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# Water quality criteria research and progress

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Water quality criteria (WQC) are threshold limits for pollutants or other hazard factors in the ambient water environment, which are based on scientific experiments and extrapolations. Until now, there is limited information available regarding the study of water quality criteria in China. It is imperative to launch national-level systematic WQC studies that focus on the regional characteristics of China and provide scientific support for the enactment or revision of water quality standards and environmental management. This article reviews the concept of WQC and discusses the methodology and global progress of WQC research. The article also summarizes the key scientific issues in WQC research, including species sensitivity distribution, toxicological endpoint selection, and models selection. Furthermore, we can adopt the derivation method used in the USA and divide WQC into acute and chronic criteria. Finally, considering the current status of WQC research in China, we point out important directions for future national studies, including the selection of native species and the comprehensive use of models.

**water quality criteria, species sensitivity, environmental management, biota**

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Water quality criteria (WQC) are the foundation for designing water quality standards. WQC provide a critical scientific basis for environmental protection agencies to regulate, evaluate, and manage water qualities [1]. Each ecosystem hosts unique biotas, and a pollutant concentration safe for one biota may have irreversible toxic effects on life in another [2]. Similarly, different regions/countries contain different aquatic biotas with various protection targets, which require individual criteria even for the same pollutant [3]. Internationally, WQC studies are regarded as an indicator of the national status of environment sciences. Therefore, developed countries have invested substantial resources in WQC studies and achieved remarkable progresses.

Environmental exposure, effect identification, and risk assessment are three major areas of WQC studies. Identification of ecological/health effects and the related mechanisms is an important area of current WQC studies, and a focus of toxicological research. Some developed countries have undertaken WQC research for decades, and have thus established comprehensive WQC research systems. However, China initiated WQC research only a few years ago, and is now building its own systems “from scratch”. So far, there are few criteria for environmental management in China, and a comprehensive WQC system for ecosystem and human health protection is lacking. Of current standards or criteria related to water body protection, only one (*Environmental Quality Standards for Surface Water*) [4] includes standard limits of pollutants for different water uses, and none specifies standards for protecting specific ecological targets. Therefore, it is imperative to investigate WQC research systems in developed countries and establish appropriate systems that are suitable for water pollution and regional characteristics in China. We expect that WQC studies will play important roles in establishing/improving the environmental standard system in China and improving

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*Corresponding author (email: wufengchang@vip.skleg.cn) the national status of environmental research and management.

## 1 Overview of WQC

WQC refer to the maximum concentrations/limits of water components that do not adversely affect specific protection targets under certain natural conditions. Instead of being a single concentration or dose, WQC are defined as ranges for different targets of protection [5]. Pollutants related to WQC include heavy metals, nonmetallic inorganics, and organics. WQC-related water quality indicators include pH, chromatography, turbidity, and coliform number. WQC and water quality standards are different (although closely related) concepts with distinct differences in scope and function. WQC are conceptions of natural science that should be determined by scientific experiments and reasoning. Generally, the accurate determination of WQC requires large funds, a long research period, and careful work. Moreover, there is uncertainty in the determined WQC because of difference in research media/objects and between research methods. In comparison, water quality standards are legally enforced limits of water pollutants (or hazardous factors) set by central or local governments. Water quality standards provide the legal basis for environmental planning and management, and are related to governmental (national or local) policies for environmental protection.

WQC form a systematic framework that is classified according to the target of protection as WQC for aquatic life and WQC for human health. Recently, given the bioaccumulation of pollutants in the food chain, non-aquatic life (e.g., wildlife) is increasingly being introduced into the scope of WQC [6]. According to the purpose of use, WQC are classified into criteria for drinking water, recreational water, agricultural water, fishery water, and industrial water. Additionally, according to the types of water pollutants, WQC are classified into criteria for heavy metals, organics, nutrient salts, and pathogenic microorganisms. In 2009, the US Environmental Protection Agency (US EPA) published its latest WQC document describing the freshwater/seawater acute/chronic criteria to protect water biota and human health for 167 pollutants (120 priority and 47 non-priority pollutants) and 23 sensory criteria [7].

WQC can be expressed numerically or descriptively. Water pollutant concentrations are defined mostly by numeric WQC. Descriptive WQC apply to situations where pollutants cannot be specified; e.g., turbidity criteria. The determination of WQC takes into account many factors and the criterion values are thus affected by various environmental factors, such as water hardness, temperature, pH, and soluble organics [8]. Distinctively, WQC are scientific, fundamental, and regional [3, 9] in nature. First, WQC are determined by studying the environmental behaviors and ecotoxicological effects of pollutants. The determination is based on frontier sciences (e.g., environmental chemistry, toxicology, ecology, and biology), and is thus intrinsically scientific. Second, WQC provide the basis for environmental regulation/management and are the cornerstone of entire environmental protection activities. Additionally, WQC studies are carried out separately in different countries based on their own regional characteristics, and the environmental and toxicological effects for different regions are different. Consequently, WQC are also regional.

