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Research Article

Effects of Urbanization on Water Quality and the Macrobenthos Community Structure in the Fenhe River, Shanxi Province, China

Linfang Wang,[1,2,3] Hua Li ,[1,3] Jinhua Dang ,[2] Ying Zhao,[2] Yu'en Zhu,[1] and Pengming Qiao[2]

[1]*School of Environment and Resources, Shanxi University, Taiyuan 030006, China*
[2]*Shanxi Province Research Academy of Environmental Science, Taiyuan 030027, China*
[3]*Institute of Resources and Environment Engineering of Shanxi University, Taiyuan 030006, China*

Correspondence should be addressed to Hua Li; lihua@sxu.edu.cn and Jinhua Dang; 984736173@qq.com

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The relationships between land use types, water and sediment parameters, and macrobenthos community structures in the upper and middle reaches of the Fenhe River and urbanization intensity were studied. Samples were collected from 23 sampling sites. Spearman rank correlation analyses were performed to assess the relationships between the percentages of impervious area or the proportions of four land uses and the water and sediment physicochemical properties, heavy metal and polycyclic aromatic hydrocarbon concentrations in water and sediment, and biological indicators of the macrobenthos communities. Some water parameters (temperature, oxidation-reduction potential, electrical conductivity, total N concentration, total P concentration, ammonia-N concentration, and nitrate-N concentration), some sediment parameters (total N concentration, total P concentration, organic matter content, percentage of particles with diameters <2 mm, and polycyclic aromatic hydrocarbon, Cd, Cr, Cu, Ni Pb, and Zn concentrations), and some macrobenthos parameters (Berger–Parker index and percentages of collectors, tolerant taxa, and Oligochaeta) significantly positively correlated with the percentage of impervious area. Some water parameters (pH and dissolved oxygen concentration), some sediment parameters (percentage of particles with diameters >2 mm), and some macrobenthos parameters (total biomass, total number of taxa, Shannon's index, N diversity index, and percentages of Ephemeroptera, Plecoptera, Trichoptera, filterers, scrapers, and sensitive taxa) significantly negatively correlated with the percentage of impervious area. The results indicate that intensification of urbanization has strongly affected the water, sediment, and macrobenthos in the Fenhe River watershed.

1. Introduction

Effects on river basins and the use of river water have increased strongly in recent years because of urbanization. In particular, land use and land cover (principally the percentage of impervious area (PIA)) have changed [1, 2]. Continual increases in the PIA have been accompanied by decreases in the areas of farmland, forest, and grassland and the canalization of natural rivers. Increases in the PIA have also led to sharp decreases in precipitation received by soil and increases in the surface runoff coefficient and runoff volume. These changes could strongly increase the water levels in rivers after heavy rainfall, which could cause riverbanks to erode and increase the sediment loads of rivers [3]. Rainwater, domestic sewage, industrial wastewater, surface runoff, and municipal pipeline water will be discharged into rivers after rain. Domestic sewage and some types of industrial wastewater contain large amounts of nitrogen- and phosphorus-containing compounds. Sewage and wastewater discharges into rivers can, therefore, supply excess nitrogen and phosphorus, which can negatively affect water quality and aquatic organism diversity. In such circumstances, many sensitive macrobenthos species will disappear and tolerant species will proliferate [4].

This study was focused on the effects of urbanization on macrobenthos organisms because these organisms live at the bottoms of aquatic systems, are long-lived, and move little. Changes in the macrobenthos species abundances and spatial distributions reflect environmental changes in river basins [5–7]. The intensity of urbanization in a river basin can be expressed as the PIA (the ratio between the land area occupied by urban residences, industrial plants, commercial premises, and roads in a river basin and the total area of the basin).

This study was performed in the upper and middle reaches of the Fenhe River (Shanxi Province, China), which is the second largest tributary of the Yellow River. The effects of land-use changes caused by urbanization on water and sediment parameters and the macrobenthos community were investigated. The relationship between the macrobenthos community and land-use pattern was also investigated. The results will be useful when establishing approaches to protect river ecology in the study area as urbanization progresses.

2. Materials and Methods

2.1. Site Description. The Fenhe River, the largest river in Shanxi Province, is 716 km long. The headwater (in Ningwu County) to the Wangzhuang section (in Lingshi County) is defined as the upper and middle reaches of the river. A total of 26,210 km^2 of land drains into the upper and middle reaches. The Fenhe River flows south to north through Shanxi Province and has tributaries originating in Lüliang and Taihang, which are mountainous areas. The river flows through three major basins (Taiyuan, Linfen, and Yuncheng) and enters the Yellow River in Wanrong County. The Fenhe River Basin has a temperate continental monsoon climate with four distinct seasons and is in a semiarid semihumid climate-transition zone. Interannual rainfall varies strongly, and rainfall is unevenly distributed through the year. Approximately 70% of the annual rainfall occurs between June and September, mainly in heavy rainfall events. Mean annual precipitation in the whole basin is 489.3 mm, and 78.8% of this falls in the wet season. Mean annual evaporation is 2008 mm, and the mean annual air temperatures in different parts of the basin are between 6 and 13°C [8]. The sampling sites we used were mainly in the upper and middle reaches of the Fenhe River and were in the main river, primary tributaries, and secondary tributaries. Some sites were upstream and others downstream of points at which industrial wastewater or municipal sewage are discharged. A total of 23 sampling sites were selected and labeled S1–S23. The locations of the sites are shown in Figures 1 and 2.

