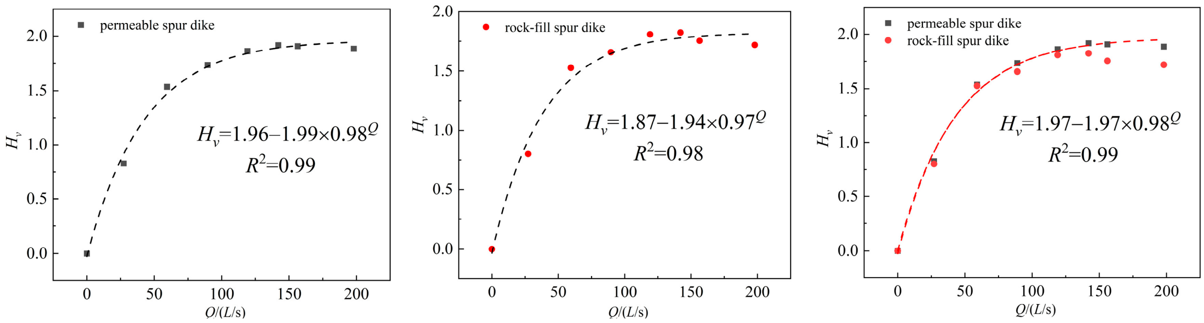

Figure 17. Relationship between flow velocity diversity index (H_v) and flow discharge ($Q_{L/s}$).

It can be seen from Table 4 and Figure 17 that in the dry season (Q < 59.5 L/s), due to the low overall velocity of the river, the flow velocity diversity index was basically the same for the permeable spur dike and the rock-fill spur dike. With an increase in the river's flow discharge, the flow velocity diversity index in the reach of the permeable spur dike was greater than that in the reach of the rock-fill spur dike. This is because of the existence of permeable holes in the permeable spur dike's body. The current upstream from the dike flows into the area downstream from the dike through a section of pipes and interacts with the overflow current and the backflow current, forming a variety of currents with different flow patterns and velocities.

Overall, the velocity diversity index increased with an increase in the river's flow discharge, basically showing an exponential function relationship. However, in the flood season (Q > 142 L/s), the greater the flow discharge, the lower the flow velocity diversity index. This is because during the flood season, the river's water level and the flow velocity are high, so the effect of spur dikes on the river's flow is reduced, and the river is basically in a high-velocity state.

3.3.2. The Effect of the Flow Velocity Diversity Index on the Success Rate of Upstream Migration by Grass Carp

The upstream migration behavior of fish is very sensitive to changes in flow velocity, and the distribution of flow velocity will affect the fish's selection of the upstream migration path. The fish will choose paths that minimize energy consumption during the process of upstream migration. The construction of spur dikes alters the original flow state of river channels and creates regions with a variety of flow velocities, which will have a direct impact on the upstream migration path of the fish, thereby affecting the success rate of upstream migration.

In this experiment, the upstream migration path of juvenile Grass Carp with a body length of 5 cm was studied. Due to experimental limitations, it was not possible to accurately identify the experimental fish using video processing software. Therefore, the video was separated into pictures frame by frame, the plane of the experimental tank was grided, and the fish were manually identified from the extracted images. Taking the head of the experimental fish as the reference point, and extracting the grid data of the moving position of the fish in each frame, the track of the movements of the experimental fish was drawn using data processing software.

Under a fixed flow discharge, the velocity in each flow zone of the spur dike varied, and the movement of the experimental fish changed with the flow zone, resulting in many types of upstream migration paths. On the basis of an overall analysis of the experimental results, the upstream migration of Grass Carp could be divided into three types: upstream, stranding, and returning.

