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Taxonomic Diversity of Fish Species in the Lower Reaches of the Yellow River

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Simple Summary: Due to the lack of water resources in the lower reaches of the Yellow River, the abundance of fish resources could be higher, and background research on fishes is rare. The current status of downstream fishery resources can be clarified by investigating fish resources in the lower Yellow River in the past four years. A total of 54 fish species were found in the downstream waters during the survey, with the recovery of populations and abundance of major economic fish, common small-sized fish, and endangered fish. By comparing and analyzing the current status of fish resources in various downstream survey sections, it was found that the confluence of Dongping Lake into the Yellow River has the highest number of fish species, which means that this water area is the most essential habitat for fish in the lower Yellow River. To protect downstream fishery resources, key protection measures should be taken for this habitat in the future.

Abstract: In order to study the community of fishery resources, five sampling sections were set up in the lower Yellow River from 2019 to 2022 to investigate the diversity of fishery resources. A total of 54 fish species were identified in the survey, belonging to 9 orders, 19 families, and 48 genera. The number of species reached its highest level since the Integrated Water Regulation of the Lower Yellow River in 1999. The original rare and endangered fish species in the lower reaches of the Yellow River, such as *Coilia nasus*, *Rhinogobio nasutus*, and *Pseudobagrus ussuriensis*, have reappeared in the lower reaches. The population and abundance of main economic fish and common small-sized fish in the lower reaches of the Yellow River have increased. These signs all indicate that, and the fishery resources are recovering slowly in the lower Yellow River. By comparing the fish resources of various investigation sections, it was found that there are differences in fish diversity: the closer to the estuarine waters, the higher the variety of fish in the Yellow River at the upper level of the taxonomic category. However, that section of the lower Yellow River where species evenness, species diversity, and community structure of fishery resources were most stable was the confluence of Dongping Lake into the Yellow River, which has the most significant number of fish species, the smallest Λ^+ value, and the most extensive G-F index. The above results indicate that Dongping Lake, as the only lake connected to the lower reaches of the Yellow River, plays an essential role in replenishing fish resources in the lower reaches of the Yellow River.

Keywords: fishery resources; fish diversity; G-F index

Key Contribution: This paper mainly tells us about the fishery resources are recovering slowly in the lower Yellow River, and the fish resources in Dongping Lake make a significant contribution to the replenishment of fish resources in the Yellow River.

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1. Introduction

The Yellow River is famous for its high sand content, and the sediment in the lower reaches is deposited into a suspended river [1]. The riverbed erosion and deposition change drastically, with pronounced flood seasons and ice floods. The Yellow River is poor in aquatic life, and its fish resources are far less abundant than those of the Yangtze River and Pearl River systems [2]. Since 1972, due to climate change, zero-flow periods have occurred frequently [3]. The spawning grounds, feeding grounds, overwintering grounds, and migration channels of fish have been destroyed by zero-flow, and these have led to the disappearance of some indigenous fishes and migratory fishes, such as *Coreius septentrionalis* and *Coilia ectenes* [2], and also caused a rapid depletion of resources [4]. The Yellow River Water Conservancy Commission began regulating and managing the water volume of the Yellow River in 1999. Since then, the lower reaches have survived the ecological crisis of fishery resources, which is caused by the interruption of the flow [5].

The investigation by the Institute of Zoology of the Chinese Academy of Sciences investigated the fishery resources of the mainstream of the Yellow River and its affiliated waters for the first time since the 1950s [6]. By the 1980s, the former State Administration of Fisheries conducted the second investigation of fishery resources in the whole basin [2]. In the last 30 years, fish investigations and research have only been carried out in sporadic reaches of the Yellow River. The examination of fishery resources in the lower reaches of the Yellow River includes the fish investigation carried out by Ru Huijun on the mainstream of the Yellow River in 2008 [7], Liu Hongbo in 2013 [8], Jie Zilin in 2015 [9], and Yang Hui in 2017–2018 [10] on fish species, spawning grounds, feeding grounds, and migration channels in the lower reaches of the Yellow River.

