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ENVIRONMENTAL QUALITY BENCHMARKS FOR AQUATIC ECOSYSTEM PROTECTION: DERIVATION AND APPLICATION

Amendment of water quality standards in China: viewpoint on strategic considerations

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Abstract Water quality standards (WQS) are the most important tool for protection of quality of aquatic environments in China and play a decisive role in the management of China's aquatic environments. Due to limited scientific information available previously, WQS were developed largely based on water quality criteria (WQC) or WQS recommended by developed countries, which may not be suitable for current circumstances in China. The Chinese government recently initiated the revision of Environmental Quality Standards for Surface Water (EQSSW) (GB3838-2002) to meet the challenge of environmental protection. This review analyzed how the WQS developed and applied in China differ from those of more developed countries and pointed out that the lack of strong scientific bases for China's WQC pose major limitations of current WQS. We focus on discussing the six aspects that require high attention on how to establish a national WQC system to support the revision of WQS (Table 1) such as development of methodology, refining water function zoning, establish priority pollutants list, improving protection drinking water sources, development of site-specific water quality criteria, and field toxicity test. It is essential that China and other developing countries established a relatively mature system for promulgating, applying, and enforcing WQC and to implement a dynamic system to incorporate most recent research results into periodically updated WQS.

Keywords Water quality standards · Water quality criteria · Amendment · Environmental management

Introduction

Water quality standards (WQS) are the legal limits of pollutants set by national environmental protection agencies and play an important role in the evaluation of quality of waters, environmental emergency response, pollution control, and effective management of risks for humans and the environment. The Water Quality Standards (GB3838-2002) (hereafter referred to as the current WQS) are the main standards for protection of aquatic environments in China (Liu et al. 2008; Zhang et al. 2010a, b). They apply to surface waters with functional uses, including rivers, lakes, canals, channels, and reservoirs and are critical in the management and protection of China's aquatic environments. The current WQS are also the basis for setting emission standards and have close relationships with various standards, such as those for seawater, fisheries waters, irrigation water, and ground water.

Most developed countries have placed priority on WQS, and they have established a relatively mature system for establishing and enforcing water quality criteria (WQC) and implementing a dynamic system of amendments to incorporate the most recent research results into periodically updated WQS or WQC (Meng et al. 2010). The United States Environmental Protection Agency (USEPA) was one of the first countries to research WQC and published the *Green Book* (WQC) in 1968; supplements have been added and improvements made several times since. WQC documents, such as the *Blue Book*, the *Red Book*, and the *Gold Book* were

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Table 1 The improvement of the fourth amendment of WQS in China

	Current standards (GB3838-2002)	After the fourth amendment
WQC and its methodology	The current *Standards* are largely based on DWHS of China or WQC or WQS published by more industrially developed countries	The WQS is established basing on the national WQC system that developed with native species by using SSD or AF method, even relative models (e.g., QSAR, BLM)
Priority pollutants list	The current WQS contains 68 priority pollutants (black list), which were deduced in 1991	Some emerging pollutants should be listed such as nutrients, hormone analogs on the basis of the current priority pollutants with updated the screening method
Water function zoning	The regulation is conducted practically based on the boundary of city or province without considering the integrality of watershed, the sensitivity of aquatic organisms, hydrology and so on	Implement water function zoning and regulation based on the types of pollutions, water condition, sensitivity of species, distribution of factories, hydrological features
Protection of drinking water sources	Aims to human health without for the protection of aquatic organism; regulation with unified standards, without consideration of the regional differences	More emphasize the protection of sensitive species, and nvironmental loads of pollutant are developed based on its WQC values
Field toxicity test	No information	WQC are deduced by in situ water conditions and local species to recheck the reliability of current WQS values
Site-Specific water quality criteria	No information	Conducted additional toxicity test with local species in order to protect those water bodies with vulnerable ecosystems or endangered species or more variable condition

subsequently issued sequentially to update methods for developing WQC as well as specific WQC (Stephen et al. 1985). In 2000, USEPA issued the *Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health* (USEPA 2000), which systematically introduced methods for derivation of WQC for protection of human health. In the following years, USEPA further amended the Water Criteria Guidelines of the United States (USEPA 2006, 2009). After 2000, Canada (CCME 2007), Australia and New Zealand (ANZECC and ARMCANZ 2000), the European Union (ECB 2003), the Netherlands (Verbruggen 2007), and the World Health Organization (WHO 2008) also issued or amended their respective WQC documents.

China's WQS were first established in the 1980s and amended over the past three decades to serve for the environmental management and protection in China. However, even so, the dramatic economic development of China and weak awareness of environmental protection both resulted in the growing environmental pollution in recent decades (Economy 2011; Liu and Diamond 2005). Thus, although a series of regulation for reduction of environmental pollution were implemented by Chinese government, it appears to have little effect, which to some extent indicated a dilemma for the environmental regulation in China (Jin et al. 2014a; Liu and Diamond 2005; Peng and Bao 2006). The current WQS were established mainly by referring to and drawing on the experience of others in setting environmental criteria and standards, including the US and WHO (Table 2) and other values are from *Drinking Water Health Standards* (DWHSs) of China (Jin et al. 2009). Therefore, it is not a suitable long-term or strategic approach, given the fundamental differences of the geographic, regional, eco-environmental, and socio-economic characteristics between China and those developed countries, including ecosystem structures and functions, sensitive aquatic organisms, economic conditions, and living habits, in which pollutants represent the highest priorities and what combinations of pollutants might occur (Wu et al. 2010; Zhenguang et al. 2013). Since derivations of criteria are influenced by all these factors, it is questionable whether the current standards provide appropriate protection to the ambient water environment in China (Meng et al. 2010; Wu et al. 2008). Additionally, the national unified standard values did not consider regional differences in background concentrations or basic properties such as hardness and alkalinity or amount of dissolved organic carbon or numerical nutrient criteria (Hu et al. 2013). Therefore, the WQS were not established based on sound scientific experimental methods or data, and therefore fail to address current magnitudes and types of environmental pollution in Chinese surface waters. Moreover, with changes in the economic and social situation as well as conditions in aquatic environments and management objectives, as well as scientific and technological development in the water environment field, it has become urgent to revise the current WQS to meet management demands (Cyranoski 2009; Fu 2008; Liu 2010; Wang 2010). Therefore, a new version of WQS, which accurately and objectively protect aquatic