Figure 1: Location of the Fenhe River Basin.

2.2. Land Use Calculations. Spatial analysis of land use was performed using remote sensing images acquired in 2015. The images were processed, and then spatial analysis was performed using a supervised classification and visual interpretation method for the area within 3 km of each sampling site. The land uses cropland, forest, grassland, water, and construction land were used in the spatial analysis, and the distribution of each land use at each sampling site was determined.

2.3. Sample Collection and Analysis

2.3.1. Measurements of Physicochemical Indicators for Water. Water flow was measured using a current meter (LGY-II LS300-A, Beijing, China). The dissolved oxygen concentration was measured using a pen-type dissolved oxygen meter (LH-D9, Hangzhou, China). The oxidation-reduction potential was measured in situ using a pen-type oxidation-reduction potential meter (CT-8022, Qingdao, China). The electrical conductivity was measured on-site using a portable conductivity meter (LH-C661, Changzhou, China). The pH and temperature were measured on-site using a portable pH meter (PHB-4, Hangzhou, China). Other physicochemical indicators were measured using methods described in the Chinese Environmental Quality Standards for Surface Water. The total nitrogen (TN) concentration and total phosphorus (TP) concentration were determined using a potassium persulfate oxidation ultraviolet spectrophotometry method. The ammonia-nitrogen (NH_4^+-N) concentration was determined using a Nessler's reagent spectrophotometry method.

2.3.2. Measurements of Physicochemical Indicators for Sediment. Each sediment sample was collected using a Peterson sediment sampler and then placed in a glass bottle and stored in a refrigerator. The samples were transported to the laboratory as soon as possible after being collected and were stored at a low temperature until they were analyzed. The sediment samples were analyzed following methods described in the Soil Physicochemical Analysis document, published by

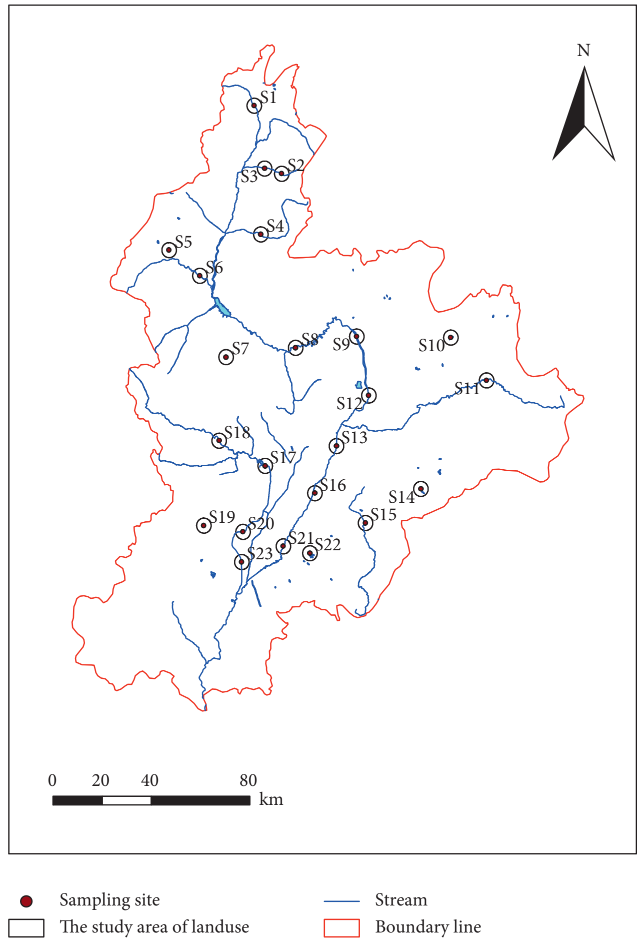

FIGURE 2: Locations of the 23 sampling sites in the upper and middle reaches of the Fenhe River.

the Institute of Soil Science, Chinese Academy of Sciences (Nanjing, China). The TN concentration was determined using a semi-micro Kjeldahl method. The TP concentration was determined using an anti-Mo-Sb spectrophotometry method. The sediment organic matter (SOM) content was determined using a potassium dichromate volumetric method. The polycyclic aromatic hydrocarbon (PAH) concentration was determined using a gas chromatography mass spectrometry method. The Cd, Cr, Cu, Ni, Pb, and Zn concentrations were determined using a HNO_3-$HClO_4$-HF microwave digestion inductively coupled plasma mass spectrometry method. The sediment particle size distribution was determined using a method described by Dickens et al. [9].