In order to further study the recovery of fish populations in the lower reaches of the Yellow River since the implementation of the ecological operation, we tracked and investigated the situation of fish communities in the lower reaches of the Yellow River for four consecutive years. We constructed a list of fish species in the lower reaches of the Yellow River and calculated indicators, such as taxonomic diversity.

2. Materials and Methods

2.1. Time and Method of Investigation

According to "The Survey and Evaluation of Fishery Resources" [11], five investigation sections were set in the lower reaches of the Yellow River. From the starting point of the lower reaches of the Yellow River to the estuary, there is the wandering reach in Zhongmu, Henan Province ("wandering reach" for short), the reach in the national aquatic germplasm resources conservation area at the junction of Shandong Province and Henan Province of the Yellow River ("protected reach" for short), the confluence of Dongping Lake into the Yellow River("Dongping Lake reach" for short), the curved reach in Jinan City and Zibo City ("curved reach" for short), and the estuary reach of the Yellow River ("estuary reach" for short) (see Figure 1). The fishery resources of the 5 downstream sections were investigated continuously in the summers and autumns of 2019, 2020, 2021, and 2022. The survey adopted the combination of drift gill nets and cage nets for fishing. The specification of the drift gill net was 50 m (length) × 2 m (height), and the mesh size was 4 cm. The specification of the cage net was 20 m × 40 cm × 40 cm. Referring to the morphological identification methods in the two books *FAUNA SINICA* [12] and *FISHES OF THE YELLOW RIVER* [13], we identified and recorded the species of captured fish. For the classification categories of each fish species, we referred to Joseph S. Nelson's book on the classification of bony fish [14].

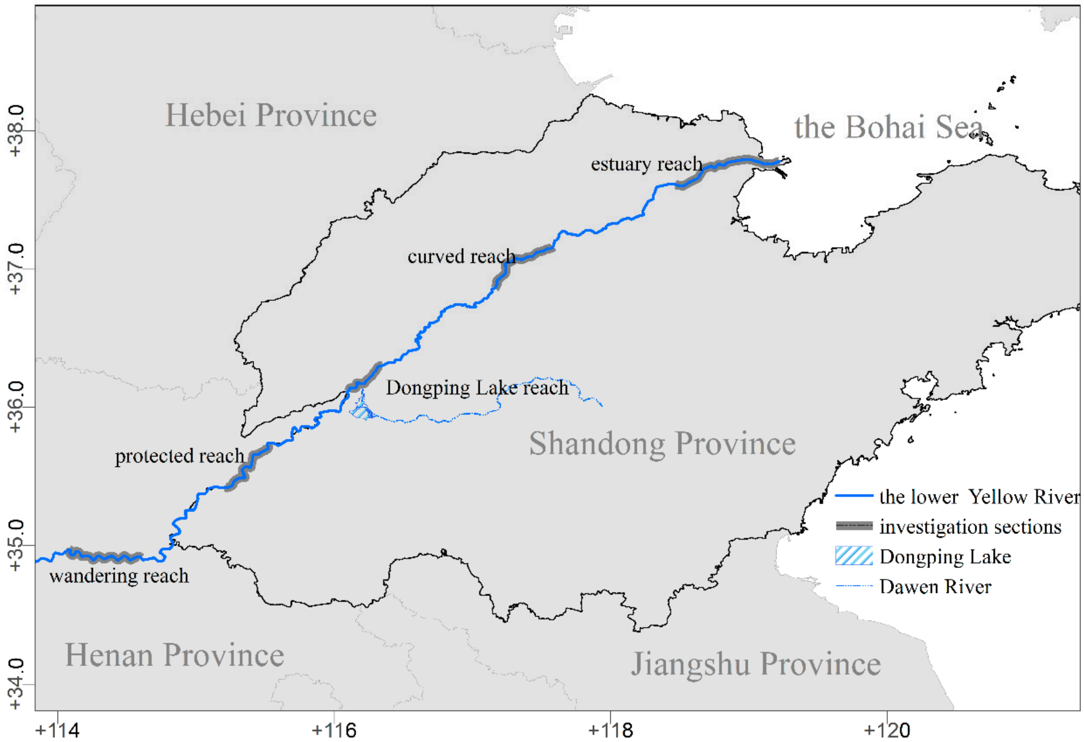

Figure 1. Survey section of the lower reaches of the Yellow River.