Table 2 Similarities between China's water quality standard and the US and WHO water quality criteria (mg L^{-1})

Pollutants	USEPA human health for consumption of water + organism (2014)	China's environmental quality standard for surface water (GB 3838-2002)	China's sanitary standard for drinking water (GB 5749-2006)	WHO (3rd) guidelines for drinking water quality (2004)
Selenium	0.17	0.01	0.01	0.01
Arsenic	0.0002	0.05	0.01	0.01
Chromium (VI)	0.1	0.05	0.05	0.05
Lead	–	0.01	0.01	0.01
Methylene chloride	0.008	0.02	0.02	0.02
1,2-Dichloroethane	0.00029	0.03	0.03	0.03
Tetrachloroethylene	0.01	0.04	0.04	0.04
Hexachlorobutadiene	0.000008	0.0006	0.0006	0.0006
Benzene	0.45–1.6	0.01	0.01	0.01
Bis(2-ethylhexyl)phthalate	0.000028	0.008	0.008	0.008
Toluene	0.3	0.7	0.7	0.7
Ethylbenzene	0.4	0.3	0.3	0.3
1,2-Dichlorobenzene	0.7	1	1	1
1,4-Dichlorobenzene	0.2	0.3	0.3	0.3
Nitrobenzene	0.01	0.017	0.017	–
Asbestos (>10 μm, million L^{-1})	7	–	700	–
Nitrates	10	10	10	–
Iron	–	0.3	0.3	–
Boron	–	0.5	0.5	0.5
Barium	1	0.7	0.7	0.7
Chlorpyrifos	–	–	0.03	0.03
2,4-D[b]	0.0000378–0.1	–	0.03	0.03
Styrene	–	0.02	0.02	0.02
Acrylamide	–	0.0005	0.0005	0.0005
DDT	7.2E−09	0.001	0.001	0.001
γ-BHC (lindane)	0.00098	0.002	0.002	0.002
1,2-Dichloroethylene	0.1	0.05	0.05	0.05
Xylene	–	0.5	0.5	0.5
Pentachlorophenol	0.00002	0.009	0.009	0.009
Microcystin-LR	–	0.001	0.001	0.001
Molybdenum	–	0.07	0.07	0.07
Bromate	–	–	0.01	0.01
Chlorite	–	–	0.7	0.7
Chlorate	–	–	0.7	0.7
Cyanogen chloride	–	–	0.07	0.07
Dichloroacetic acid	–	–	0.05	0.05
Carbofuran	–	–	0.007	0.007
Atrazine	–	–	0.002	0.002
2,4,6-Trichloro phenol	0.0014	–	0.2	0.2
Epichlorohydrin	–	0.02	0.0004	0.0004

[a] Means no limited value is given

[b] 2,4-Dichlorophenol 0.01; 2,4-dimethylphenol 0.1; 2,4-dinitrophenol 0.01; 2,4-dinitrotoluene 0.0000378 mg L^{-1}

environments in China and meet needs of regional water pollution control authorities, are in order.

However, until recently, there has been no systematic research to establish a national WQC system in China due to the lack of fundamental research in this field. Fortunately, learning from the experiences in dynamic amendments of WQS by many developed countries, the amendment of environmental aquatic criteria will also attempt to attain balance between environmental protection and socio-economic development of China. Therefore, key question surrounding the process of amending WQS for China is how to objectively evaluate the current WQS so that the subsequent amended WQS are better suited for current socio-economic and environmental conditions and lead to reduction of pollution and effective, rational, and cost-effective remediation technologies.

In this review, how the current WQS of China differ from those of more developed countries, which were the core of the previous environmental management system in China, were evaluated, and the lack of scientific rigor in development of WQC specific to China was a major issue with the current WQS strategic considerations on how to establish a national WQC system to support in the revision of WQS are provided. The proposed comprehensive and systematic research for development of a basis for China's WQC will provide scientific and technological support for the amendment, as well as a reference for the other developing countries.

Basic framework of the current WQS

Over the past three decades, the current WQS have served as a critical cornerstone for law enforcement and management related to aquatic environments. The current WQS have provided intermediate targets to address water quality in successive 5-year plans. The result has been continuously improving water quality even though there has been continuous development of industry over this period. The basic items of the EQSSW apply to defined surface waters with designated uses, such as rivers, lakes, canals, channels, and reservoirs across the country. Supplementary changes have specified items of surface sources of centralized drinking water and apply only to those waters. The current version (GB3838-2002) contains 109 control items, including 24 basic items and 85 items pertaining to centralized drinking water sources. Like in some other countries, different water quality criteria are established for various levels of protection for different classified uses of water. The WQS were formulated according to primary uses of water bodies in China. For instance, there are functions which need higher quality water and those for which water of lesser quality are acceptable. The 24 basic items are divided into grades I–V, which refer to national nature reserves, key zones for protection of surface drinking water, surface drinking water sources, industrial/recreational water, and agricultural/landscape water, respectively. The current WQS cover pollutants more commonly observed in surface waters and generally match scopes adopted in developed countries.

However, there have been some limitations associated with limit values specified by the current WQS. For example, 40 limits listed in the current WQS adopted values given by the US criteria or guidelines set by WHO. Additionally, 14 of the limits for 16 priority pollutants were the same as those published in the WHO guidelines (Table 2) (Jin et al. 2009; Wu et al. 2010). Given the diversity of bio-sensitivity in different biotas, the adopted WQC may not be suitable to fully protect the most sensitive species in Chinese fresh waters. For many priority pollutants, the WQC are more rigorous than those specified by WHO or USEPA. For instance, the Chinese standard value of dibutylphthalate (0.003 mg L^{-1}) is stricter than the two classes of WQC values for protecting human health provided by the USEPA or consuming water and organism (2 mg L^{-1}) and only consuming organism (4.5 mg L^{-1}) without any supporting information (Table 3). The standard value of diethyl phthalate (0.3 mg L^{-1}) is also stricter than that provided by USEPA (17 mg L^{-1} for consuming water and organism and 44 mg L^{-1} for consuming only organism). As a result, based on these too rigorous standards, the desired results in protection of water bodies are difficult to achieve, so these standards should be re-evaluated and amended.

