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Review Article

Progress in the Research of the Toxicity Effect Mechanisms of Heavy Metals on Freshwater Organisms and Their Water Quality Criteria in China

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Water quality criteria are the scientific basis for formulating water quality standards and environmental management practices. Due to the development of urbanization and industrialization, the problem of heavy metal pollution has become a serious environmental problem. Heavy metals not only have major impacts on aquatic organisms, but also seriously threaten human health. However, the current environmental criteria refer to the maximum value limitations of environmental factors in environmental media where harmful or detrimental effects are not produced on specific protected objects. This study reviewed the sources, hazard levels, toxic effect mechanisms, and the current research status of China's water quality criteria for heavy metal pollutants. In addition, the focus and direction of future research on the toxic effects of heavy metal on aquatic organisms and the necessary criteria changes were discussed. The present study would provide an important theoretical basis for the future research of water quality criteria and risk assessment of heavy metal pollutants.

1. Introduction

Heavy metals are becoming one of the most serious environmental problems due to their persistence, biological toxicity, nondegradability, and capability of entering the food chain. In addition, heavy metal pollutants have even been found to react with some organic substances under certain conditions to convert them into even more toxic metal-organic complex pollutants [1, 2]. Aquatic organisms can accumulate and concentrate heavy metals to a certain extent. However, when the concentration and toxicity levels of heavy metals exceed the tolerance of aquatic organisms, they will produce serious toxic effects on their related indicators and even their life activities. At the same time, genetic mutations or variations may be caused, which will result in changes in species diversity and survival rates. Since heavy metal pollutants have the potential of eventually being transmitted to humans and other advanced organisms through the food chain, they also pose serious threats to human health. For example, heavy metals are not easily eliminated after entering the human body and tend to continuously accumulate over time. Once they exceed the physiological load of the human body, they will cause physiological structural changes. These changes will then lead to acute, chronic, or long-term hazardous effects. For example, Zn, Cd, methyl Hg, Se, and Ni are teratogenic. Under environmental conditions with high concentrations of heavy metals, the ingestion of excessive amounts of heavy metals will lead to poisoning effects with possible serious consequences [3].

In recent years, due to the major potential harmful effects of heavy metals in water on both aquatic organisms and humans, many experts and researchers have carried out intensive investigations regarding the ecological toxicity of heavy metals. In particular, the aforementioned studies have focused on the acute, subacute, and chronic toxic effects on organisms of nonessential elements, such as Hg, Cd, Pb, Cr, and As [4, 5]. In addition, some researchers have examined the toxicity or carcinogenesis of heavy metals in relationship to both humans and animals. The results revealed that the reactive oxygen produced by the stimulation of such heavy metals as Fe, Cu, Cd, Cr, Hg, Ni, and Pb can produce a series of toxic effects on organisms. These effects include lipid peroxidation and thiol protein consumption, as well as reactions with nuclear proteins and DNA which cause damage to biological macromolecular substances [6].

The water quality criteria specify the maximum concentration levels of toxic substances in water which will not adversely affect specific protected objectives under certain natural conditions. As the basis of the protection of water quality, the water quality criteria provide an important scientific basis for environmental protection agencies to safeguard aquatic ecosystems. The vast majority of water quality criteria are obtained by evaluating the species sensitivity distributions (SSD) of factors and/or impacted species [7]. At the present time, water quality criteria are indispensable scientific and theoretical foundations for environmental protection agencies to formulate water quality standards, evaluate water quality, and conduct effective water quality management processes [8]. Aquatic biological criteria refer to the maximum allowable concentrations of pollutants in aquatic environments which do not produce long-term or short-term adverse or harmful effects on aquatic organisms. These allowable concentration levels are the core components of water quality criteria [9]. Since different ecosystems have different biota, it has been observed that toxic concentrations which may be harmless to one biota may have irreversible toxic effects on another biota [10]. Therefore, aquatic biological criteria should have obvious regional characteristics [11]. Due to these differences in aquatic biota in different regions and countries, the baseline values of the same pollutants will vary depending on the objects to be protected. The United States was the first country to study water quality criteria. Since the 1960s, the United States Environmental Protection Agency (US EPA) successively promulgated water environment criteria documents and subsequently formed a relatively complete water quality criteria system [12]. In recent years, major progress has been made in the study of water quality criteria in China. A comprehensive water quality criteria system has been gradually established, which has successfully integrated aquatic biological, human health, sediment, ecological, and nutrient criteria, respectively. The key technological foundations of China's water quality criteria system have been established, such as the "3 Phyla and 6 Families;" "biological effect ratio;" "estimation of relationships among species;" "water effect ratio;" and "biological ligand model (BLM)." A variety of Chinese aquatic biological criteria values based on indigenous biotoxicity data were determined, such as the types of heavy metals (Cd, Pb, Cu, Cr, and Zn); eutrophic substances (ammonia nitrogen); new organic pollutants (for triclosan); polycyclic aromatic hydrocarbons (phenanthrene, pyrene); and POPs (PFOS, PFOA). In addition, the sediment criteria values and ecological criteria values of various pollutants were derived. It is firmly believed that the research and establishment of water quality criteria values in China will provide scientific support for the formulation and revision of accurate and effective water quality criteria values which specifically pertain to China's national situation.