2.2. Calculation Method of Correlation Index

2.2.1. Inclusion Index at Taxonomic Level, $TINCL_i$

The diversity of fish composition in taxonomic categories (order, family, genus, and species) was identified [15,16]. As the $TINCL_i$ value increases, the average number of lower taxa contained in the upper taxa will also increase, and the distribution of species in these taxa will be more concentrated, the phylogenetic relationship will become closer, and the taxonomic diversity will be lower. The expression of the index is:

$$TINCL_i = \frac{1}{N_i} \sum_{j=1}^{N_i} C_{kj}\ (k < i)$$

where N_i is the number of the i-level taxonomic category and C_{kj} is the number of the jth k-level taxonomic category.

2.2.2. Taxonomic Distinctness Index

A taxonomic diversity index can be expressed as the average taxonomic distinctness index (Δ^+) and variation in the taxonomic distinctness index (Λ^+). The higher the value of Δ^+, the more distant the phylogenetic relationship between communities. The lower the value of Λ^+, the higher the uniformity of species composition among communities. According to the research method proposed by Warwick et al. [17,18], the taxonomic diversity of common fishes in the lower reaches of the Yellow River was analyzed by using the indexes of Δ^+ and Λ^+, and the calculation formula was as follows:

$$\Delta^+ = \sum\sum_{i<j} \omega_{ij} / [S(S-1)/2]$$

$$\Lambda^+ = \sum\sum_{i<j} (\omega_{ij} - \Delta^+)^2 / [S(S-1)/2]$$

where: ω_{ij} is the path length of the ith and jth species in the classification tree and S is the number of species appearing in the community. Because all fishes belong to Chordata, only five taxonomic levels, namely class, order, family, genus, and species, were used in this study. According to Nelson's system, the weighted path length of an individual in the phylogenetic classification tree was determined: ω_1 = 16.667 among species, ω_2 = 33.333 among genera, ω_3 = 50.000 among families, ω_4 = 66.667 among orders, and ω_5 = 83.333 among classes. TAXDTEST calculated the above taxonomic diversity indexes in PRIMER 5.2 software package.

2.2.3. Genus-Family Diversity Index (G–F Index)

The G-F index was first used by Jiang Zhigang to study the community structure of birds and animals [19], and in recent years, it has been gradually used to study the taxonomic diversity of fish at the level of different families and genera [20,21]. The G-F index is calculated by calculating the intergeneric diversity index D_G and interfamily diversity index D_F, and then the G-F index is obtained through a corresponding calculation. The calculation formula is as follows:

$$D_{Fk} = -\sum_{i=1}^{n} P_i \ln P_i$$

$$D_F = \sum_{i=1}^{m} D_{Fk}$$

$$D_G = -\sum_{j=1}^{p} q_j \ln q_j$$

$$D_{G\text{-}F} = 1 - D_G / D_F$$

where D_F is the F index. $P_i = S_{ki}/S_k$, S_k is the number of species in k families in the fish list, and S_{ki} is the number of species in k families and i genera in the fish list. n is the number of genera in k families, and m is the number of families in the fish list. D_G is the G index, and $q_j = S_j/S$, where S_j is the number of species in genus j in the fish list and S is the number of species in the fish list. p is the number of genera in the list, and $D_{G\text{-}F}$ is the G-F index.

3. Results

3.1. Species Composition

As shown in Table 1, from 2019 to 2022, a total of 54 species of fish were identified in the investigation of the lower Yellow River. Those fishes belonged to 9 orders, 20 families, and 48 genera. At the level of order, Cypriniformes have the most significant number of fish species, with 33 species belonging to 29 genera and 3 families, accounting for 61.11% of the total fish species. This is followed by the orders of Perciformes and Siluriformes, with 7 species belonging to 6 families and 6 genera and 6 species belonging to 4 families and 5 genera, respectively, accounting for 12.96% and 11.11% of the listed fish species. At the family level, the family of Cyprinidae have the most significant number of species (25 genera and 29 species), followed by 4 species belonging to Cobitidae and 3 species belonging to Bagridae. The number of species belonging to the remaining families is 1–2.