Existing limitations and challenge

Formulating a unified WQS for surface waters across China's vast territory and many natural zones, each with their distinct characteristics, is a difficult task. The environmental standards of many other countries around the world are established according to their environmental criteria, reflecting their respective national conditions and regional characteristics, such as pollution sources, biota, geological geography, environmental factors, and social and economic conditions (Wu et al. 2010). In a developing country, like China, which lacks historical perspective and a mature research establishment on environmental criteria, the current WQS were derived from and/or based on environmental criteria or standards of developed countries were adopted (Wu et al. 2010). Although the current WQS were not completely in conformity with China's actual pollution control conditions, they undoubtedly produced positive outcomes when applied in China during the early stages of social development when environmental protection was in its infancy (Li et al. 2012). With increasing intensity and diversity of industrial capacity and resulting contamination of the environment as well as evolution of awareness of and philosophies towards quality of the environment by the Chinese government, some inherent limitations of the current WQS have become increasingly clear. Specifically, there are several principal limitations: (1) compared with the developed countries, China is suffering not only from a wide variety of high-concentration pollutants but also from environmental

Table 3 Differences between China's water quality standards and the US and WHO water quality criteria (mg L^{-1})

Pollutants	USEPA (2013) Human health for consumption of		China's EQSSW (GB 3838-2002)	China's DWHSs (GB 5749-2006)	WHO (3rd) guidelines for drinking water quality (2004)
	water+organism	organism only			
Copper	1.3	–[a]	1(III)	1	2
Zinc	7.4	26	1(III)	1	–
Mercury	–	–	0.0001(III)	0.001	0.006
Acrolein	0.003	0.4	0.1	0.1	–
Di-*n*-butyl phthalate	0.2	0.4	0.003	0.003	–
1,1-Dichloroethylene	0.2	4	0.03	0.03	–
Antimony	0.0056	0.64	0.005	0.005	0.02
Nickel	0.61	4.6	0.02	0.02	0.07
Thallium	0.00024	0.00047	0.0001	0.0001	–
Silver	–	–	–	0.05	–
Diethyl phthalate	4	90	–	0.3	–
Chloride	–	–	250	250	–
Parathion	–	–	0.003	0.003	–
Malathion	–	–	0.05	25	–
Demeton	–	–	0.03	–	–
Aluminum	–	–	–	0.2	–
pH	5–9	–	6–9	≥6.5 ≤8.5	–
Methylmercury	–	$0.3\ \text{mg kg}^{-1}$	1.0×10^{-6}	–	–

[a] Means no limited value is given

problem of new and conventional pollutants coexisting (Zhang et al. 2010a, b); (2) moreover, the environmental protection in China starts late, and the research on the fundamental theory of water quality criteria is seriously deficient (Meng et al. 2010); (3) the currently applicable standard method in China only includes the acute toxicity test method for the photogenic bacterium, daphnia magna, zebra fish and scenedesmus without considering the difference of species sensitivity in different areas, so it is necessary to draw experience of the developed countries to develop the standardized test method in China (Jin et al. 2009; Zheng et al. 2016); (4) due to the difference in industrial structure between China and foreign countries, the content of some pollutants (such as pesticides) is high in the surface water of China (Zheng et al. 2016). Due to the deficiency of toxicity data, it is very difficult to develop the water quality criteria, let alone the development of site-specific water quality criteria; (5) some chemical indexes, such as dissolved oxygen (DO), biochemical oxygen demand (BOD), chemical oxygen demand (COD), are employed to regulate water quality in the current WQS. However, as comprehensive indicators of organic contaminants in the water, such indexes could hardly protect aquatic organism directly, especially for these sensitive species ; (6) in the current WQS of China, approximately 50 % of analytical methods developed before 2001, even in the 1980s, due to the limited analytical measures then, which cannot afford the protection of water quality at the moment of pollution boom in China (Liu and Diamond 2005; MEPPRC 2002). They attempt to apply one set of limits regardless of whether they are intended to protect humans or aquatic organisms. The current WQS stipulate that water bodies classified as water grades II and III can be used as source water for centralized drinking water supply and fisheries. But the same limits can hardly encompass the requirements for protection of both human health and sustainable populations of aquatic organisms. For example, current Zn standards stipulate a value of 0.05 mg L^{-1} for water grade I (national nature reserves), 1.0 mg L^{-1} for water grades II and III (key zones for protection of surface drinking water and habitat for rare aquatic organisms), and 2.0 mg L^{-1} for water grades IV and V (industrial/recreation water and agricultural/landscape water). Zn is an essential trace element, but it can cause adverse effects to aquatic organisms. The criterion for Zn set by the USEPA to protect fresh water aquatic organisms is 0.120 mg L^{-1}, whereas it is 26.0 mg L^{-1} to protect human health, with the criterion for protecting human health greater than that for protection of aquatic organisms. Acute and chronic criteria for Zn derived to protect fresh water aquatic organisms in China are 0.09 and

0.035 mg L^{-1}, respectively, whereas it is 20.8 mg L^{-1} to protect human health (Wu et al. 2011a). If standard values of water grades II and III are set so as to protect aquatic organisms, they will be too rigorous for protection of sources water of drinking water (Koukouzika and Dimitriadis 2005; Poynton et al. 2007). Another example is Cu, values for water grades II and III in the *Standards* are both 1.0 mg L^{-1}, whereas based on the species sensitivity distribution method a value of 0.009 mg L^{-1} was derived (Wu et al. 2011b). Obviously, limits for Cu do not adequately protect aquatic organisms. Thus, one set of limitations of applying the same level of protection cannot provide full protection for humans and aquatic organisms.