2.3.3. Invertebrate Macrobenthos Measurements. Macrobenthos were collected using a Surber net (30 cm × 30 cm, 500 μm mesh) when it was possible to wade into the river at the sampling site and using a 1/16 Peterson sampler when it was not possible to wade into the river. Three samples were collected at each sampling site, one from each side and one from the center of the river channel [10]. The collected material was washed using a 60 mesh sieve; then, the material retained by the sieve was placed on a white porcelain plate. The macrobenthos organisms were removed and fixed in a 10% formaldehyde solution and then transported to the laboratory, where the species were identified and counted. The macrobenthos species were identified and the functional feeding groups classified using the publications Research on Microdrile Oligochaeta in China [11], Economic Fauna of China [12], and Identification Manual for the Larval Chronomidae (Diptera) of North and South Carolina [13]. Diversity was evaluated using Shannon's index [14]. The Berger–Parker dominance index was calculated using a method described by Xu [15]. The comprehensive (N) diversity index for the macrobenthos was calculated using a method published in the Technical Guide for Watershed Ecosystem Health Assessment [16].

2.4. Data Analysis. Analyses of variance followed by Duncan's post hoc analyses and Spearman's rank correlation analyses were used to investigate relationships between the environmental parameters and biological indicators and the land uses. The statistical analyses were performed using SPSS 19.0 software (IBM, Armonk, NY, USA). Curves were fitted to scatter plots of the PIA data and biological indicator data using Origin 8.0 software (OriginLab, Northampton, MA, USA).

3. Results

3.1. Relationships between the Physicochemical Indicators for Water and Land Use. The land uses in the areas 3 km around the sampling points are shown in Figure 3. The water flow and PIA did not correlate significantly. However, the water temperature, oxidation-reduction potential, electrical conductivity, TN concentration, TP concentration, and NO_3^--N concentration significantly positively correlated with the PIA and percentage of cropland and significantly negatively correlated with the percentages of grassland and forest. The water pH and dissolved oxygen concentration negatively correlated with the PIA (Table 1).

3.2. Relationships between Physicochemical Indicators for Sediment and Land Use. The percentage of particles with diameters <2 mm, SOM content and TN, TP, PAH, Cd, Cr, Cu, Ni, Pb, and Zn concentrations in the sediment positively correlated with the PIA. The percentage of particles with diameters >2 mm significantly negatively correlated with the PIA, and the percentages of forest and wetland positively correlated with the PIA. The SOM content and TN, TP, Cd, Cr, and Pb concentrations positively correlated with the percentage of cropland. The TP concentration negatively correlated with the percentages of grassland and forest, and the PAH concentration negatively correlated only with the percentage of forest (Table 2).

3.3. Relationships between the Macrobenthos Community Structures and Land Use

3.3.1. Macrobenthos Community Compositions and Quantities. In total, macrobenthos from 37 genera or species were found at the 23 sampling sites in the upper and middle reaches of the Fenhe River. The macrobenthos were from 25

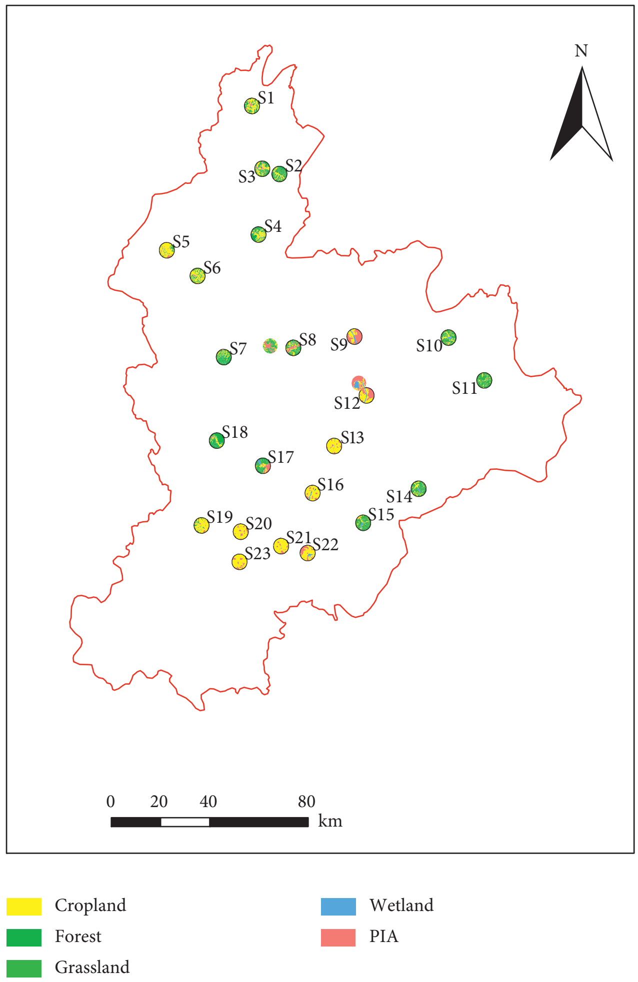

FIGURE 3: The results of spatial analysis of land use types.