Among them, 23 species of fish belonging to 23 genera, 7 families, and 4 orders were identified in the wandering reach. In the protected reach, 34 species belonging to 30 genera, 10 families, and 6 orders were found. In the Dongping Lake reach, 39 species belonging to 33 genera, 9 families, and 6 orders were observed. In the curved reach, 32 species belonging to 29 genera, 11 families, and 6 orders were recorded. Lastly, 23 species belonging to 22 genera, 9 families, and 6 orders were discovered in the estuary reach.

Table 1. Composition of fish species in the lower reaches of the Yellow River.

Order	**Family**	**Fish Species**	**Wandering Reach**	**Protected Reach**	**Dongping Lake Reach**	**Curved Reach**	**Estuary Reach**
Salmoniformes	Salangidae	*Protosalanx hyalocranius*	+				
		Hemisalanx prognathus		+			+
Anguilliformes	Anguillidae	*Anguilla japonica*			+		
Clupeiformes	Engraulidae	*Coilia nasus*			+	+	+
Cypriniformes	Cyprinidae	*Abbottina rivularis*		+	+		
		Parabramis pekinensis	+	+	+	+	+
		Culter alburnus	+	+	+	+	+
		Hemiculter bleekeri		+	+	+	
		Hemiculter leucisculus	+	+	+	+	+
		Ctenopharyngodon idellus	+		+	+	+
		Squaliobarbus curriculus	+	+	+	+	+
		Megalobrama terminalis		+	+		
		Xenocypris argentea	+	+	+	+	+
		Gnathopogon taeniellus				+	
		Hemibarbus labeo		+			
		Hemibarbus maculatus	+	+	+	+	
		Carassius auratus	+	+	+	+	+
		Gobio rivuloides			+		
		Cyprinus carpio	+	+	+	+	+
		Hypophthalmichthys molitrix	+	+	+	+	+
		Opsariichthys bidens	+				
		Pseudorasbora parva	+	+	+	+	
		Rhodeus ocellatus		+	+		
		Rhodeus sinensis	+	+	+	+	
		Pseudolaubuca engraulis			+	+	+
		Saurogobio dabryi	+	+	+	+	
		Saurogobio dumerili		+			
		Rhinogobio nasutus		+	+		
		Squalidus argentatus		+			
		Aristichthys nobilis	+		+		+
		Acheilognathus macropterus	+		+	+	
		Acheilognathus chankaensis				+	
		Cultrichthys erythropterus	+	+	+	+	+
	Cobitidae	*Paramisgurnus dabryanus*		+	+	+	
		Misgurnus anguillicaudatus	+	+	+	+	
	Botiidae	*Leptobotia orientalis*		+			
		Parabotia fasciata			+		
Siluriformes	Bagridae	*Pelteobagrus nitidus*		+	+	+	+
		Pelteobagrus fulvidraco	+	+	+	+	+
		Pseudobagrus ussuriensis		+	+		+
	Siluridae	*Silurus asotus Linnaeus*	+	+	+	+	+
	Clariidae	*Clarias gariepinus*		+			
	Ictaluridae	*Ictalurus punctatus*			+		
Beloniformes	Hemiramphidae	*Hyporamphus intermedius*			+	+	
Mugiloidei	Mugilidae	*Liza haematocheila*		+	+	+	+
		Mugil cephalus				+	+
Synbranchiformes	Synbranchidae	*Monopterus albus*		+			
	Mastacembelidae	*Mastacembelus aculeatus*				+	
Perciformes	Sinipercidae	*Siniperca chuatsi*			+		
	Gobiidae	*Rhinogobius cliffordpopei*			+		
		Rhinogobius giurinus	+	+	+	+	
	Osphronemidae	*Macropodus chinensis*					+
	Channidae	*Channa argus*	+	+	+	+	+
	Polyprionidae	*Lateolabrax maculatus*				+	+

Note: '+' indicates that the species appears in the surveyed water area.