Based on the aforementioned important issues, this research study summarized the sources and potential hazards of heavy metal pollutants in water, as well as the toxic effect mechanisms of heavy metals on aquatic organisms. In addition, the status of the current research regarding the water quality criteria of heavy metals in China was examined. Then, using the obtained insights, this study also presented suggestions for the focus and direction of future research regarding the biological toxic effects of heavy metals on aquatic organisms and potential revisions to China's current criteria system. The further studies of the ecological toxic effects of heavy metals on aquatic organisms will provide important references for the evaluations of the ecological toxicity of heavy metals on aquatic organisms, as well as assisting in identifying effective environmental treatment methods for heavy metal pollution in water bodies. Therefore, the results of the present study provide an important theoretical basis for the examination of water quality standards and risk assessments of heavy metal pollution hazards.

2. Hazards of Heavy Metal Pollutants in Water Bodies

Once heavy metals enter the water body, they will cause certain toxicity to aquatic organisms. Heavy metals are defined as naturally occurring metals having atomic number (Z) greater than 20 and an elemental density greater than 5 g/cm^3 [4]. Some toxic heavy metals, such as Ni, As, Cr, Zn, Cu, Cd, Co, and Pb, have the potential to cause serious environmental damage. The ion forms of Cd^{2+}, Pb^{2+}, Hg^{2+}, Ag^{+}, and As^{3+} act with biological organisms to form corresponding toxic compounds. At the present time, with the increases in the bioaccumulations and concentrations of heavy metals in environments, the toxicity characteristics of heavy metals have changed. Ligands and oxidized states play important roles in the bioavailability of heavy metals [13]. If the cumulative concentrations or effects of heavy metals reach certain limits, destruction of cell metabolism will result, and the impacts of the heavy metals will become toxic [14]. The toxic effects of metals mainly cause the functional loss of brain and nervous system functions, and serious damage to blood content, liver, spleen, kidney, viscera, and other organs. This damage results in physical weakness, hypomnesia, skin allergic reactions, hypertension, and other symptoms [15]. Therefore, based on these factors, the World Health Organize (WHO) is globally studying the toxicity mechanism of heavy metals. In some cases, several regulatory agencies have also approved standardized limitations for the discharge of wastewater containing heavy metals. In previous related studies, researchers have also vigorously carried out examinations into heavy metal pollution hazards. As a result, new technologies for heavy metal wastewater treatments have been developed in order to achieve the goal of reducing the harmful effects of heavy metals on the environment as soon as possible [16].

There are a wide range of sources for heavy metals to enter the environment, including wastewater, waste gas, and waste residue. The known sources of heavy metals and their harmful effects on the human body are shown in Figure 1. Table 1 lists the specific hazards of some specific heavy metals on humans, as well as the current maximum harmful concentration levels (maximum contaminant level, MCL) [17] and the limitation values of the surface water environmental quality standard in China.

3. Toxic Effects and Mechanisms of Heavy Metals on Aquatic Organisms

3.1. Toxic Effects of Heavy Metals on Aquatic Organisms. Due to the close contact between aquatic organisms and water bodies, the heavy metals in the water bodies can easily enter the aquatic organisms. Heavy metals enter aquatic animals mainly through the following three ways. (1) Aquatic animals use gills and other organs to absorb heavy metal ions dissolved in water into their bodies. Then, the aquatic organisms accumulate heavy metals on skin surface cells or convey the heavy metals to various organs or tissues of the body through their blood. (2) Aquatic animals absorb heavy metals into their bodies via their digestive tracts through food intake and so on. (3) Heavy metals are absorbed through the animals' subcutaneous layers and then enter the bodies of the organisms through osmotic exchanges between the heavy metals and the impacted body surfaces of the aquatic organisms [41].