TABLE 1: Environmental parameters for water at the sampling sites and the relationships between the parameters and land use.

Variable	Min	Max	Mean	SD	*r*				
					Cropland (%)	Grassland (%)	Forest (%)	Wetland (%)	Percentage of impervious area (PIA, %)
Water temperature (°C)	10.10	26.80	19.21	4.21	0.308**	−0.425**	−0.386**	0.446**	0.356**
pH	7.83	9.07	8.52	0.33	−0.191	0.257*	0.120	0.011	−0.270*
DO (mg/L)	3.02	10.80	6.82	2.03	0.235*	0.118	−0.166	−0.031	−0.271*
Flow (m/s)	0.05	3.32	0.54	0.72	−0.117	0.059	0.127	−0.027	−0.100
ORP (mv)	155.00	281.00	224.47	47.66	0.381**	−0.219*	−0.346**	0.047	0.247*
EC (μs/cm)	329.00	2000.00	1034.16	668.06	0.528**	−0.326**	−0.464**	−0.155	0.382**
TN (mg/L)	1.28	54.90	15.83	14.07	0.726**	−0.304**	−0.469**	−0.254*	0.810**
TP (mg/L)	0.01	5.66	0.93	1.49	0.630**	−0.243*	−0.450**	−0.157	0.814**
NH_4^+-N (mg/L)	0.03	43.80	8.12	13.11	0.344**	−0.229	−0.012	−0.194	0.566**
NO_3^--N (mg/L)	0.02	10.30	2.20	2.34	0.334**	−0.235*	−0.371**	−0.084	0.411**

DO, dissolved oxygen concentration; ORP, oxidation-reduction potential; EC, electrical conductivity; TN, total nitrogen concentration; TP, total phosphorus concentration; NH_4^+-N, ammonia-nitrogen concentration; NO_3^--N, nitrate nitrogen concentration; SD, standard deviation. $^*P < 0.05$; $^{**}P < 0.01$.

families, six classes, and four phyla. There were nine genera or species of Annelida (24.3% of the total species), five genera or species of Mollusca (13.5% of the total species), 22 genera or species of Arthropoda (59.4% of the total species), and one species of Turbellaria (13.5% of the total species). The dominant species in the phylum Annelida was *Limnodrilus hoffmeisteri.* In the Arthropoda phylum, 20 genera or species were in the Insecta class, and these were mainly Diptera,

Table 2: Environmental parameters for sediment at the sampling sites and the relationships between the parameters and land use.

Variable	Min	Max	Mean	SD	r Cropland (%)	Grassland (%)	Forest (%)	Wetland (%)	Percentage of impervious area (PIA, %)
TN (g/kg)	0.74	1.49	1.02	0.19	0.260*	−0.240*	−0.195	0.220*	0.449**
TP (mg/kg)	0.60	1.65	0.80	0.24	0.322**	−0.216*	−0.270*	−0.037	0.219*
SOM (g/kg)	13.71	84.05	32.99	18.95	0.253*	−0.260*	−0.126	0.051	0.322**
Particle size >2 mm (%)	0.00	38.69	6.22	10.95	−0.139	−0.196	0.294*	0.307*	−0.54**
Particle size <2 mm (%)	61.31	100.00	93.78	10.95	0.139	0.196	−0.294*	−0.307**	0.54**
PAHs (mg/kg)	0.28	23.33	2.83	5.03	0.026	−0.185	−0.296*	0.206*	0.658**
Zn (mg/kg)	28.91	119.73	48.7	21.69	−0.024	−0.034	−0.183	0.276*	0.353**
Pb (mg/kg)	8.47	20.74	13.44	3.19	0.414**	−0.591**	−0.140	0.140	0.209*
Cd (mg/kg)	0.06	0.27	0.12	0.05	0.351**	−0.436**	−0.185	0.152	0.363**
Cr (mg/kg)	16.33	98.64	37.10	16.06	0.232*	−0.014	−0.439**	0.164	0.394**
Ni (mg/kg)	7.21	32.27	16.08	5.90	−0.150	−0.094	−0.165	0.573**	0.538**
Cu (mg/kg)	5.85	65.78	15.89	12.61	−0.107	−0.210*	−0.276*	0.636**	0.787**

TN, total nitrogen concentration; TP, total phosphorus concentration; SOM, sediment organic matter content; PAHs, polycyclic aromatic hydrocarbon concentration; SD, standard deviation. $^{*}P < 0.05$; $^{**}P < 0.01$.

Ephemeroptera, Plecoptera, and Trichoptera. Of these, four genera or species were aquatic: Ephemeroptera, Plecoptera, and Trichoptera (EPT). *Baetis* spp. were the dominant EPT species. There were 12 genera or species of aquatic insects in the Diptera order, and *Orthocladius* sp. 1 was dominant. The most macrobenthos genera or species found at a sampling site in the upper and middle reaches of the Fenhe River was 11 at Leiming Temple (site S1).