3.2. TINCLi

The inclusion index at the taxonomic level was used to analyze the composition diversity of common fishes in the lower reaches of the Yellow River to explore the concentration degree and genetic relationship of fish species at each rank. It can be seen from Table 2 that the average values of families, genera, and species of common fishes in the lower reaches of the Yellow River are 2.22, 5.33, and 6.00, respectively, under the level of order. The average values of genera and species at the family level are 2.40 and 2.70, respectively, and the average value of species at the genus level is 1.13.

Table 2. The TINCLi index of fish species in the lower reaches of the Yellow River.

Site	Family/Order	Genus/Order	Species/Order	Genus/Family	Species/Family	Species/Genus
wandering reach	1.75	5.75	5.75	3.29	3.29	1.00
protected reach	1.83	5.00	5.67	2.73	3.09	1.13
Dongping Lake reach	1.67	5.50	6.50	3.30	3.90	1.18
curved reach	1.57	4.14	4.57	2.64	2.91	1.10
estuary reach	1.50	3.67	3.83	2.44	2.56	1.05
lower Yellow River	2.22	5.33	6.00	2.40	2.70	1.13

The comparison of the inclusion index of each section of the lower Yellow River shows that the differences in each section are significant. Still, there is no regularity at the level of order. At the family and genus levels, the inclusion index of taxonomic distinctness of the section of the Dongping Lake reach is higher than that of other sections.

3.3. Taxonomic Distinctness Index

Within a specific range, the value of Δ^+ is related to the distance of the genetic relationship between communities. The smaller the value of Δ^+, the closer the genetic relationship between communities is. The Λ^+ value is related to the evenness of species composition among communities. The smaller the Λ^+ value, the higher the evenness is. According to the survey list of fishery resources in the lower reaches of the Yellow River from 2019 to 2022, as shown in Table 3, the average taxonomic distinctness index of fish (Δ^+) in the lower reaches of the Yellow River is 52.54, and the variation in taxonomic distinctness index (Λ^+) is 241.70. The maximum value of Δ^+ is 56.98 in the estuary reach and decreases in turn along the estuary to the upstream. The minimum value of Δ^+ is 47.50 in the wandering reach of Henan Province. The variation of the Λ^+ value is basically opposite to that of the Δ^+ value in each section. The minimum Λ^+ value is 225.73 in the estuary reach, followed by the Λ^+ value of 240.27 in the Dongping Lake reach. The highest Λ^+ value is 250.66 in the wandering reach of Henan Province, and the Λ^+ value in the protected reach is basically consistent with that in the curved reach.

Table 3. The Δ^+ index and the Λ^+ index of fish species in the lower reaches of the Yellow River.

Index	Wandering Reach	Protected Reach	Dongping Lake Reach	Curved Reach	Estuary Reach	Average
Δ^+	47.50	51.66	53.13	53.43	56.98	52.54
Λ^+	250.66	244.82	240.27	247.00	225.73	241.70

3.4. G-F Index

The closer the G-F index approaches 1, indicating that the distribution of various species among various families and genera becomes more uniform, the more stable the community structure will be. The G-F index is close to 0 or negative, which indicates that the species diversity is small and the system tends to be unstable. The average G-F index of the lower Yellow River is low, only 0.14, with an interfamily diversity index D_F of 3.90, and an intergenus diversity index D_G of 3.30. Among them, the G-F index, DF index, and D_G index of the Dongping Lake reach are the highest in the downstream sections, which are

0.21, 4.50, and 3.57, respectively. They are followed by the curved reach, protected reach, and estuary reach. The G-F index of the wandering reach in Henan Province is negative.