Due to the lack of an explicit scientific basis that relates to China, some limit values given by the WQS have considerable uncertainty associated with them. Due to a lack of data describing exposures and risks of chemicals to health of humans or ecological receptors and basic toxicological information, previously the WQS were not developed based on an assessment of risk. Without convincing evidence, it is difficult to reconcile these discrepancies. For example, the limit for Ni is 13-fold less than that recommended by the USEPA. For some pollutants included in the current WQS, no recommended value has been provided by the USA or WHO. For instance, WHO has not provided recommended values for silver (Ag) and the non-priority pollutant aluminum (Al) due to the lack data on toxicity to humans. In the current WQS, values for COD, Mn for water grades I, II, III, IV, and V are 2.0, 4.0, 6.0, 10.0, and 15.0 mg L^{-1} respectively; these are not based on scientific data but rather on subjective experience.

Strategic considerations on how to establish a national WQC system

Appropriate strategies must be established before subsequent stepwise amendments are implemented. Development of a national WQC system suitable for the various regional characteristics across China to support the amendment process is a prerequisite; specifically, several issues must be addressed (Fig. 1).

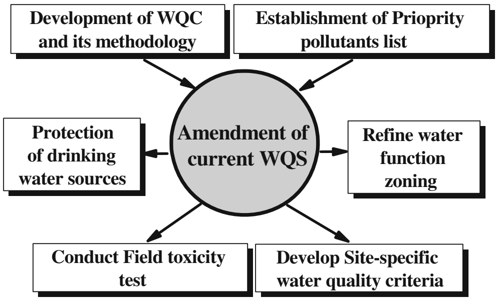

Fig. 1 The sketch map of amendment of current WQS

Development of water quality criteria methodology

The methodology is the foundation to develop WQC, and many developed countries have established the WQC and assessment method suitable to their own development in accordance with their own geographic climate conditions, ecosystem characteristics, and pollutant discharge status (Alabaster and Lloyd 2013; Wilhm and Dorris 1968). The history of amendments to WQS in the EU or USA, which were based on internationally accepted methodologies and theories, suggested that improvements in theories and methodologies have been a driving force behind evolution of WQC. Establishment of a completely novel methodology would be costly and time consuming (Jin et al. 2014a). Development of WQC in China should make use of experiences, theories and methodologies developed in other jurisdictions; for example, the development of the current WQS was mainly based on WQC established by the USA during 1980–2000 (Zhang et al. 2010a, b). With the accumulation of environmental research, the USA has continuously revised WQC with the latest released in 2013. For instance, for NH_3-N, the standards set the chronic criterion value as 0.91 mg L^{-1}, based on the limits for the protection of fresh water aquatic organisms, while it was revised to 1.9 mg L^{-1} by the USA in 2013 (USEPA 2013) .

Comparing with other countries, the USA has established its relatively developed WQC and research method system after decades of research and experience accumulation. For instance, in order to prevent the pollutants from causing hazards to the aquatic organism under the short-term and long-term conditions, the USA respectively adopted the criteria maximum concentration (CMC) and criteria continuous concentration (CCC) to protect the water quality condition. In order to guarantee reliability of criteria value and avoid occurrence of under-protection and over-protection, the toxicity data should incorporate at least three phyla and eight families during derivation of the CCC and CMC (USEPA 1985), and it is also recommended to adopt the derivation methods based on statistic analysis, such as the toxicity percentile ranking method, and species sensitivity distribution. In order to fully protect aquatic products and food safety of aquatic products during selection of evaluation indexes, the USA adopted the final acute value, final chronic value, final plant value, and final residual value to comprehensively consider the toxicity effect of pollutant. In the water environmental management, it is required that the frequency that the 4-day average concentration of targeted pollutant in water body exceeding the CCC should not be more than one time in 3 years, which can guarantee the ecological restoration of water ecosystem. In contrast, the derivation of water quality criteria in the European Union is more conservative. According to the requirements of the "the Technical Guidelines document" issued by the European Union in 2003, the predicted no effect concentration

(PNEC) should be calculated by using the species sensitivity distribution (SSD) or assessment factor (AF) on the basis of minimal 10 no observed effect concentrations (NOEC) of at least 8 different organisms. When more than one sensitive toxicity values were collected for one species, the toxicity values with the similar experiment conditions to local water quality should be selected (ECB 2003). The WQC of Netherlands greatly differs from that of the USA, although the deduction method of Netherlands is similar with that adopted in the USA and it is only required that the minimum number of species for calculating WQC should not be less than 5, but the identification of acute toxicity value or chronic toxicity value of specific organism should be based on the life cycle of the organism, which properly protects some organism with short life cycle and high sensitivity for pollutants, and hence reasonably protects the biological diversity (NIPHE 2001). There are also some other countries such as Japan, Australia, Canada, and New Zealand using the SSD and AF methods to develop WQC, but they mostly decide the final criteria value on the basis of their own water ecosystem characteristics and difficulty degree of protection. For example, there are few rivers in New Zealand, Japan, and Australia, and pollutants are mostly concentrated in the coastal cities, so relatively lower criteria values are used in protection of water body. However, they pay less attention to the impact of water environmental factors (such as suspended particles, and TOC) on the pollutant toxicity, even though many researchers have proven that environmental factors have significant impact on the toxicity of some pollutants.