3.3.2. Relationships between the Biological Indicators and Land Use. The macrobenthos community structure indicators and feeding function indicators correlated to different degrees with the different land use types (Table 3). The percentages of predators and shredders did not significantly correlate with the PIA. However, the biomass, total number of taxa, Shannon's index, N diversity index, and percentages of EPT, filterers, scrapers, and sensitive taxa negatively correlated with the PIA. The Berger–Parker index and percentages of collectors, tolerant taxa, and Oligochaeta significantly positively correlated with the PIA. The percentage of scrapers and the Berger–Parker index did not significantly correlate with the percentage of cropland. The biomass and percentages of collectors, tolerant taxa, Oligochaeta, and shredders significantly positively correlated with the percentage of cropland. The total number of taxa, Shannon's index, N diversity index, and percentages of EPT, filterers, predators, and sensitive taxa negatively correlated with the percentage of cropland.

Exponential lines were fitted to plots of the data for the total number of taxa, Shannon's index, Berger–Parker index, and percentage of EPT against the PIA, and the results are shown in Figure 4.

The total number of taxa, Shannon's index, Berger–Parker index, and percentage of EPT all had significant relationships with the PIAs. The total number of taxa, Shannon's index, and percentage of EPT significantly negatively correlated with the PIAs. The percentage of EPT was generally zero when the PIA was >~8%. The Berger–Parker index significantly positively correlated with the PIA.

The percentages of predator and shredder macrobenthos did not significantly correlate with the PIA. However, the percentage of collectors positively correlated with the PIA, and the percentages of filterers and scrapers significantly negatively correlated with the PIA (Figure 5). The percentages of filterers and scrapers were zero when the PIA was >~3%. The percentage of collectors reached a maximum when the PIA was >~20%.

The N diversity index and percentages of sensitive taxa and tolerant taxa had nonlinear relationships with the PIA. The percentage of Oligochaeta linearly correlated with the PIA. The percentages of Oligochaeta and tolerant taxa positively correlated with the PIA. The N diversity index and percentage of sensitive taxa significantly negatively correlated with the PIA (Figure 6). When the PIA reached a particular value, the N diversity index reached a plateau and fluctuated within a small range. This indicated that the macrobenthos community only contained tolerant species and that the sensitive taxa had all disappeared.

4. Discussion

4.1. Relationships between the Environmental Parameters and the PIA. The water temperature, oxidation-reduction potential, electrical conductivity, and TN, TP, and NO_3^--N concentrations negatively correlated with the PIA, but the pH and dissolved oxygen concentration significantly positively correlated with the PIA and percentage of cultivated land and negatively correlated with the percentages of grassland and forest. This indicated that urbanization strongly affected water quality in the river basin. The more rapid the urbanization process the more seriously polluted urban rivers will become. The "heat island effect" may

Table 3: Macrobenthos community parameters for the sampling sites and the relationships between the parameters and land use.

Variable	Min	Max	Mean	SD	r Cropland (%)	Grassland (%)	Forest (%)	Wetland (%)	Percentage of impervious area (PIA, %)
Biomass/(g/m^2)	0.14	213.33	27.62	54.52	0.336**	−0.186	−0.105	−0.322**	−0.382**
Total number of taxa	0.00	15.57	4.3	3.58	−0.461**	0.300**	0.361**	−0.177	−0.661**
Shannon diversity index	0.00	2.27	1.11	0.70	−0.392**	0.368**	0.374**	−0.263*	−0.558**
Berger–Parker index	0.00	1.10	0.52	031	−0.126	0.337**	−0.167	0.069	0.705**
N diversity index	89.42	1.22	32.58	23.74	−0.385**	0.438**	0.234*	−0.239*	−0.258*
EPT (%)	0.01	1.00	0.21	0.33	−0.305**	0.450**	0.261*	0.392**	−0.419**
Collector (%)	25.81	100.00	74.05	20.78	0.308**	−0.358**	0.112	−0.066	0.76**
Filterer (%)	0.00	48.39	4.24	10.50	−0.278*	0.377**	0.177	−0.079	−0.287*
Scraper (%)	0.00	31.58	2.90	6.87	−0.065	−0.091	0.234*	0.483**	−0.535**
Predator (%)	0.00	19.23	5.21	6.71	−0.490**	0.601**	0.157	0.015	−0.186
Shredder (%)	0.00	50.00	11.82	16.96	0.489**	−0.077	−0.334**	−0.220*	−0.060
Sensitive taxa (%)	0.00	38.10	5.12	10.64	−0.400**	0.310**	0.454**	−0.023	−0.390**
Tolerant taxa (%)	0.00	100.00	55.97	37.12	0.355**	−0.377**	−0.644**	0.031	0.605**
Oligochaeta (%)	0.00	100.00	20.24	35.19	0.370**	−0.251*	−0.324**	−0.083	0.660**

EPT, Ephemeroptera, Plecoptera, and Trichoptera; SD, standard deviation. $^*P < 0.05$; $^{**}P < 0.01$.