4. Discussion

4.1. The Fishery Resources in the Lower Reaches of the Yellow River Are Recovering Slowly

Surveys of fishery resources in the lower reaches of the Yellow River are fewer than those in the Yangtze River and the Pearl River. The earliest reports of this system were conducted by Professor Li Sizhong in the 1950s and 1960s. His research has been published in the book *The evaluation study of the ecological scheduling efficacy in the lower Yellow River* by the Institute of Zoology of the Chinese Academy of Sciences [6]. According to the book, 103 and 118 species of fish were found in the Henan and Shandong sections, respectively. In the 1980s, 80 species of fish were investigated in the Yellow River System Fishery Resources Survey Project of the former State Administration of Fisheries in five stations: Yiluohekou, Huayuankou, Sunkou, Luokou, and Lijin in the lower reaches of the Yellow River [22]. While the fishery resources in the lower reaches of the Yellow River were rich, large-sized fish, such as *Acipenser dabryanus* and *Psephurus gladius*, could still be found there. In the following 20 years, because of a water shortage [3], there are few relevant fish investigation studies. The habitat of aquatic organisms was destroyed due to the zero-flow, and the fishery resources decreased sharply, and especially the migratory fish in the lower reaches basically disappeared due to the interruption of migration [4,23–25]. Since the Yellow River implemented unified water regulation and management in 1999, there has been no further zero-flow in the lower reaches. Nevertheless, the resources in the lower reaches of the Yellow River have been affected by the zero-flow, the ecological diversity has declined significantly, and nearly half of the fish species have disappeared from the Yellow River Basin [2]. In 2008, Ru Huijun conducted a survey of fishery resources in the mainstream of the Yellow River, and there were only 54 species of fish in the whole basin [7]. Liu Hongbo found 27 species of fish in the Shandong and Henan sections of the lower reaches of the Yellow River in 2013 [8]; Jie Zilin found 7 species of fish in the Liuyuankou section of Kaifeng in the lower reaches of the Yellow River in 2015 and 8 species of fish in the Penglou section of County Fan [9], and Yang Hui et al. investigated 31 species of fish in the protected reach of the lower Yellow River in 2017 [10]. During the investigation period of this study, 54 species of fish were investigated in the lower reaches of the Yellow River, with the highest number of species since the implementation of ecological regulation in the Yellow River in 1999. The continuous functional flow and ecological regulation of the Yellow River promote the restoration of the damaged habitats in the lower reaches of the Yellow River. The fishery resources in the lower reaches of the Yellow River have generally been recovering slowly since the 21st century, which is shown as follows: (1) Some rare and endangered fishes originally distributed in the lower reaches of the Yellow River have re-emerged and formed populations in different sections of the river, such as *Rhinogobio nasulus*, *Pseudobagrus ussuriensis*, and *Megalobrama triangularis*, and *Coilia ectenes*, which was once the main fishery resource in Shandong Province of the Yellow River in the 1980s believed to have disappeared for 30 years [26,27], reappeared in the catches of the lower reaches of the Yellow River in this study; (2) The main economic fish resources, such as *Cyprinus carpio*, *Hypophthalmichthys molitrix*, *Silurus asotus*, *Ctenopharyngodon idella*, *Squaliobarbus curtatus*, and *Culter ilishaeformis*, as well as small-sized fishes, such as *Parabramis pekinensis*, *Pseudolaubuca engraulis*, *Xenocypris argentea*, *Pseudobagrus maculatus*, and *Pelteobagrus nitidus*, frequently appear at each investigation station in the downstream, and the resources are considerable.

4.2. The Diversity of Fishery Resources in Different Sampling Reaches of the Lower Yellow River Is Different

The higher the TINCLi index, the more concentrated the distribution of species at the taxonomic level will be. The indexes of the upstream wandering reach, protected reach, and Dongping Lake reach are higher than those of the downstream reaches, indicating that the genetic relationship of the fishes in the upstream is closer. That is because only freshwater fishes are caught in the upstream sections, with the main groups being orders of Cypriniformes and Siluriformes. While the fish species in the curved reach and estuary reach are closer to the estuary, in addition to freshwater fishes, there are also some fish that can live between seawater and freshwater, such as *Coilia nasus* [26,27], *Liza haematocheila*, *Mugil cephalus* [28], and *Lateolabrax maculatus* [29]. The closer to the estuary, the higher the diversity of fish in the Yellow River in the high-level classification.