3.1.1. Bioaccumulations of Heavy Metals. Heavy metals can be enriched in organisms. Once heavy metals in the water environments enter aquatic organisms, they are not easily metabolized, decomposed, and excluded from the bodies of the animals. Besides, the heavy metals very easily accumulate in such organs as the liver and kidney of the animals. The results of the studies conducted by Olivares et al. [42] revealed that the main mechanism of heavy metal enrichment in organisms was through the combination with metal binding proteins in the mechanism bodies, such as the metallothionein. Rainbow and White [43] found that the processes involved in the uptake of heavy metals by organisms do not need to consume energy. In addition, since heavy metals are not easily excreted from the body, cumulative toxic effects may occur. Rzymski et al. [44] studied the enrichment of different heavy metals by bivalves, and the results indicated that bivalves have very high enrichment capacities for the heavy metals Cu and Cd. Topcuoglu et al. [45] studied the content levels of heavy metals in aquatic organisms in the Black Sea region of Turkey. The results showed that the heavy metals Pb, Cd, and Cr were the most abundant in mollusks and shellfish, while Fe and Zn were the least abundant.

3.1.2. Early Developmental Toxicity of Organisms. Heavy metals can be very toxic to organisms in the early stages of development. It has been found that during the embryonic and alevin stages of fish, they can be easily injured by heavy metal pollutants. It has been observed that once heavy metals enter the larvae, they can potentially react with nucleic acids, enzymes, vitamins, hormones, and other substances in the organisms and change chemical structures and biological activities. In addition, damage to the functions of such multiple systems as genetic development and endocrine and central nervous system development may occur. These changes may even lead to the disease and death of the affected organisms [46, 47]. García-Alonso et al. [48] found that the embryos and larvae of marine Polychaete Nereis Succinea were more sensitive to Ag, and exposure to $AgNO_3$ had significantly increased the lethality and aberration rates of embryos. In the studies conducted by Munley et al. [49], it was found that the early embryonic growth and egg laying rates of Fruticicolidae were inhibited after exposure to the heavy metals Co, Cu, Pb, and Ni for 28 days and 56 days, respectively. In addition, such heavy metals as Cu, Pb, and Zn have been found to significantly affect the development and hatching rates of the early embryos of aquatic organisms, leading to such consequences as delayed embryonic development [50].

3.1.3. Bio-Immunotoxicity. Heavy metals cause a certain degree of immunotoxicity to aquatic organisms by interfering with the normal function of the aquatic organism's immune organs and immune system. It is generally believed that exposure to low-dose heavy metals or short-term exposure to such metals has immunostimulation effects and can enhance the phagocytic activities of the blood cells in organisms [51, 52]. However, exposure to high-dose heavy metals or long-term exposures can significantly interfere with the phagocytic abilities of biological cells. This is mainly due to the fact that heavy metals have the ability to conjugate with cell membranes during this process, thereby changing the fluidity of the cell membranes and the permeability of ion pumps on cell membranes. The affects will include decreases in the stability of the cell membranes and decreases in phagocytic activities [53, 54]. The results of the studies conducted by Paul et al. [55] indicated immunotoxicity of Pb in freshwater fish. It was observed that Pb interfered with the bacteriophage and cell adhesion of intestinal macrophages. At the same time, the serum content levels of TNF had significantly decreased. Qin et al. [56] reported that heavy metal cadmium exposure negatively affected enzyme activities in crabs (Potamidae). In another related study, Vijayavel et al. [57] showed that Ni exposure promoted the formation and phagocytosis of superoxide anions in the haemolymph of crab but significantly inhibited phenoloxidase activities. The results of the study conducted by

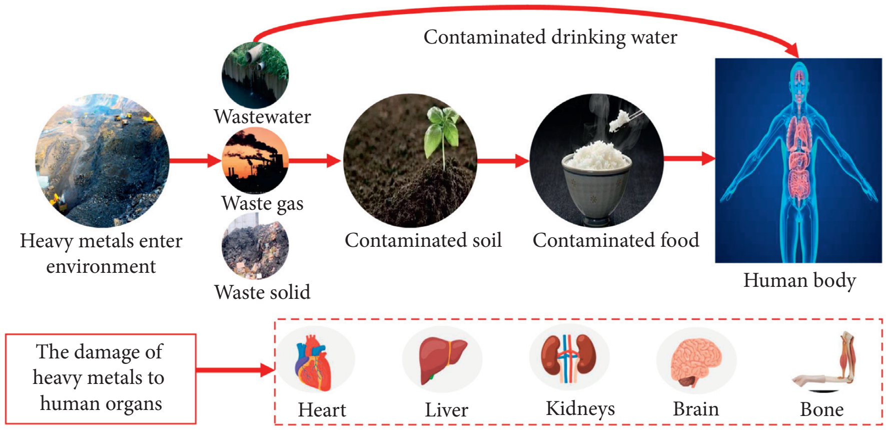

FIGURE 1: Sources of heavy metals and its hazard to the human body.