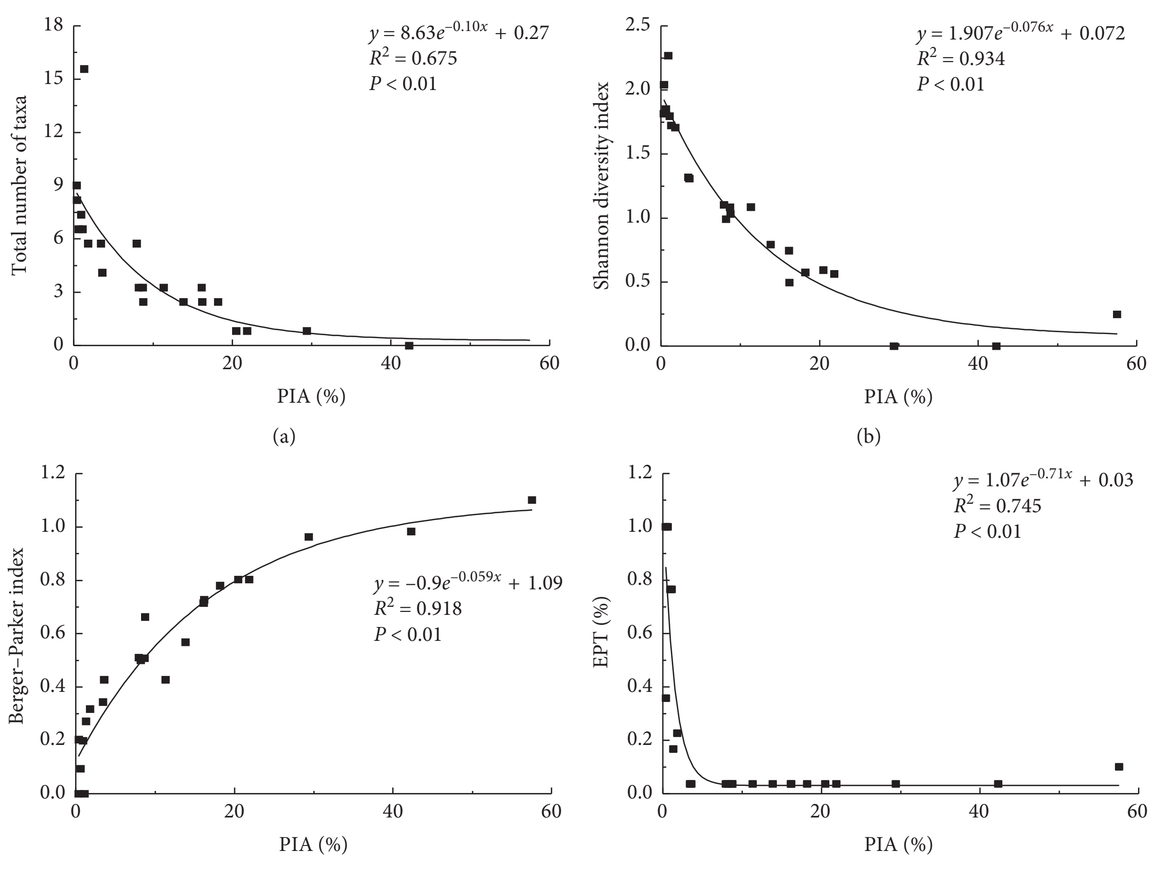

Figure 4: Relationships between the total number of taxa, Berger–Parker index, Shannon's diversity index, and percentage of Ephemeroptera, Plecoptera, and Trichoptera (EPT) and the percentage of impervious area (PIA) with exponential lines fitted to the data.

explain a high degree of urbanization causing high river water temperatures. Large amounts of domestic and industrial waste are discharged into the Fenhe River. This will increase the electrical conductivity by increasing the salt concentrations and the TN and TP concentrations by increasing the amounts of nutrients entering the water. These results were consistent with the results of previous studies in China and elsewhere [7, 17, 18].