The quality and quantity of toxicity data are the bases for deriving WQC. The toxicity data for WQC can be obtained from various sources such as published literatures, toxicity databases, governmental reports, survey documents. However, the sources largely decide the necessity of the toxicity data screening and evaluation process (Meng and Wu 2010). The reliability and relevance are two factors applied by many countries to evaluate the quality of available toxicity data (Jin et al. 2014b). Reliability refers to the toxicity tests conducted based on the standard test methods (e.g., ASTM, OECD) and also includes well-recorded relevant experimental parameters (e.g., chemical properties, the detail information of tested organisms, exposure types, water index, exposure duration, effect endpoint, does-effect relationship). The relevance refers to the extent a test that reflects the ecologically significant hazards; and the toxicity data that describe the toxicity effect related to survival, development, and reproduction generally are identified as qualified data; however, the test conducted at tissue or sub-cellular scale should be excluded (e.g., enzyme induction, gene expression) due to their little ecological significance (ANZECC and ARMCANZ 2000; European-Communities 2011; NIPHE 2001; USEPA 1985). Although the similar sensitivity for different biota reported by some researches, to some extent, weaken the contribution of environmental factors to toxicity effect of organism, there are still multifarious toxicity mechanisms of different chemicals to species and the characteristics of different bio-systems (Dyer et al. 1997; Jin et al. 2011; Jin et al. 2012b; Maltby et al. 2002; Maltby et al. 2005). Therefore, native species and the invasive species well incorporated into local ecology are recommended for WQC derivation given the potentially under-protection and over-protection behaviors. The toxicity data of three phyla and eight classes developed by USEPA are proposed to deduce the WQC of China, given its well consideration of the different sensitivity of species and trophic levels to objective pollutants (Chen 2005; Feng et al. 2012a; Meng and Wu 2010). However, with the further development of WQC, Liu et al. suggested that the toxicity data of three phyla and six classes could also be used to calculate the value of WQC of China when there is lack of toxicity data (Liu et al. 2012). The generally used calculated models include assessment factors (AF), species sensitivity distributions (SSDs), ecotoxicology (e.g., AQUATOX). The large uncertainty for AF method mainly attributes to the significance of assessment factor during derivation of WQC and the experience-based choice of assessment factor (1 ~ 1000) in a specific case; therefore, AF method could be applied for lack of toxicity data or to screen toxicity data as a tool (Chapman et al. 1998; Jin et al. 2014b; Zabel and Cole 1999).

The SSD method played a significant role in development of WQC, and its application should require certain quantity of toxicity data (Jin et al. 2014b). It was reported that application of SSDs generally requires the minimum quantity of toxicity data about 4 ~ 10 according to specific conditions, and more than 5 toxicity data are generally used for WQC derivation (Jin et al. 2014b; van Straalen and Denneman 1989; Wheeler et al. 2002). Aldenberg et al. (Aldenberg and Jaworska 2000). discussed the confidence limits for hazardous concentrations of chemicals and fractions of affected species using Bayesian and classical formulas under normal species sensitivity distribution and found out that the confidence limit for the affected fraction of species was vastly affected by the sample size of toxicity data and decreased greatly with the increase of quality and quantity of toxicity data; the confidence limit of hazardous concentration would be more than 20 % when the sample size is less than 10. Another key problem for SSDs is the determination of HC*p* (concentration affecting p% of organisms) during the WQC derivation. Up to now, 5 is often used empirically for deriving WQC partly because that the calculated HC5 is consistent with the NOEC of multispecies toxicity test, but there has not been any scientific arguments (Hose and Van den Brink 2004; Maltby et al. 2005; Solomon and Takacs 2002; Stephan and Rogers 1985). In addition, due to the difference between natural aquatic conditions and simulated toxicity test, the WQC are generally calculated by HC5 reducing an assessment factor. However, assessment factors are generally applied empirically based on the reliability and relevance of toxicity data, which to some degree, increases the uncertainty for ecological protection (Jin et al. 2013). Ecotoxicology models (AQUATOX and CASM) are also developed in deriving WQC. However, the application of ecotoxicology models is limited due to its requirement for mass toxicity data and calibration with local toxicity data, and thus should be improved according to the environment condition of China. In addition, interspecies correlation estimates (ICEs) developed by USEPA could be used to predict the acute effect of chemicals on organisms based on collected toxicity data and built-in regression models. However, its inadequacy for predicting the chronic effect limited its application in the long-term regulation for environmental quality (Jin et al. 2014b). In recent years, biotic ligand model (BLM) and quantitative structure activity relationship models (QSARs) are employed to calculate water quality criteria. The BLM is based on the toxicity which is decided not by metal-ligand complexation but the completion of different cations at the site for toxicity should also be involved (e.g., competing cations, organic matter complexation, inorganic ligand complexation, site of action) (Di Toro et al. 2001; Wu et al. 2012), such as the WQC values of copper, silver zinc, and nickel that were calculated by USEPA and European Union (Di Toro et al. 2001; Santore et al. 2002). However, its physicochemical properties limited its wide uses for various pollutants (de Schamphelaere and Janssen 2002; Wu et al. 2012). The QSARs were developed based on the relationships between physicochemical parameters and toxicity of a compound and started to be used to research the toxicity of organic compounds and inorganic compounds in recent years. For example, Wu et al. predicted WQC of metal cations from physicochemical properties of metals with QSARs (Wu et al. 2012).

Due to the interruption of various environmental factors and self-regulation function of cell, organ, individual, population, community, and ecological system, the toxic effect of pollutant on organism becomes more complicated (Jin et al. 2015; Rovida et al. 2015). Due to limited information of traditional single test based on individual testing standard, it is hard to accurately assess the risk of pollutant to individual, population, and community, thus limiting the prediction of environmental risk. As the quality of environmental protection improves, it becomes more and more important to combine existing information sources systemically to assess the environmental risk of pollutant comprehensively. In respect to this point, Integrated Testing Strategies (ITS) was recently proposed to be used in environmental risk management by National Institute for Public Health and the Environment (RIVM) (Rovida et al. 2015; Zhou 2015). In the regulation and control of pollutant, ITS was used to combine different information in a quantifiable way to meet a certain need of environmental protection (Rovida et al. 2015). Specifically, adverse outcome pathway (AOP) is expected to causally organize eco-toxicological information at molecular, cellular, tissue, organ, and population levels to present adverse outcomes comprehensively and make safety assessment more efficient (Jin et al. 2015; Tollefsen et al. 2014; Villeneuve et al. 2014; Wei et al. 2016; Zhou 2015). AOP does not only emphasize the effect of each individual key event (KE) but also lineages (key events relationships, KERs) of molecular initiating events (MIEs) and the following key events. Therefore, AOP framework could be more efficient to present the adverse effect of toxicant at the organ level, and even population level, and have large potential to improve the efficiency of environmental risk management. For example, AOP framework was utilized to describe the adverse outcome pathways of ethinylestradiol (EE2) for the inhibition of spawning in zebra fish (*Danio rerio*) and dioxin-like compounds (DLCs) for the inhibition of aryl hydrocarbon receptor (AhR) (Cosme et al. 2015; Wei et al. 2016). Therefore, ITS and AOP can be developed to solve aquatic environment problems in China.