TABLE 1: Potential toxic effects of heavy metals and the current maximum harmful concentration levels (MCL) and GB3838-2002 in China.

Heavy metal	Hazards	MCL (mg/L)	GB3838-2002 in China (mg/L)	References
As	Cancer of the skin, lungs, bladder, and kidneys; cancer and other internal tumor diseases; vascular diseases and diabetes; infant mortality and weight loss of newborns; hearing loss; developmental abnormalities and neurobehavioral disorders	0.05	0.05	[18–20]
Pb	Anemia; cancer; kidney disease; neurological impairment; mental retardation; mental impairment; and behavioral problems in children	6.0×10^{-3}	0.05	[21–23]
Hg	Damage to the immunity of the renal reproductive system; damage to the blood, cardiovascular, and respiratory systems and the brain	3.0×10^{-5}	1.0×10^{-4}	[24–26]
Cd	Renal cancer damage; bronchiolitis; chronic obstructive pulmonary disease; emphysema; fibrotic bone damage	0.01	5.0×10^{-3}	[27–29]
Cr	Severe diarrhea; vomiting; pulmonary congestion; liver and kidney damage	0.05	0.05	[30–32]
Cu	Increased blood pressure and breathing; kidney and liver damage; convulsions, spasms, vomiting, and even death	0.25	1.0	[21, 33, 34]
Zn	Gastric nausea; skin irritation; spasms; vomiting; and anemia	0.8	1.0	[21, 35]
Se	Gastrointestinal discomforts; hair and nail loss; fatigue; cardiac arrhythmia; and nerve injuries	/	0.01	[36]
Ni	Dry coughing; bone, nose, and lung cancer; shortness of breath; chest tightness and chest pain; nausea and vomiting; dizziness and headache	0.2	/	[37–39]
Sb	Damage to tissue; cancer; inhibition of enzyme activities	6.0×10^{-3}	5.0×10^{-3}	[6, 40]

Chandurvelan et al. revealed that cadmium exposure increased the content of phagocytic basophils and eosinophils in mussels and caused significant DNA damage [58].

3.1.4. Genetic Mutations and Variations. Long-term exposure to water containing heavy metals can also cause mutations and mutations in the genetics of aquatic organisms. It has been determined that once heavy metals enter organisms, they become enriched and concentrated. When the dosage concentrations of heavy metals exceed a certain level or after long-term exposure to heavy metals, damage will result in the tissues and organs of the exposed organisms. In addition, large numbers of reactive oxygen species (ROS) and electrophilic metabolites will be induced, which will then combine with DNA molecules until the cells of the organisms suffer oxidation attacks in their external rings. This will lead to a series of lipid reactions in the organisms, such as peroxidation, alterations of genetic substances, and oxidation of base ribosomes, finally resulting in cell death or the development of cancerous cells [59–61]. Hix and Augusto [62] showed that DNA becomes highly methylated when attacked by large numbers of methyl radicals induced by iron ions. The results obtained by Pfohl-Leszkowicz et al. [63] also showed that heavy metal ions can significantly inhibit methyltransferase activities, and such heavy metal ions as Pb, Cu, and Zn have the ability to inhibit 5-methyltransferase activities. Also, Rossiello et al. [64] found that excessive exposure to Pb can result in low methylation of DNA.

3.1.5. Endocrine Disruption Toxicity. Heavy metals, like other endocrine disruptors, can cause some damage to the endocrine system of aquatic organisms. One of the mechanisms of heavy metal exposure which leads to such metabolic diseases as hypertension and diabetes may be that heavy metals, organochlorine pesticides, and polychlorinated biphenyls are known typical endocrine disruptors, which can interfere with hormone synthesis and secretion and form endocrine disruptive toxicity conditions. For example, the heavy metals Cd, Mn, and Cr may increase the incidence of metabolic disorders. Moreover, exposure to metal endocrine disruptors may increase the risks of oxidative stress and mitochondrial dysfunction [65]. It has further been found that when exposed to sublethal concentrations of lead and cadmium, adult *Micropogonias undulatus* displayed significant increases or decreases in blood steroid concentrations, ovarian steroid secretion activities, and ovarian development [66]. Li et al. [67] found that corticotropin-releasing hormones, thyroglobulin, and the α and β gene expressions of thyroid receptors were significantly induced after minnow larvae were exposed to mercury for four days. Also, the content levels of thyroxine T3 and T4 were observed to have increased.