## 2 History of WQC development

In 1898, A. Ф. Nikitinski, a Russian hygienist, published *The effects of petroleum products on river water quality and fish* and first introduced the concept of environmental criteria [10]. The USA launched the first WQC study. The development of WQC has been accompanied by the publishing of WQC research papers, reports, and monographs. In 1907, Marsh published the first WQC study in the USA—*The effect of some industrial wastes on fishes* [11]. Later, scientists investigated various WQC problems and introduced related theories and methods [12–14]. Since the 1960s, the US EPA has published a series of environmental criterion documents such as the *Green Book*, *Blue Book*, *Red Book*, and *Gold Book* [15–21], thus establishing a comprehensive WQC system. In 1999, Canada published *Canadian Water Quality Guidelines for the Protection of Aquatic Life* [22]. In 2000, the US EPA published *Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health* to systematically explain the derivation of WQC for human health [23]. In 2002, 2004, 2006, and 2009, the US EPA revised *National Recommended Water Quality Criteria* [24–26]. Since 2000, many countries (e.g., Australia, New Zealand, Canada, and the Netherlands) and organizations [e.g., the European Union (EU) and World Health Organization] have also published or revised water quality criteria [27–31].

China commenced water quality criterion studies relatively late, and initial efforts were limited to collecting and organizing international publications. In 1981, the China Building Industry Press published the Chinese translation of *Water Quality Evaluation Standard* [32]. Later, more translations and review books on water quality criteria and standards were published to introduce researches done in the USA, EU, and other countries and by international organizations [33–36]. In 2010, Meng et al. [8] published *Introduction of Theory and Methodology of Water Quality Criteria* and systematically described WQC-related methodologies. The book examined WQC case studies and research methods in other countries and discussed some problems in these WQC studies.

## 3 WQC theories and methods

According to the target of protection, WQC are classified into criteria for protecting aquatic life and criteria for protecting human health. The two groups of criteria have different theories and methods. The derivation methods of aquatic life WQC mainly involve assessment factors and statistical extrapolation. The derivation methods of human health WQC are classified into criteria that are related to carcinogenic and noncarcinogenic effects according to the toxicological features of pollutants.

### 3.1 Aquatic-life WQC

Aquatic-life WQC are the maximum water pollutant concentrations that do not have short- or long-term adverse or hazardous effects on aquatic life. Internationally, there are two mainstream WQC systems. The US WQC guidelines adopt a toxicity percentile rank method and present two types of criteria: criteria maximum concentrations (CMCs) and criteria continuous concentrations (CCCs). The US guidelines require that acute toxicological data for deriving CMC should consider at least three phyla and eight classes to ensure appropriate protection for more than 95% of life species. In comparison, EU guidelines determine WQC by deriving predicted no-effect concentrations (PNECs) [28]. The EU guidelines require using at least 10 chronic toxicological data for eight life species to obtain PNECs, and recommends calculating criteria by considering either the species sensitivity distribution (SSD) or assessment factors. The SSD approach gives a chronic criterion that protects more than 95% of species, which is denoted $HC_5$ (Figure 1). The SSD approach was first proposed by Kooijman [37], and then modified in subsequent works [38–42]. It constructs a sensitivity distribution curve for a known pollutant based on all available toxicological data related to that pollutant and extrapolates the curve to the criterion level (the concentration corresponding to the target percentage). The criterion level is usually denoted $HC_5$, which is the concentration hazardous to 5% of species [43].

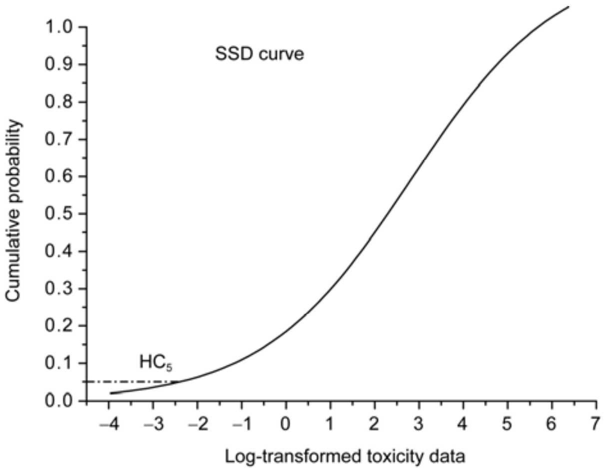

**Figure 1** Schematic diagram of $HC_5$ derivation using species sensitivity distribution (SSD).

In addition to these two mainstream systems, other countries (e.g., Australia, Canada, the Netherlands, and New Zealand) have issued their own WQC guidelines [27, 29, 30, 44]. These guidelines also use assessment factors and extrapolation methods to derive WQC. However, they use different descriptions and classification systems to define WQC [19, 28, 45], as summarized in Table 1.