China mainly selects the conventional organisms such as *Chironomidae* larvae and zebra fish as the test species to implement the toxicity experiment, but seldom considers the difference of local organisms' sensitivity to pollutants, which leads to a large deviation of experimental toxicity data from the actual water body (Jin et al. 2012a; Jin et al. 2012b). Moreover, the climate ecological condition in China is diversified, which leads to large differences in the concentration distribution of actual pollutant in water bodies and the constitution of species in specific water ecosystem and biology sensitivity, so it is very difficult to provide comprehensive protection for the water body in China using a uniform standard for the same pollutant. The lack of toxicity data in China limits the selection of derivation method of WQC. For example, the toxicity percentile ranking method adopted by the USA and the species SSD adopted by the European Union are based on many reliable toxicity data, so China's WQC value has to be deducted by the evaluation factor (EF) method based on the limited toxicity data. The evaluation of the impact of pollutants on the aquatic organism with multiple indicators not only can provide protection for the aquatic organism but also guarantees the other uses of other water bodies. For instance, the USA uses the final plant value to evaluate the impact of pollutants on the plant during derivation of CMC and CCC and adopts the final residue value to evaluate the potential risk in using aquatic organism as food.

However, the criteria values in the currently applicable EQSSW (GB3838-2002) of China are mostly from the DWHSs of China, and these standards are prepared for the purpose of protecting human body and do not involve the distribution characteristics of species' sensitivity to the specific pollution in different water ecosystems. Therefore, they are difficult to provide as a reasonable protection for the aquatic organism. China is a vast country with diversified climate conditions, so the specific hydrological condition, water ecosystem characteristics, and recovery capability should be considered in environmental protection by adopting WQC. However, in environmental regulation, the water quality is currently still evaluated using the conventional indicators, such as the COD, BOD, total phosphorus (TP), total nitrogen (TN), and other physicochemical indicators. Although these indicators can effectively control the water quality pollution within a short period, these are insufficient to effectively balance the economic development and protection of the aquatic organism due to the difference in water quality and biology sensitivity. For example, the frequency of pollutants exceeding CCC in the USA will not be more than one time in 3 years, and the Netherlands divides the toxicity test into acute test or chronic test on the basis of the physiological characteristics and life cycle of aquatic organism, which not only investigate the growth and development characteristics of sensitive organism but also give consideration to the possibility of recovery and reconstruction of specific ecological system after pollution.

China is suffering from the above-mentioned problems in the development of WQC. In addition, in the context of promoting economic development by the industry and manufacturing industry in China, the coexistence of conventional pollutants (such as heavy metal, POPs) and new pollutants (estrogen-like hormone, nanometer materials, novel antibiotics, new pesticides, etc.) becomes the obvious characteristics of environmental pollution in China, which sufficiently supports the urgency of developing the WQC conforming to the environmental water quality characteristics of China. In the face of a variety of pollutants, the development of WQC for all pollutants will require much time and effort, so that it will be favorable to the efficient implementation of water environmental management in China by the intensified regulation of the pollutants with higher ecological or environmental hazards through developing the list of China's priority pollutants (Guillén et al. 2012; Mitchell et al. 2002; Snyder et al. 2000). Jin et al. recommend that ranking the pollutants in water body of China should be built on multiple environmental risk indicators, such as the persistence, bio-concentration, carcinogenicity, and environmental availability of pollutants. The development of priority pollutants list should not only consider the geographic climate, environmental background value, and difference of cultural customs but shall also give consideration to the route of transmission, migration, and transformation of pollutants in environment and also the impact of other environmental factors on the toxicity of these pollutants (Boxall et al. 2012; Bu 2012; Jin et al. 2014a; Jin et al. 2009).

In recent years, research on WQC in China has also made progress, and these advances in methods, infrastructure, and data on endemic species can now be incorporated into the revisions of the New Standards. Criteria for ten priority pollutants including Zn, Cd, Cu, PCP, and NH_3-N have been promulgated for the protection of fresh water aquatic organisms and should be brought into the new WQS. Additionally, the improvement in instruments and analytical methods and detection limits for quantification of contaminants have been constantly improved. Accordingly, the *Standards* for analytical methods of water pollutants should be updated. Breakthroughs have recently been made in several key scientific issues, including SSD (Liu et al. 2014), BLM (Chen et al. 2011; Feng et al. 2012b), interspecies correlation estimation models (ICE) (Feng et al. 2013a; Feng et al. 2013b), toxicological endpoint identification, and quantitative ion character-activity relationship (QICAR) analysis for predicting WQCs of metals or metalloids (Mu et al. 2014; Wu et al. 2012), which will likely remain the focus of WQC studies in China.

Refining water function zoning

Although several function zoning programs have been implemented to reduce water pollution, the water quality as a whole has not been significantly improved under the situation of rapid economy growth, for example, the conflict between the ecological water requirement and water consumption of human activities because of the neglect for the integrity of water ecosystem (Ping et al. 2012; Zhou et al. 2007). In addition, in order to simplify the water regulation process, the present division of water function was conducted based on the boundary of city or province, which hardly provides efficiently management for a watershed (Meng et al. 2004). Thus, the framework used by the current WQS should be amended and WQC should be developed with clear definitions of the targets to be protected (humans or aquatic organisms). Protection of human health as well as the health of aquatic ecosystem has become an important objective for water environment management (Montgomery et al. 1995). A classification system based on defined protection objectives is not only in line with an urgent need in China's current water environment management but is also consistent with the trend of scientific development of international WQS. WQCs for protection of human health are derived from data describing effects of pollutants on human health, whereas WQC for protection of aquatic organisms are based on toxicological data describing susceptible aquatic organisms. Because the objectives of WQS, as well as the data and methods used to derive them, are inherently different for protection of humans and aquatic organisms, the practice of using identical limits for all receptor targets could lead to over-protection of one group and under-protection of the other, resulting in misuse of scarce resources. Therefore, the current water function zoning should be refined and monitored based on the structure of biocenoses, especially for sensitive species (e.g., zooplankton, phytoplankton, benthic organism), physiochemical parameters (hardness, pH, dissolved oxygen, the renewal frequency of water), and species of pollutants. Specifically, firstly, the zoning of water function could be determined by terrain, climate, hydrology, and the degree of human interference to eliminate the differentiation of districts in the same watershed. Secondly, grading the protection of water ecosystem is based on the species and distribution of organism and its basic uses. Thirdly, the load of water ecosystem for human activities, such as water taking, using and discharge, could be evaluated. Fourthly, the pollution "hot spot" and the pollution-sensitive zone for better environmental regulation could be identified (Hughes and Larsen 1988; Omernik 1987).