1. Upstream Migration

During the dry season (Q = 27.3 L/s, Q = 59.5 L/s), the experimental fish could swim easily without water stress in the mainstream zone and the mainstream transition zone. During the normal flow season (Q = 89.6 L/s, Q = 119.1 L/s), most of the experimental fish displayed upstream migration behavior in the backflow zone and the mainstream transition zone downstream from the dike. Due to the turbulence, backflow, and vortexes in the backflow zone downstream from the dike, the experimental fish in the backflow zone easily lost direction. After constant trying and wandering, some experimental fish would sprint across the dike's head and then move upstream. When the spur dike was permeable, due to the existence of the permeable hole, when the experimental fish moved near the permeable hole downstream from the dike, they could sense the direction of the incoming flow, pass through the permeable hole, reach the area upstream from the dike, and then continue to complete the process of upstream migration. The routes of upstream migration are shown in Figure 18.

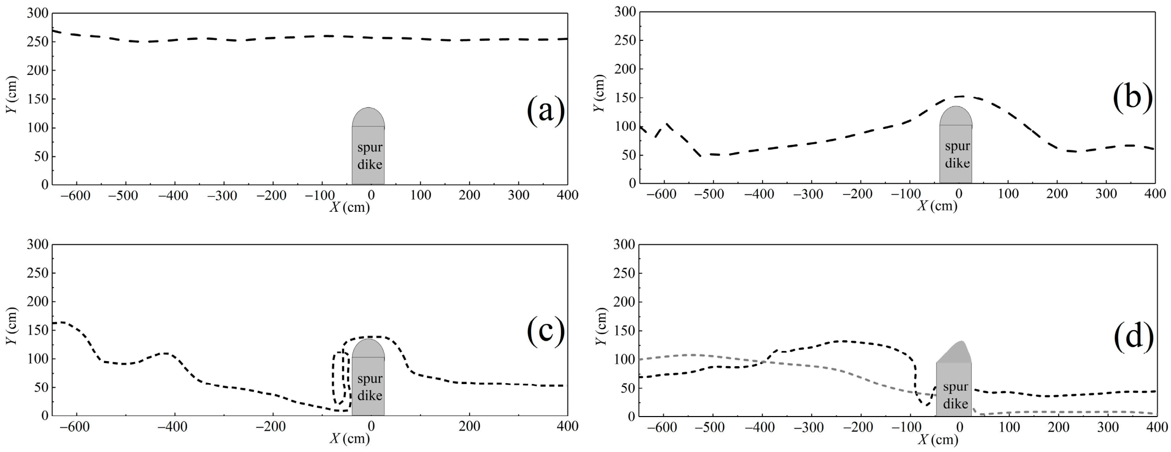

Figure 18. Example upstream movement paths of juvenile Grass Carp in the experimental flume: (**a**) upstream in mainstream zone when Q = 27.3 L/s; (**b**) upstream in mainstream transition zone when Q = 59.5 L/s; (**c**) upstream in backflow zone when Q = 89.6 L/s or Q = 119.1 L/s; (**d**) upstream pass through the permeable hole.

2. Stranding

During the dry season (Q = 27.3 L/s), the flow velocity in the backflow zone was less than 0.1 m/s, which did not reach the induced velocity of the experimental fish. Some experimental fish in the backflow zone were unable to correctly find the upstream direction, and the experimental fish hovered in a large area of the water. In the flood season (Q > 142 L/s), the flow velocity downstream from the dike was large, and the experimental fish were unable to migrate upstream due to water stress and finally wandered and stayed within a small range. During the flood season (Q > 142 L/s), almost all of the experimental fish migrated upstream along the sidewall of the flume on one side of the spur dike to the zone of slow flow downstream from the spur dike, where the velocity was low, and they would become stranded there. When the spur dike was permeable, during the normal water season (Q = 119.1 L/s), some experimental fish would pass through the permeable holes and rest in the backwater zone upstream from the dike, ultimately becoming stranded upstream from the dike. The migration routes of stranding are shown in Figure 19.