Currently, aquatic-life WQC are derived primarily on the basis of assessment factor, toxicity percentile rank, or SSD. According to the methodology used, these approaches have different advantages, disadvantages, and scopes of application. The assessment factor approach requires fewer basic data and a simple calculation. However, as an empirical approach, it relies on toxicological data for sensitive species and involves considerable uncertainty. Moreover, this approach fails to take into account interspecies relations and the bioaccumulation of pollutants. Because of these disadvantages, the assessment factor approach is used only for comparison or when data are difficult to obtain. The toxicity percentile rank approach differentiates the acute and chronic toxicities of pollutants, and considers the bioaccumulation effect. However, it uses data for only four genera with a cumulative probability of nearly 0.05 to calculate WQC values, and therefore involves uncertainty. Additionally, it does not consider interspecies relations. China has adopted this approach in WQC-related studies. The SSD approach can effectively represent a whole ecosystem as it uses available toxicological data for all species and assumes target species are randomly selected from the ecosystem. However, this approach does not consider bioaccumulation and may result in substantial differences in criteria values when different models are used. This approach may be used when sufficient acute/chronic toxicological data are available. Currently, the SSD approach is adopted by Australia, New Zealand, and the EU. In the foreseeable future, this will be the main approach employed in WQC studies. The above approaches do not factor in the effect of field media on criteria and (except in the case of the toxicity percentile rank approach) do not consider bioaccumulation and bio-amplification. These limitations indicate the directions of future WQC research.

### 3.2 Human-health WQC

Human-health WQC are the maximum water pollutant concentrations that pose no risk to human health [46]. In 2000, the US EPA issued *Methodology for Deriving Ambient Water Quality Criteria for the Protection of Human Health* [23] and established basic theories and methods for studying human-health WQC. The guideline defined two toxicological effect endpoints for different pollutants. For suspected or confirmed carcinogens, the human-health WQC are defined as water pollutant concentrations that increase lifetime risk by $10^{-6}$ under exposure to concentrations, excluding additional cancer risks from exposure to other specific pollutant

**Table 1** Representative water quality criterion systems in developed countries [a)]

| Country (issuing department) | Year | Criterion type | Criterion grade | Description |
|---|---|---|---|---|
| USA (SEPA) | 2009 | Aquatic life criteria (ALC) | CMC | An estimate of the highest concentration of a material in ambient water to which an aquatic community can be exposed briefly without resulting in an unacceptable adverse effect. Exposure to a 1-hour average concentration of the chemical does not exceed the criterion more than once every 3 years on average. |
| | | | CCC | An estimate of the highest concentration of a material in ambient water to which an aquatic community can be exposed indefinitely without resulting in an unacceptable adverse effect. This is the chronic criterion.<br>Exposure to a 4-day average concentration of the chemical does not exceed the criterion more than once every 3 years on average. |
| | 1993 | Sediment quality criteria (SQC) | – | A single-value criterion estimated using acute toxicity data, interstitial water concentration criteria, and partition coefficient for sediment organic carbon (equilibrium partitioning method). |
| European Union (ECB) | 2003 | Predicted no-effect concentrations (PNECs) | – | A single-value recommended criterion for risk assessment. |
| Canada (CCNE) | 1999 | Water quality guideline (WQG) | – | A single-value criterion. |
| Australia and New Zealand (ANZECC & ARMCANZ) | 2000 | Trigger values (TVs) | High reliability trigger value (HRTV) | Derived using >5 kinds of chronic toxicity data from one species, or >1 kind of data from multiple species. |
| | | | Medium reliability trigger value (MRTV) | Derived using acute toxicity date from >5 species. |
| | | | Low reliability trigger value (LRTV) | Derived using acute toxicity data from <5 species. Serve as reference. Not used as criterion. |
| The Netherlands (RIVM) | 2001 | Environment risk levels (ERLs) | Negligible concentration (NC) | A pollutant concentration that does not produce significant effect on an ecosystem, obtained by dividing MPC by a safety factor. |
| | | | Maximum permissible concentration (MPC) | A maximum pollutant concentration that does not produce hazardous effects on any species in an ecosystem. Pollutant emission must be controlled if exceeding this concentration. |
| | | | Ecosystem serious risk concentration ($SRC_{ECO}$) | A pollutant concentration expected to produce possible serious effects in an ecosystem (50% of species and/or 50% of enzymatic processes). Wastewater treatment must be strengthened if exceeding this concentration. |

a) – indicates the information is not available.