Development of priority pollutants list

It is necessary to develop the priority pollutants list for more effectively implementing environmental regulation (Keith and Telliard 1979). According to the current negative status of environmental pollution in China, the development of priority pollutants list shall be in accordance with the toxicology experiment and physicochemical characteristic of pollutants. Currently, there are many researches on the toxicity and environmental migration transformation rule of the conventional pollutants (such as heavy metal and POPs), and the water quality criteria can be deducted in accordance with the existing water quality criteria methods (such as the SSD, AF, toxicity percentage sorting method); however, the physicochemical property and mechanism of toxication of new types of pollutants (nanometer materials, new pesticides, estrogen-like matters, etc.) as well as the toxical sensitivity of organisms in different areas of the environment have not been sufficiently researched and the development of scientific and reasonable water quality criteria will be very difficult, so the environmental toxicity can be initially predicted on the basis of the cytotoxicity test (neurotoxic test) and mathematical analysis model (USEtox); in combination with the priority pollutants list sorted out by some scholars, the existing pollutant discharge standards can be amended and supplemented (Crofton et al. 2011; Hao et al. 2014). On the basis of the existing function division of water bodies in China, the environmental supervision should be conducted for subdivided water bodies based on the structure of biological community (zooplankton and phytoplankton, benthonic animal, etc.), physicochemical composition of water (such as the hardness, pH, dissolved oxygen, and renewable speed of water body), pollutant index (distribution of pollution sources, pollutant types, etc.) and other characteristics. In addition, special WQC for some endangered species should be developed based on their living habits.

The pollutants in the current WQS should include those that are most toxic, are already detected in certain regions, or are a common concern of the international community and exert certain environmental risks. In fact, some pollutants of lesser concern in developed countries may deserve priority for attention in China because origins, types, and emissions of pollutants might be different in China (Yan et al. 2012). For example, The WQC for the heavy metals should be emphasized because of their pollution in many rivers of China (Cheung et al. 2003). Historical research on toxic substances conducted in China was based on methods developed in other countries. There have been large amounts of data for toxicities of organochlorine, organophosphorus pesticides, polycyclic aromatic hydrocarbons, and other persistent organic pollutants conducted in other countries but less research on priority pollutants in China (Jin et al. 2012a; Jin et al. 2012b; Jin et al. 2014a; Jin et al. 2009). WQC of pollutants with potential to have major effects on ecosystems and human health should be a priority. Based on experiences of more developed countries, an attempt was made to rank priority pollutants in China by the use of multiple criteria and ranking approaches and then focus on those pollutants that had the greatest potential, based on persistence, bioaccumulation potential, toxic potency, and potential to be released into the environment (Pei et al. 2013). Additionally, more recently recognized or emerging pollutants that have been detected more frequently in China should be included in the revised water quality standards. Preliminary methodological studies need to be conducted with awareness of the latest progress globally.

Protection of drinking water sources

Protection of drinking water sources must be enhanced. Surface water is an important source of drinking water, and the quality of sources of water directly determines the safety of drinking water. After purification at water plants, the quality of water from a centralized drinking water source should meet the requirements of hygienic standards for drinking water (Shi et al. 2012). Currently, water treatment plants in China are widely adopting the conventional purification process of "coagulation-sedimentation-filtration-disinfection," which has limited capacity to remove multiple poisonous and harmful substances (Hu et al. 2013). Therefore, enhanced protection of water source areas is fundamental to safeguarding drinking water quality and protecting human health. Efforts should be directed toward rigorously monitoring pollutants likely to be present at concentrations that pose potential health risk to human and wildlife, and avoid using resources by monitoring for residues that are less likely to exceed thresholds for significant effects on humans or ecosystems. Moreover, mechanisms of toxic action should be established to allow regular revision and re-examination of the limit values, and thereby ensuring maximum protection of human health. In the last few years, China has experienced a large number of water pollution emergencies, and there is an urgent need for establishing a rapid emergency response system based on accurate WQC intended for aquatic organism protection (Liu and Diamond 2005). In this context, establishing WQC for heavy metals and selected organic pollutants should be a priority.

WQC for nutrients should also be a priority in the amended standards. Eutrophication is now a serious problem affecting nearly 70 % of surface waters in China due to unregulated discharge of amounts of nitrogen and phosphorous from anthropogenic sources such as agriculture, industries, and domestic households (Cheung et al. 2003; Xie et al. 2003). China is a vast territory with distinctly different natural environments and corresponding striking regional differences. For instance, lakes in China might vary due to climatic conditions, including temperature and light. Enrichment with nitrogen and or phosphorus at concentrations that might trigger blooms of phytoplankton should be controlled (Beman et al. 2005; Xie et al. 2003; Xu et al. 2010). It is neither accurate nor scientific to use a single standard to evaluate the health of lakes under complex and diverse ecological and environmental conditions. The current WQS do not raise the representation and control standards of eutrophication itself but simply stipulate the standard limits of total nitrogen and total phosphorous, without mentioning the indicator *chlorophyll a*. In fact, chlorophyll *a* and aquatic algae growth are correlated. Total nitrogen, total phosphorous, and chlorophyll *a*, and phosphorous are causal variables of eutrophication in lakes and reservoirs and chlorophyll *a* is the outcome variable. Since the method for quantification of chlorophyll *a* has matured, it is often used to indicate the presence of nutritive salts such as nitrogen and phosphorous (Bell et al. 2014; Stow et al. 2014). Accordingly, surveys should be conducted to understand the regional differences in cultural eutrophication, and regional nutrient classification needs to be completed before proper nutrient WQC. To set limits for classification based on subregion nutritive salt criteria, China could be divided into several regions, including the Eastern Plain lake area, Yunnan-Guizhou Plateau lake area, and Northeast China Plain mountainous region as well as the Inner Mongolia-Xinjiang Plateau and Qinghai-Tibet Plateau.