3.2. Toxicity Effect Mechanisms of Heavy Metals on Aquatic Organisms. Heavy metals can cause certain toxicity to aquatic organisms including animals, plants, and microorganisms. Some aquatic organisms live in environments containing heavy metals for long periods of time. These organisms are able to adjust their physiological and biochemical indicators in order to improve their irritability and tolerance to heavy metals. However, if fish live in water which is polluted by heavy metals for long periods of time, they will produce corresponding proteins and enzymes in their bodies in order to resist heavy metal ions, such as heat shock proteins (HSP), metallothionein (MT), transferrins (TF), glutathione transferase (GT), catalase (CAT), and superoxide dismutase (SOD), thereby reducing the cell damage caused by heavy metal exposure [68].

3.2.1. Toxicity Effect Mechanisms of Heavy Metals on Aquatic Animals. When such harmful heavy metals as Cd and Hg enter organisms, they will compete with other substances in the body. At that time, the sulfhydryl of MT can potentially react with harmful heavy metals and play an antidotal role by discharging harmful substances (such as heavy metals) from the body [69]. It has been determined that SOD can disproportionate superoxide anion radicals to produce H_2O_2, which can then scavenge free radicals which are harmful to organisms. Also, CAT can catalyze H_2O_2 to produce harmless H_2O and O_2. At the same time, it can synergize with SOD and POD to scavenge excess free radicals and peroxides in vivo. Xu et al. [70] found that MT expressions increased after being induced by Cd stress, which in turn resulted in the elimination of hydroxyl and peroxide, and the promotion of the mechanisms which produce stress responses in order to resist oxidation. Chen et al. [71] studied the changes of transferrin content in the livers of *Pseudosciaena crocea* under heavy metal Cd exposure. The results revealed that the Fe ions in the serum of the *Pseudosciaena crocea* had increased rapidly after being treated with heavy metal Cd ions. The maximum value was reached within 24 hours, after which it then slowly decreased and returned to its initial normal value. In another related study, Hansen et al. [72] exposed trout (*Salmo platycephalus*) to water containing Cd and Zn for 15 days and found that the Cd and Zn in the gills of the fish were significantly absorbed. In addition, the Cd levels were found to be significantly correlated with the level of SOD transcription. It has also been observed that aquatic animals secrete abundant mucus when polluted by heavy metals, which tends to improve their tolerance to heavy metals to a certain extent [73].

3.2.2. Toxicity Effect Mechanisms of Heavy Metals on Aquatic Plants. The toxic effects of heavy metals on aquatic plants include cell membrane structural damage; inhibitions of respiration, photosynthesis, growth, and development processes; and toxicity to genetic materials. Heavy metals entering plants can change the autioxidant enzyme activities, induce ROS production, and cause oxidative damage effects. At the same time, heavy metals can interfere with the normal physiological and biochemical reactions [11, 74] of plants by interfering with the activities of transcription factors in some cells and inducing apoptosis, which severely impacts the normal vital activities of the plants. When studying the effects of Cu^{2+} stress on the growth and physiological and biochemical characteristics of *Sargassum hemiphyllum*, Fu et al. [75] found that appropriate concentrations of Cu^{2+} stress ($\leq$0.05 mg/L) had a positive effect on the growth and physiological and biochemical indexes of *Sargassum hemiphyllum*. However, excessive concentrations of Cu^{2+} stress (0.05 mg/L) had negative effects on the growth of *Sargassum hemiphyllum* and its stress resistance abilities. In the studies conducted by Jian et al. [76] regarding the physiological and biochemical characteristics of the wetland plant Ludwigia prostrata under Cd and Pb stress conditions, it was found that the growth rates of the Ludwigia prostrata were significantly inhibited. In addition, the content levels of chlorophyll a, b, and chlorophyll $a + b$ were observed to be decreased with the increases in the heavy metal concentrations, and the effects on the superoxide dismutase activities in Ludwigia prostrata had displayed different trends. The results of another previous study showed that the heights and root numbers of *Oenanthe javanica* were significantly reduced, and the biomass fresh weights were significantly lower, under high concentrations of Cu. At the same time, the content levels of total chlorophyll, chlorophyll a, and soluble proteins displayed downward trends [77]. In addition, the ultrastructure characteristics of the plant cells; permeability, growth, and development of the cell membranes; absorption and metabolism of the water and nutrients; photosynthesis, respiration, and antioxidant enzyme activities in vivo; and the genetic material in vivo were also seriously affected by exposure to heavy metals [78].