sources. For noncarcinogens, the WQC are defined as the maximum water pollutant concentrations that do not have adverse effects on human health. Human-health WQC values are calculated from dose-effect parameters such as the no observed adverse effect level (NOAEL) and lowest observed adverse effect level (LOAEL), as explained in Figure 2.

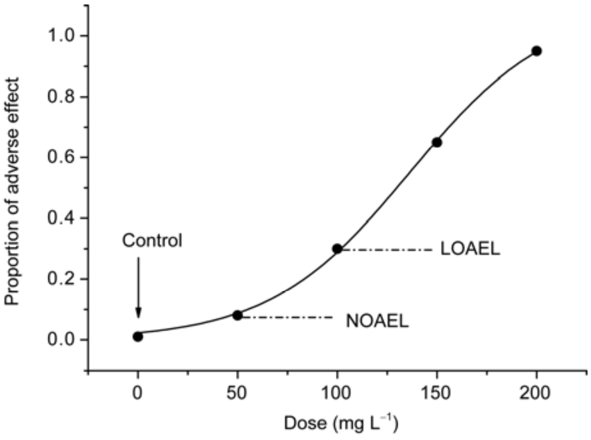

**Figure 2** Schematic diagram of dose-response relationship.

## 4 Progress in WQC research

### 4.1 International progress

Recently, global studies have made remarkable progresses in determining WQC. First, from the viewpoint of pollutants, studies on different pollutants involve different factors. Organic pollutants have relatively complicated toxicological effects. Therefore, WQC studies involving organic pollutants should specify toxicological endpoints for life species to allow the derivation of criterion values. The toxicological effects of inorganic pollutants (mainly heavy metals) are sensitive to environmental factors; consequently, studies should focus on the effects of water-environment factors on the biological availabilities. Scientists have started WQC-related studies on organic pollutants. For example, given the wide detection of methyl tert-butyl ether (MTBE) in surface and underground water, the USEPA studied the aquatic ecotoxicology and WQC of MTBE [47], including the responses of fish, invertebrates, and algae to the MTBE concentration and the acute toxicity of MTBE to marine species. The study determined the WQC for MTBE to be 26 mg $L^{-1}$. Hohreiter et al. [48] investigated the aquatic-life WQC for formaldehyde. They collected data on the acute toxicity of formaldehyde to fish and aquatic invertebrates, and determined the CMC and CCC to be 4.58 and 1.61 mg $L^{-1}$ respectively. Yin et al. [49] studied the toxicity of 2,4,6-trichlorophenol to nine representative aquatic animals and an alga, and determined the CMC and CCC to be 1.01 and 0.23 mg $L^{-1}$ respectively. Regarding WQC for heavy metals, studies should sufficiently consider the effects of water-environment factors (e.g., hardness, temperature, and organic solutes) on bioavailability. In revised US EPA WQC for copper, a biotic ligand model (BLM) was introduced to derive the criteria, and the effects of water parameters and the bioavailabilities of different copper forms on aquatic toxicity were also considered [50]. These advances provide an important reference for future WQC studies on heavy metals. WQC studies for different pollutants have different important aspects. Studies on common pollutants usually set the toxicological endpoint as death or growth inhibition. Some newly identified pollutants and endocrine disruptors (e.g., estrogenic substances) require different endpoints because they have irreversible toxicological effects on biological development and reproduction before causing death. Therefore, in a study on the WQC of 17α-ethinylestradiol (EE2), Caldwell et al. [51] selected reproductive toxicity as the endpoint and determined the PNEC to be 0.35 ng $L^{-1}$.