Similar to the TINCLi index, the value of Δ^+ decreases from the estuary reach to the upstream, which is mainly related to the number of migratory fish species present in each survey section. The farther away from the estuary, the probability of the occurrence of migratory fish will be lower. In the wandering reach, no migratory fish were found, where the fish's genetic relationship is closer than that in the other section reaches. The value of Λ^+ in the surveyed water area is the lowest in the estuary reach, indicating that the uniformity of species composition among communities in the water area is at the highest level among the survey stations. This is due to the water area being affected by marine dynamics. Migratory fish, such as *Coilia nasus*, *Liza haematocheila*, *Mugil cephalus*, and *Lateolabrax maculatus*, can live in the brackish and freshwater areas, resulting in the highest evenness degree of community composition in the estuary. The value of Λ^+ in the Dongping Lake reach is only higher than that in the estuary reach, and this is because the small-sized fish, such as *Abbottina rivularis*, *Gobio rivuloides*, and *Pseudorasbora parva*, in Dongping Lake can enter the Yellow River through the sluice gate of Dongping Lake and inhabit the nearby waters due to the influence of the water coming from Dongping Lake. Although no migratory fish, such as *Liza haematocheila* and *Lateolabrax maculatus*, were collected in this water area, the fish of Cypriniformes were more abundant than those in other investigation stations, which also leads to the low value of Λ^+. The fish species in the protected reach and curved reach are more abundant than those in the wandering reach, which leads to the highest Λ^+ value in the wandering reach.

The higher the G-F index, the more stable the community structure was. It can be seen from Table 4 that the G-F index of the lower reaches of the Yellow River is only 0.14, indicating that the overall community structure stability of the lower reaches is poor [17]. The main reason is that the number of fish species in the lower reaches is relatively tiny. Among the downstream stations, the index of the Dongping Lake reach is the highest, which is related to the high number of fish species in the Dongping Lake reach. The inflow of Dongping Lake into the Yellow River is influenced by the upstream Dawen River and the water from the South-to-North Water Transfer Project, with abundant nutrients [30], causing the species number and abundance of phytoplankton [31] and zooplankton [32] to be much higher than those in the Yellow River Basin. The fish species in the lake are abundant [33], and the dominant species of small-sized fish in the lake, such as *Abbottina rivularis*, *Gobio rivuloides*, and *Pseudorasbora parva*, can spread from Dongping Lake to the Yellow River Basin, resulting in more fish species in the Dongping Lake reach and a stable fish community structure compared with other investigation stations [34]. The stability of the community structure in the wandering reach is the worst because the number of fish species investigated is the smallest, resulting in the G-F index, D_F index, and D_G index being lower than other sections.

Table 4. The G-F index of fish species in the lower reaches of the Yellow River.

G-F Index	Wandering Reach	Protected Reach	Dongping Lake Reach	Curved Reach	Estuary Reach	Lower Yellow River
D_F	2.83	4.18	4.50	4.18	3.81	3.90
D_G	3.14	3.36	3.57	3.34	3.08	3.30
$D_{G\text{-}F}$	−0.11	0.19	0.21	0.2	0.19	0.14

5. Conclusions

Affected by the ecological regulation of the Yellow River, the number of fish species in the lower reaches of the Yellow River increased significantly compared with the investigation in the early 21st century, and especially some rare and endangered fish, such as *Coilia nasus*, *Rhinogobio nasutus*, and *Pseudobagrus ussuriensis*, reappeared in the lower reaches of the Yellow River. The population and quantity of the main economic fish and common small-sized fish in the lower reaches of the Yellow River have increased, and the fishery resources in the lower reaches of the Yellow River are recovering slowly.

The lower Yellow River's fish species diversity differed among the investigated sections. The closer to the estuary, the higher the fish species diversity of the Yellow River was. Dongping Lake, as the only lake connecting with the lower reaches of the Yellow River, plays a vital role in supplementing the fish resources in the lower Yellow River.

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