3.2.3. Toxicity Effect Mechanisms of Heavy Metals on Aquatic Microorganisms. Bacteria and fungi are common microorganisms in aquatic ecosystems. They are both considered to be decomposers and microconsumers of organisms. They also include primary producers, such as the photosynthetic bacteria of autotrophic bacteria. Microorganisms enhance the suitability of cells to heavy metal stress by secreting secondary metabolites, including organic acids, glycoproteins, and polysaccharides. These extracellular metabolites combine with heavy metal ions to enhance the resistance of cells to stress. However, it has been found that heavy metal ions often cause oxidative damage to organisms, which in turn induces the production of excess oxygen free radicals, destroys the cell membranes of organisms, and damage the normal respiratory metabolic pathways of organisms [79]. Zhang et al. [79] examined the toxicity of heavy metals to Vibrio Qinghaiensis Q67 in the Fuyang River. It was found that the heavy metal ions inhibited the activities of reduced flavin mononucleotides and oxidized flavin mononucleotides, resulting in the transformations between them becoming abnormal. Xu [80] used white rot fungi to adsorb heavy metals, and the results showed that high concentrations of Cd stress had significantly inhibited the growth of *P. chrysosporium*, as well as causing changes in the mycelium morphology and decreases in lignin degrading enzymes (LiP and MNP). Zhou et al. [81] used the recombinant luminescent bacterium *E. coli* HB101 pUCD607 to study the singular toxicity of Zn^{2+}, Cu^{2+}, and Hg^{2+} and the combined toxicity of binary mixing systems. The experimental results showed that the sequence of toxicity of single heavy metal ions to recombinant luminescent bacterium was $Hg^{2+} > Zn^{2+} > Cu^{2+}$.

4. Water Quality Criteria of Heavy Metals for Aquatic Organisms in China

The aim of water quality criteria for aquatic organisms is to protect aquatic organisms from not have long-term or short-term adverse or harmful effects exposed to the maximum allowable concentrations of pollutants in water environments. At the present time, the two most representative international water quality criteria systems are those of the United States and the European Union. In the United States, the current water quality criteria guidance system has adopted a toxicity percentage ranking method and is considered to be a dual-value criteria system [6]. The criteria values obtained using this type of method include the criteria maximum concentration (CMC) and the criteria continuous concentration (CCC). The European Union determined its water quality criteria system by deducing the predicted no effect concentration (PNEC) [82]. In addition to the aforementioned two mainstream water quality criteria systems of the United States and the European Union, the Netherlands, Canada, Australia, and New Zealand have also developed their own respective water quality criteria programmatic documents. In China, research regarding water quality criteria started relatively late, and the initial research had only involved the collection and collation of foreign data. However, in recent years, many domestic researchers have carried out corresponding studies on water quality criteria specifically for China and have focused major attention on the aquatic biological water quality criteria of heavy metals. In this study, heavy metals copper, zinc, lead, and chromium were taken as examples to review the research progress of water quality standards for heavy metals in China.

4.1. Copper. Copper is an essential trace element for life and also one of the main elements of heavy metal pollution in water. The copper found in water mainly originates from atmospheric deposition, agricultural runoff, copper sulfate usage to control algae blooms, and the direct discharge of copper-containing industrial wastewater. Generally speaking, copper is more toxic to aquatic organisms than to humans and other terrestrial organisms, especially water fleas [83]. The toxicity of copper in natural water varies with the changes in hydrochemical properties. Although many soluble components contribute to the improvements of copper toxicity in freshwater, the main controlling factors include calcium, pH, and dissolved organic matter (DOM). These substances affect the gills of the competing cations and are related to copper toxicity through a series of geochemical processes which form various complexes in all directions. These are considered to be inferior to noncomplex biological/toxic metal ions (such as Cu^{2+}). Specifically, copper tends to be found in harder type water bodies (e.g., water bodies with higher DOM content). Calcium hardness comes from the weathering effects of rock-forming minerals (mainly carbonate rock and feldspar). Meanwhile, DOM is mainly derived from the decomposition of terrestrial and aquatic vegetation and biota [84]. There are corresponding reports currently available regarding the research conducted on the freshwater aquatic biological benchmarks of copper in China. For example, Wu et al. [85] collected and screened biological species in freshwater locations and the corresponding toxicity data by taking the freshwater aquatic ecosystems in China as the protected objects. The freshwater biological water quality criteria of copper in China were deduced by adopting an internationally accepted evaluation factor method, toxicity percentage ranking method, and a species sensitivity distribution method [6, 86, 87]. The results indicated that the baseline value of copper obtained using the evaluation factor method was 2.00 μg/L. The CMC and CCC of copper obtained using the toxicity percentage ranking method were 9.10 and 5.63 μg/L, respectively. The short-term and long-term dangerous concentrations of copper which would result in the protection of 95% of the species obtained using the SSD method were 30.0 and 9.44 μg/L, respectively. It was found that there were some differences in the water quality criteria values of copper obtained using the aforementioned three methods. The comparative analysis results indicated that an SSD method should be recommended as the preferred method for copper benchmark deduction in China.