3. Returning

During the dry season (Q = 27.3 L/s), the experimental fish in the backflow zone downstream from the spur dike were unable to accurately sense the direction of the incoming flow and swam freely downstream. When the experimental fish in the backflow zone downstream from the dike attempted to migrate upstream through the dike's head during the normal water season (Q = 119.1 L/s), some of the weaker experimental fish retreated backward due to the high velocity and intensity of turbulence in the mainstream zone of the dike's head. The migration routes of returning are shown in Figure 20.

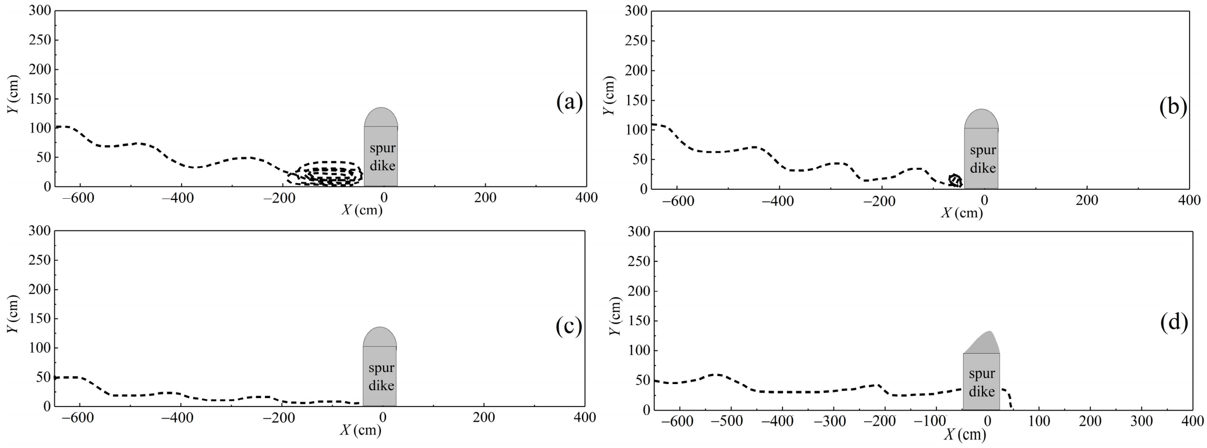

Figure 19. Example movement paths of stranded juvenile Grass Carp in the experimental flume: (**a**) hover stranded in backflow zone when Q = 27.3 L/s; (**b**) hover stranded in backflow zone when Q > 142 L/s; (**c**) direct stranded in backflow zone when Q > 142 L/s; (**d**) stranded after passing through the dike hole.

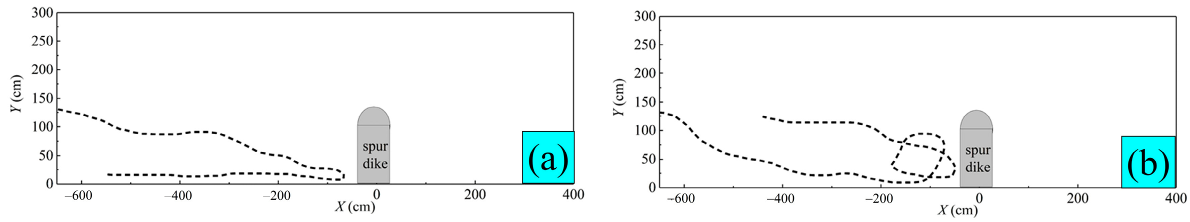

Figure 20. Example movement paths of returning juvenile Grass Carp in the experimental flume: (**a**) return in backflow zone when Q = 27.3 L/s; (**b**) return in mainstream zone when Q = 119.1 L/s.