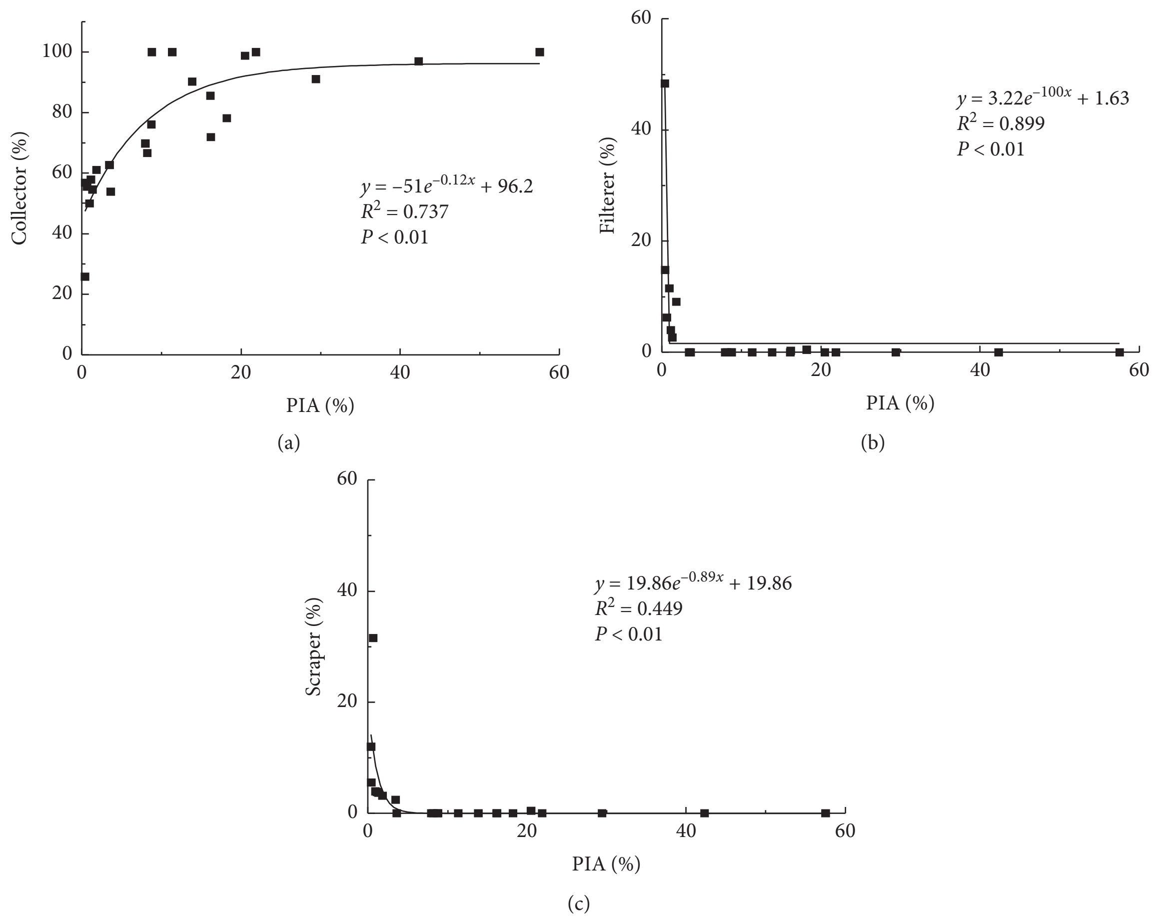

Figure 5: Relationships between the percentages of the macrobenthos functional groups and the percentage of impervious area (PIA).

The SOM content and TN, TP, Cd, Cr, and Pb concentrations in sediment positively correlated with the PIA and percentage of cropland probably because urbanization decreases industrial and agricultural activities and leads to increased nutrient and heavy metal emissions in rivers. These nutrients and heavy metals will form complexes and adsorb to suspended particulate matter and then enter the sediment, which will act as both a sink for and a secondary source of nutrients and heavy metals. The percentage of sediment particles with diameters <2 mm positively correlated with the PIA, and the percentage of sediment particles with diameters >2 mm significantly negatively correlated with the PIA and significantly positively correlated with the percentages of forest and wetland. This is probably because construction in highly urbanized areas will expose previously unexposed soil and, therefore, decrease the sediment particle size. Canalization of a natural river will also decrease the complexity of the river channel, increasing the proportion of fine silt. The upper reaches of the Fenhe River Basin are generally not strongly urbanized, and water flow is low and sediment mainly consists of gravel. The degree of urbanization increases downstream, and the water flow increases. This decreases the vegetation cover around the river, meaning that serious soil erosion occurs. This causes the sediment particle size to be lower in the middle than the upper reaches of the Fenhe River. Similar conclusions have been drawn in studies in other parts of China and elsewhere [7, 17, 19]. Sediment is a source of pollutants to water. Sediment is an important reservoir of heavy metals and organic matter. If the physical and chemical properties of the aquatic environment change, nutrients, heavy metals, and persistent organic pollutants previously deposited in the sediment can be released to the overlying water, meaning the sediment is a secondary source of pollutants. The correlations between the nutrient concentrations, organic matter concentrations, and PIAs in the water and sediment samples supported this conclusion.

4.2. Relationships between the Macrobenthos Biological Indicators and PIA. The biomass, total number of taxa, Shannon's index, N diversity index, and percentages of EPT, filterers, scrapers, and sensitive taxa negatively correlated with the PIA, but the Berger–Parker index and percentages of collectors, tolerant taxa, and Oligochaeta positively correlated with the PIA. Urbanization decreased benthos diversity and biomass. A small number of pollutant-resistant groups (e.g., Oligochaeta and Chironomidae) became dominant, but sensitive taxa (represented by EPT) decreased in abundance or disappeared. Intense urbanization has caused a range of