4.2. Zinc. Zinc is widely distributed throughout nature, and it is an essential trace element for life. However, when the concentrations of zinc exceed a certain level, it will produce certain toxicity effects on organisms. Many countries throughout the world have studied the toxicity of zinc and formulated corresponding criteria or standards [88–90]. The average daily intake of Zinc from dietary sources is approximately 10 to 15 mg, and the adult body contains approximately 2 to 3 g of zinc. Due to the low demand for zinc in organisms, when zinc concentrations exceed the requirements, it will become a harmful substance and produce certain toxic effects. Furthermore, since zinc is far more toxic to aquatic organisms than to humans, the water quality criteria of zinc developed by various countries tend to be quite different. For example, in the newly issued criteria document of zinc issued by the EPA (US), the freshwater aquatic biological criterion of zinc is 120 μg/L. Meanwhile, the human health protection standards are 7,400 μg/L (potable water + aquatic organisms) and 26,000 μg/L (only portable aquatic organisms). However, China's current water quality standards do not correspond with China's water environment characteristics [11, 91]. For example, the five types of zinc standards in the GB 3838-2002 Surface Water Environmental Quality Standard [92] are 50, 1000, 1000, 2000, and 2000 μg/L, respectively, and the standard value of zinc in the GB 11607-89 Fishery Water Quality Standard [93] is 100 μg/L. Wu et al. [94] collected and collated the biological species and toxicity data in freshwater areas in China. The water quality criterion of zinc for the protection of freshwater aquatic organisms in China was deduced according to several commonly used methods, including an evaluation factor method, toxicity percentage ranking method, and SSD method. The results showed that there were significant differences in the sensitivities of different organisms to zinc toxicity. For example, crustaceans had the strongest sensitivity and amphibians had the weakest sensitivity. The order of sensitivity was determined to be as follows: crustaceans > other species > fish > amphibians. Finally, it was recommended that the criteria value obtained using a toxicity percentage ranking method should be the water quality criteria value of zinc. Currently, the CMC and CCC of Zn are 89.7 and 34.5 μg/L, respectively. At the same time, based on the different species sensitivity levels, the acute biological criteria values for protecting fish, crustaceans, and other invertebrates were determined to be 298.9, 67.3, and 76.9 μg/L, respectively, and the chronic biological criteria values were 36.9, 12.9, and 14.8 μg/L, respectively.

4.3. Lead. Heavy metals such as lead in drinking water are harmful to humans. To protect consumers, the maximum allowable concentration of lead in water has been established. Lead can cause nerve damage even when exposed to low levels of lead, especially in infants and children [95]. As a nonessential element in plant metabolism, the toxicity of lead is usually related to physiological processes, in which it interferes with the normal functions of cells to organs, including seed germination and delayed growth, water deficiency, nutritional disorders, and reduced photosynthesis, respiration, and transpiration processes [96–98]. It is known that exposure to lead can also result in the excessive production of reactive oxygen species (ROS) which potentially destroy membranes, lipids, nucleic acids, and proteins [97, 98]. In addition, the toxicity of lead is partly dependent on its biological activities, which are related to the subcellular distributions and chemical forms of plant cells [96]. For plants, the toxicity effects of lead are dependent on the concentrations and type of lead, exposure times, and the ecological types and plant species involved [99, 100]. Even very small dosages can be toxic to organisms [101]. Although the concentrations of lead in water usually do not exceed 0.6 μmol/L [102], there have also been reports of high exposure concentrations (e.g., 4.3 μmol/L) [103]. Therefore, it is of major significance to study the lead aquatic biological criteria which are suitable for the water environments of river basins in China for the protection of freshwater aquatic organisms. Kieber et al. [104] collected and screened 25 acute toxicity data cases of lead in freshwater organisms in China. In the present study, the aquatic biological criteria technology methods of the United States were used for the estimations of the aquatic biological criteria of lead in order to calculate the aquatic biological criteria of lead for freshwater organisms in China. It was determined that the criteria for lead should be 0.131 mg/L, with a chronic criterion of 0.0051 mg/L. At the same time, the criteria calculation technology of the Netherlands and Australia-New Zealand was utilized to compare the criteria calculation results. The results indicated that the criteria calculation method of the United States was relatively feasible. An ecological risk assessment for lead exposure in the Liao he River Basin was carried out using the obtained lead criteria values. The results revealed that there were certain ecological risks of lead exposure throughout most of the area.