By analyzing the upstream migration paths of Grass Carp, the upstream type of migration can be considered to be successful, while stranding and returning can be considered to be unsuccessful. The impact of the diversity of flow velocity on Grass Carp's upstream migration was verified by calculating the success rate. The success rate of upstream migration indicates the ratio of the number of fish that successfully migrated upstream to the total number of fish under different flow discharge rates after the spur dike was established, and it is calculated as follows:

$$\mathrm{ARR}(\%) = \frac{\sum_{i=1}^{n} \mathrm{N_i}}{\mathrm{n\,N}} \tag{6}$$

where *ARR* is the success rate of upstream migration, $\mathrm{N_i}$ is the number of fish that succeeded in the *i*th experiment, N is the total number of fish released in each experiment, and n is the number of experiments.

The results of the success rate of upstream migration of Grass Carp under different flow discharges are shown in Table 5.

Table 5. Upstream migration success rate of Grass Carp under different flow discharges.

Q (L/s)	Velocity Diversity Index	Experimental Permeable Spur Dike Upstream-Migration Success Rate *ARR* (%)	Rock-Fill Spur Dike Upstream-Migration Success Rate *ARR* (%)
27.3	0.828	76	72
59.5	1.537	88	76
89.6	1.734	96	92
119.1	1.862	92	80
142.0	1.917	20	16
156.4	1.907	4	0
198.0	1.885	0	0

The relationship between the flow velocity diversity index of the river and the success rate of upstream migration is shown in Figure 21.

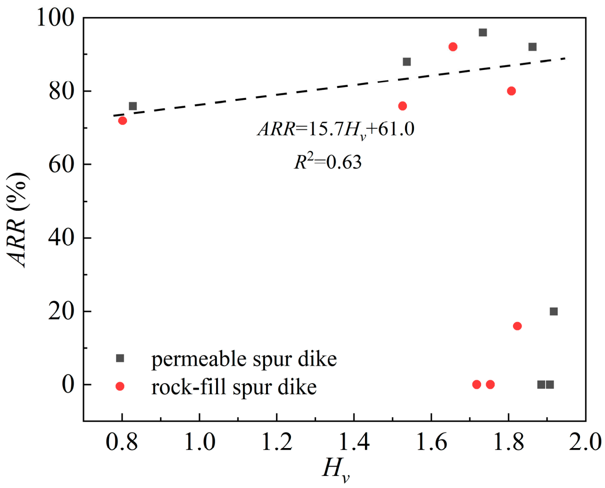

Figure 21. Relationship between velocity diversity index and upstream migration success rate of fish.

It can be seen from the figure that the success rate of the upstream migration of fish initially shows a linear growth trend with an increase in the velocity diversity index, but there is a turning point when it exceeds the critical point, and the success rate of upstream migration decreases sharply with an increase in the velocity diversity index, as shown in the lower right-hand corner of Figure 21. This turning point is when the river velocity reaches 60% of the critical velocity of the fish. When the flow velocity of the river exceeds 60% of the critical velocity of Grass Carp, the current will hinder the upstream migration behavior of the fish, and the greater the flow velocity, the greater the obstruction. During the flood season, the flow velocity exceeds the critical velocity of Grass Carp, which makes it difficult for Grass Carp to swim against the current, and long-term exposure to such conditions will cause damage to the fish's bodies. Therefore, few experimental fish could successfully migrate upstream in the flood season, so the success rate of upstream migration in Grass Carp is close to zero at this time.

4. Discussion

In this study, the distribution of velocity in the reach of spur dikes under different flow discharge rates was obtained, and the velocity diversity index H_v was used to characterize the diversity of the flow. The experimental results and previous studies [8,11] showed that the diversity of flow increases with an increase in the river's flow discharge rate under medium and low flow discharge rates (the normal flow season and dry season), and the diversity of the flow in the reaches of permeable spur dikes is greater than that in the reaches of rock-fill spur dikes. Compared with previous studies, this study found that at the high flow discharge rate (flood season), due to the high water level, the barrier effect of the spur dike on the river's channel was reduced, the river channel has a high velocity, and the diversity of the flow is reduced compared with the medium flow discharge rate.