Development of site-specific water quality criteria in China

During the implementation of water quality criteria, the organisms in some water areas cannot be properly protected by the current applicable water quality criteria due to the difference of biological sensitivity in these areas, so the Site-Specific Water Quality Criteria (SSWQC) should be developed for these water bodies (Peters et al. 2014). In accordance with the document issued by the EPA of the USA, SSWQC research can be developed in the following cases: (1) the sensitivity of native species in the targeted area is higher or lower than the risk threshold value of water quality criteria; (2) the difference in the physicochemical properties (such as the temperature, hardness, or pH) of target water body and laboratory toxicity experiment water body leads to the change of biological availability or toxicity of pollutants; (3) the toxicity or biological availability of pollutants is changed due to the seasonal change of physicochemical property of water body; (4) the currently applicable water quality criteria cannot comprehensively protect the national (provincial) water quality criteria; (5) other factors or the combined effect of these factors lead to the revision of currently applicable criteria (DEQIS 2016). The procedures designated by SSWQC are as follows: (1) *determination of mixing zones*: the concentration of pollutants in the mixing area can be higher than the concentration of water areas outside of the mixing area, and the mathematical model and color formation method can be used to determine the boundary of mixing area, so as to simulate the impact of water temperature and pollutants; (2) *recalculation procedure*: the water quality criteria for the aquatic organism is usually deduced on the basis of the toxicity data obtained by testing the representative species in this water area; re-deduction of water quality criteria can be made on the basis of the testing result of biological toxicity at a specific point; (3) *site assessment*: comprehensively evaluate the water sample at specific site and distribution characteristics of sediment pollutants so as to calibrate the residue-based limits of toxic substances at the site based on specific conditions; (4) *biological translator*: use the biological toxicity test method to compare the difference between the pollutant toxicity in actual water body and simulation experiment result in the laboratory, so as to facilitate the prediction of toxicity effect of pollutants in the targeted water body; (5) *chemical translator*: chemical translator can convert dissolved metal criteria of specific point back to the total metal concentration so as to facilitate the calculation of the waste load limit of pollutants. In this way, the specific environmental conditions of given water bodies could be reflected based on the pollution evaluation for multiple sites, and then more reasonable limits may be developed; (6) *water effect ratio*: the biological availability of some pollutants may be low due to the effect of environmental factors, thus, the WQS value for these pollutants should be adjusted based on their toxicity test in laboratory and specific sites (GLEC 2016). Great lakes are the main freshwater lakes in the USA and also the important water source region and habitats for the wild animals in the USA, and the aquatic conditions and the distribution of species vary in different waters and the necessity of SSWQC is undoubted. Therefore, in accordance with the current situation of China, it is very necessary to develop the SSWQC for the class I and class II water body with some models, such as biotic ligand model (BLM) (Niyogi and Wood 2004), so as to comprehensively and efficiently protect the quality of water environment of China and endangered species.

Field toxicity test

For the precondition for development of water quality criteria, firstly, there should be a causal relationship between the toxicity effect of pollutant and the concentration of pollutant; secondly, the causal relationship could be validated through experimental model; finally, if the pollutant concentration of actual water body is within the predicable scope, the obtained no-effect concentration can be used for water quality management. Although the derivation mode of water quality criteria based on vigorous dose-response relationship can provide protection for the majority of many water bodies, it is difficult to comprehensively evaluate the environmental risk of given pollutants based on a simple dose-response relationship, such as the long-term cumulative effect, nutritive salt fluctuation, immunosuppressive effect, biological movement stimulation effect, and price effect (Cormier et al. 2008b). Therefore, the water quality criteria developed based on laboratory toxicology test will be very difficult to provide comprehensive protection for the aquatic organism under the complicated natural condition, and after all, there may be large error for protecting complicated environment by employing simplified dose-response relationship. Therefore, in order to obtain more scientific and reliable value of water quality criteria, it is very necessary to deduct the water quality criteria based on the toxicology experiment with field water body and species. In order to more truthfully reflect a variety of the nature of actual water body, it is allowed to use the field toxicity data or the combined toxicity from field and laboratory tests to deduce the water quality criteria in the USA and Europe, etc. (Annapolis 2007; Crane and Babut 2007; Monteiro 2012). Cormier et al. (2008a) suggested that the risk threshold value of pollutants should be deduced with a variety of analysis method using the field and laboratory toxicity data (Cormier et al. 2008a). Therefore, the complicated and diversified ecological environment in China leads to the difference in the biological sensitivity, and the increasing type and concentration of pollutants in the ecological environment may lead to the low efficiency and irrationality when using the uniform water quality criteria to implement the environmental management. Therefore, the water quality criteria of China should be deduced with multiple methods based on toxicological tests of conventional and native species under the similar conditions to the targeted waters.

The amendment of the current WQS presents the opportunity to promote governmental and public awareness of environmental protection, as well as to upgrade infrastructures and economic empowerment. During the amendment process, strategic planning can encourage the transition of economic growth from being at the expense of environment to enhancement of environmental quality, achieving the objectives of reducing pollutant emissions and spurring the incubation of greener industries and technologies. Also, amendment of the current WQS may also stimulate a change of environmental management from pollution control to environmental quality improvement and risk management. In this context, the amendment efforts should be directed toward highlighting the pivotal roles of the current WQS in the management and protection of aquatic environments.

Conclusions

The fundamental role of WQC in the amendment of WQS has been recognized by the Chinese government and scientists. For the first time in the history of amendment events, the fourth amendment of the WQS should be set based on national WQC instead of those used/recommended by other countries or organizations. This change will be accompanied by reforms in the areas of amendment ideas, frame structure, and threshold values. Correspondingly, the amendment of the current WQS should feature significantly improved scientific soundness and practicality. Additionally, this amendment will reduce the margin between Chinese environmental standards and those issued by developed countries, which is expected to open a new chapter of Chinese WQS and provide a critical reference for future amendments of other standards.

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