4.4. Chromium. Hexavalent chromium (Cr^{6+}) is a typical transition metal pollutant found in wastewater which results from electroplating, leather tanning, or pigment manufacturing [105]. Cr^{6+} is a strong oxidant with cytotoxicity, mutagenicity, and carcinogenicity, which causes serious pollution effects in manufacturing wastewater. Excessive exposure to chromium may result in serious damage to many aquatic organisms, carcinogenic effects in humans, and skin irritations and corrosion [106]. Therefore, many countries rank it as a priority to control such toxic pollutants and stipulate that the maximum permissible concentration in drinking water is 50 μg/L. The two valence states of Cr, Cr^{3+} and Cr^{6+}, are stable in the environment and known to have different properties. It has been found that appropriate amounts of Cr^{3+} can reduce blood sugar concentrations in human plasma, improve insulin activities, promote sugar and fat metabolism, and enhance the stress response abilities of the human body. However, Cr^{6+} is a powerful oxidant known to have strong carcinogenic, teratogenic, and mutagenic effects. It is considered to be highly harmful to organisms [107]. It is generally believed that the toxicity of Cr^{6+} is 100 times higher than that of trivalent Cr. It is precisely because of its serious biological toxicity effects that the research regarding the toxicity of hexavalent chromium has received major attention. Liao et al. [108] screened China's widespread freshwater aquatic biological species and collected the existing acute and chronic toxicity data. Then, by combining with the local toxicity data obtained in this research group's experiments, a species sensitivity ranking method, SSD method, and Australia's water quality criteria technology were used to deduce the freshwater aquatic biosafety criteria of Cr^{6+} in China [109]. Then, the double-

Table 2: Comparison of water quality criteria of heavy metals in China and the US EPA [12, 91].

Heavy metal	China (μg/L)		US EPA (μg/L)	
	Acute	Chronic	CMC	CCC
Zn	89.7	34.5	120	120
Cd	2.10–7.30	0.21–0.23	2	0.25
Cr	45.79	14.22	16	11
Cu	30	9.44	12	9
Hg	1.743	0.467	1.4	0.77
Pb	131	5.1	67.54	25.46

value criteria for Cr^{6+} in the freshwater aquatic organisms of China were obtained. The CMC of Cr^{6+} obtained using the three methods were 23.97, 22.84, and 29.06 μg/L, and the CCC were 14.63, 10.35, and 9.00 μg/L, respectively. On the same order of magnitude, there were some differences observed when compared with the criteria values of the United States. Therefore, it was suggested that the criteria values should be used to deduce the CMC and CCC values.

The water quality criteria of several common heavy metals in China and US EPA are shown in Table 2. By comparing with the corresponding heavy metal water quality standards of the two countries, it is found that there is a certain difference in the values of the two countries' benchmark values, which is mainly caused by the differences in biota, water quality, and species between the two countries. Therefore, water quality parameters, species distribution, and geographical factors should be considered when formulating water quality benchmarks, and it is recommended to use the BLM model.

5. Conclusions and Prospects

At the present time, experts and researchers around the world have completed a great deal of valuable research regarding the toxic effects and mechanisms of heavy metals. As a result, major achievements have been reached in the field of effective water environment quality standard systems. However, the current water quality standards in China do not efficiently combine with the characteristics of the actual water environments of the country. Currently, the toxicity effect mechanisms of heavy metals on aquatic organisms are not consistency and not comprehensive, systematic studies have not been carried out on the construction of a water environment criteria system specifically for China's national situation. Therefore, it was necessary in this study to propose an effective water quality criteria system for China on the basis of insights obtained from the mature experiences of other countries. In future research endeavors, the following points will need to be considered.

(1) Water environmental factors such as temperature, hardness, and pH will affect the toxicity of metals; besides, emerging pollutants, such as antibiotics, microplastics (MP), endocrine disruptors (BPs), and personal care products (PPCPs), are known to be entering water bodies to form more complex systems with heavy metals, such as particulate matter and DOM. Therefore, analyses of the corresponding toxic effects of these new types of pollutants and the subsequent impacts of the current water quality criteria should be the focus of future research; the BLM model should be considered in the derivation process of water quality criteria.

(2) Some heavy metals found in the environment may be trace metals. However, whether or not the toxic effects of heavy metals occur during the processes of migration or transformation should be continuously tracked. In addition, corresponding models should be established to monitor, predict, and evaluate the toxic changes of heavy metals in ecosystems.

(3) A set of systematic theories and methodologies is needed for the study of China's water quality criteria and standards. In future water quality criteria research, its theory and methodology should be continuously explored, as well as systematically studying the key scientific problems of the existing water quality criteria, in order to form a guideline document suitable for China's national conditions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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