In the dry season and normal flow season, fish choose the zone with their preferred velocity for upstream migration and an upstream migration path with the shortest distance. In these seasons, the success rate of upstream migration increases linearly with an increase in the diversity of velocity. In the flood season, fish will take refuge in the preferred velocity zone, and the success rate of upstream migration decreases sharply. Both the experimental results and the results of DeLonay [23] suggested that the number of low-cost upstream migration paths can be increased by controlling the discharge from reservoirs to improve the success rate of reproduction in fish. However, DeLonay [23] mainly calculated the energy consumption cost function of upstream migration for fish, without considering the influence of spur dikes and did not quantify the relationship between the success rate of upstream migration and the diversity of the flow. The results of this study and Northcote's [29] research agree that permeable spur dikes with migration channels for fish will improve the success rate of upstream migration.

The most prestigious among the four major species of freshwater fish is the Grass Carp. Each year from April to July, the Grass Carp migrates to its spawning grounds to lay eggs. When the young Grass Carp develop to a body length of 5.00 to 15.00 cm, they need to migrate into lakes. Therefore, upstream migration plays an important role in the survival and reproduction of Grass Carp. This study did not consider the impact of the diversity of flow velocity on the growth and mortality of Grass Carp. A flow velocity that is too low will affect the spawning and direction of migration of Grass Carp, and a flow velocity that is too high will cause harm to or even kill Grass Carp. Therefore, the diversity of flow will affect the growth and mortality of Grass Carp, and these factors will also indirectly affect the migration behavior of fish in the natural environment.

Due to the restrictions of the model scale effect, the ratio between the permeable holes of the model spur dike and the body size of the fish was too small compared with that of the prototype, which will affect the probability of fish migrating upstream through the permeable hole. Moreover, this study only focused on juveniles of a single species (Grass Carp) and did not include research on other age groups of Grass Carp or other fish species. However, this study provides ideas and methods for research analyzing the influence of constructing spur dikes on the upstream migration behavior of fish. Subsequent studies could be conducted on other fish species to further analyze and obtain widely applicable theoretical results. If the conditions permit, telemetric tracking technology could be applied in the prototype dike's reach to observe the upstream migration path of fish.

5. Conclusions

The effects of the diversity of a river's flow velocity on the success rate of the upstream migration of Grass Carp under the influence of rock-fill spur dikes and experimental permeable spur dikes were studied through a hydrodynamic experiment and an experiment on the upstream migration of juvenile Grass Carp, and the following conclusions were obtained:

1. The body length of juvenile Grass Carp ranges from 2 cm to 8 cm, and the critical velocity increases with increasing body length but gradually slows down and eventually stabilizes at around 0.1 m/s. The critical velocity of juvenile Grass Carp increases with the increase in body length, basically following a power function relationship.
2. The velocity diversity index increases with an increase in flow discharge, basically showing an exponential function relationship. The flow velocity diversity index of the permeable spur dike's reach was larger than that of the rock-fill spur dike's reach.
3. When the flow velocity is within the range of Grass Carp's preferred velocity, the success rate of upstream migration increases linearly with an increase in the flow velocity diversity index. When the flow velocity exceeds the range of Grass Carp's preferred velocity, the success rate of upstream migration drops sharply.
4. Compared with the traditional rock-fill spur dikes, the experimental permeable spur dikes provide upstream migration channels and shelters for fish, allowing them to move upstream from the backflow zone to the mainstream zone, shortening the total length of the upstream migration path, avoiding the high-velocity zone, and saving physical energy. Therefore, given the ability of spur dikes to shape the diversity of the flow patterns of local rivers and reduce the impact on fish during upstream migration, the experimental permeable spur dikes are superior to the traditional rock-fill spur dikes.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Chongqing Jiaotong University Animal Care and Use Committee with approval number CQJU-2021-106. The number of collected animals in our study was kept as low as possible, and the manipulation was painless and fast.

Data Availability Statement: The data in figures and tables used to support the findings of this study are included herein.

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Conflicts of Interest: The authors declare no conflict of interest.

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