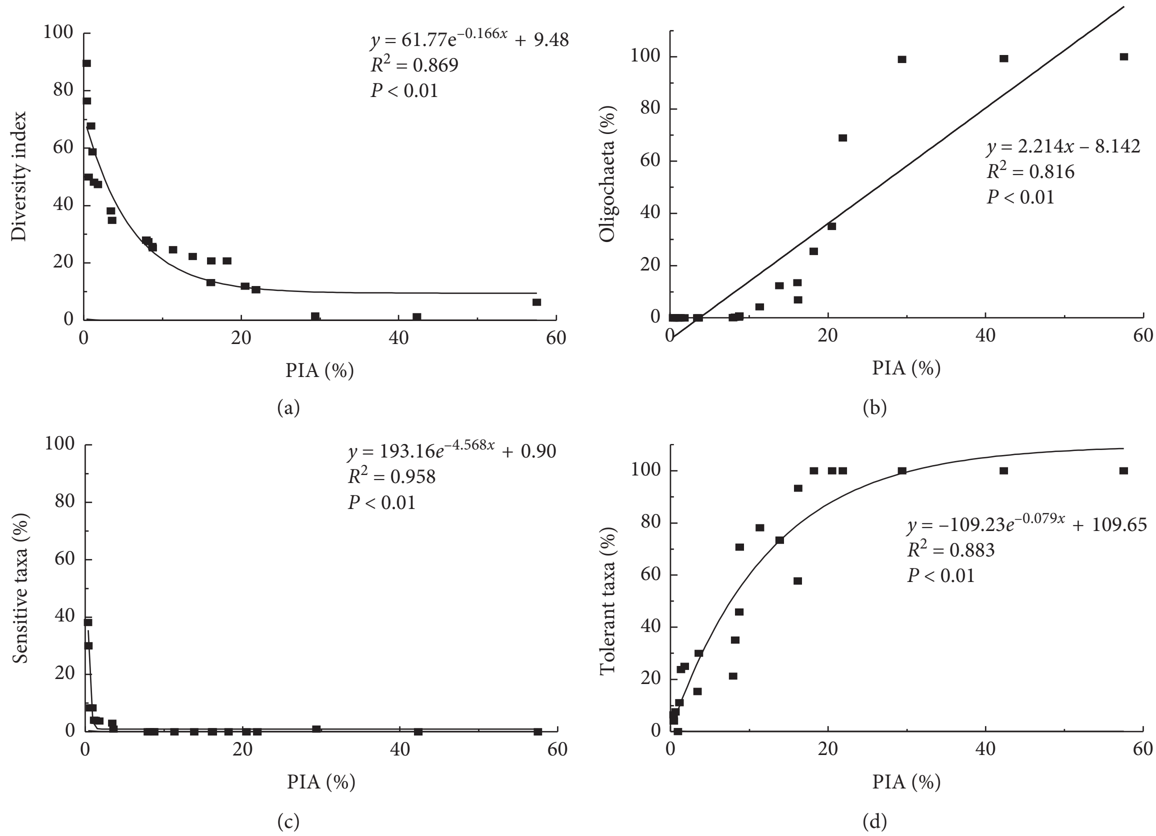

Figure 6: Relationships between the N diversity index and percentages of Oligochaeta, sensitive taxa, and tolerant taxa and the percentage of impervious area (PIA).

periphyton in the basin to decrease and the numbers of scrapers and filterers to decrease because of changes in the hydrological conditions and the numbers of collectors to increase because of increased nutrient loads. Similar conclusions were drawn in previous studies performed in China and elsewhere [17, 19, 20]. The total number of taxa, Shannon's diversity index, Berger–Parker index, percentage of EPT, N diversity index, and percentages of intolerant and pollutant-resistant groups nonlinearly correlated with the PIA, which was consistent with the conclusions drawn in a study performed by Liu et al. [7]. However, Li et al. [17], King [20], and others found linear correlations. The nonlinear relationships indicate that the indicators changed in one way up to a PIA threshold and then in another way above the threshold. When the PIA was >~8%, the percentage of EPT was zero. This was consistent with the conclusion reached in a previous study that the benthos group may be altered when the PIA is >10% or 8%–12% [21, 22]. The percentages of filterers and scrapers decreased to zero when the PIA was >~3%, and the percentages of gathers and collectors reached maxima when the PIA was >20%.

5. Conclusions

The Fenhe River Basin, which is in the middle reaches of the Yellow River, is an important area in terms of ecological functions and grain and cotton production. The basin is economically developed and densely populated. The basin has played an important role in the economic development of Shanxi Province. However, development has increased in recent years, and cities in the basin have expanded rapidly. Population growth and economic development in the upper and middle reaches of the Fenhe River have accelerated changes in land use. These changes have caused habitats in the upper and middle reaches of the Fenhe River to become degraded and the concentrations of pollutants in the river water and sediment to increase rapidly. This has caused the numbers of macrobenthos cleaning species to decrease sharply and the numbers of pollutant-tolerant species to increase. The macrobenthos now consists of a small number of species with unevenly distributed populations. The results of this study indicate that habitats in the upper and middle reaches of the Fenhe River are being degraded to a worrying degree.

Data Availability

All the data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

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