Second, from the viewpoint of criterion type, different types of WQC may require completely different methods of derivation. Traditional aquatic ecotoxicity indirectly reflects the biohazard of pollutants with the concentration in environment media, which is not strictly scientific. The tissue residue concentration (TRC) has been introduced to overcome this limitation. The TRC reflects the bioavailability of a substance and also its absorption, metabolic efficiency, and exposure routes. Because of this wider representativeness, the TRC is considered a superior substitute to the external concentration [52]. Correspondingly, research methods have been developed to describe toxic reactions using tissue concentrations. The USA and Canada have introduced the concept of the tissue residue criterion [6, 53], which is defined as the maximum permissible concentration of a substance in aquatic life tissues. This new concept is used for the protection of wild animals (birds and mammals) that feed on aquatic life. Similarly, tissue residue criteria aimed to protect aquatic life and human health have also been introduced. Despite having different protection targets, all these criteria are expressed as residue concentrations in aquatic life tissues. The use of the TRC provides definite evidence of pollutant uptake without complication arising from environmental factors. Furthermore, it directly links bioaccumulation to toxic reactions and reduces uncertainty due to differences in species and environment factors. Based on the tissue residue theory, Steevens et al. [54] calculated the tissue residue criteria of 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-TCDD) in fish tissues using the SSD approach, and the criteria range was 0.057–0.699 ng $g^{-1}$, protecting 99% and 90% of fish, respectively. Beckvar et al. [55] studied the criteria for mercury and dichlorodiphenyl-trichloroethane residues in fish tissues employing different methods, and calculated the criteria to be 0.2 and 0.6 mg $kg^{-1}$ respectively.

Third, from the perspective of methodology, different WQC research methods rely on different principles. For example, cases of combined pollution and joint toxicity are common and should be considered in WQC studies. Chèvren et al. [56] developed a method to define consistent and comparable water quality criteria for mixtures of herbicides having a similar mode of action, and applied it to calculate the quality criteria of six organophosphorus pesticides, three pharmaceuticals, and other similar compounds. They found that two pesticides and two pharmaceuticals conformed to the hypothesis of parallel species sensitivity curves, and they proposed that their method can be used to calculate WQC for mixed-pollution modes. In addition, predictive models are increasingly used in WQC studies to minimize animal use and better protect animal rights. Recently, the USEPA developed an interspecies correlation estimate (ICE) modeling technique for WQC research. The technique attempts to predict toxicity data for species from a toxicological database and thus avoids experiments on animals [57]. Dyer et al. [58] predicted the toxicity of 55 chemicals from data for surrogate species, and compared the predicted values with actual criteria determined by the USEPA. They found the two sets of values to be comparable (i.e., they had the same order of magnitude). Their results suggest that ICE models may be a valid tool for predicting toxicity to unknown species and determining WQC for pollutants with limited toxicity data [59].

## 4.2 Progress in China

Compared with developed countries, China commenced WQC research only recently. Because of the lack of sufficient fundamental studies and there being no available operable methodology in China, the country's water quality standards have been based on the criteria and standards of developed countries. This deficiency in methodology may potentially result in over- or under-protection of ecosystems.

First, pollutant toxicity data are critical for WQC studies. Currently, China acquires necessary toxicity data from international databases and publications, including ECOTOX (http://cfpub.epa.gov/ecotox/) and PAN (http://www.pesticideinfo.org/). A national toxicity database remains absent in China. With respect to toxicity testing, China has issued acute toxicity test standards for limited species (e.g., zebra fish and daphnia) [60–62], but test standards for chronic toxicity and other species are unavailable. As a result, data are screened following other international standards. Realizing this deficiency, the Chinese science community has been striving to close the gap. Wu et al. [3] systematically summarized the theories and methods outlined in WQC research [26], and derived aquatic-life criteria for several typical organic pollutants and heavy metals [63–66]. Additionally, our group pioneered studies on WQC systems in China and established systematic theories and methods.

Second, with respect to pollutant WQC, Chinese scientists have studied WQC for inorganic and organic pollutants following methods employed in other countries. Most initial studies on pollutant WQC (e.g., WQC for acrylonitrile, sodium thiocyanate, acetonitrile, and chlorophenols) were performed following the US EPA standards [67–70]. Later studies adopted methods employed in other countries, and used the internationally recognized SSD approach to study pollutants and calculate their WQC [17]. Additionally, recent studies in China examined sediment quality criteria [71], an important component of WQC. Zhu et al. [72, 73] carried out a preliminary study of sediment quality criteria for four heavy metals and two organochlorine pesticides in a water body of Tianjin (China) through equilibrium partitioning. Table 2 summarizes recent WQC results obtained in China. These case studies expedited the advance of WQC research in China. There are noticeable differences (Table 2) between criteria determined in China and those issued in the USA, primarily owing to the different biotas in the two countries [78].

## 5 Key scientific problems in WQC research

There are many scientific aspects to WQC research. In general, the main factors in deriving WQC include the reliability of underlying data and the scientific validity of statistical analyses. Additionally, other factors such as data screening, SSD feature analysis, and toxicological endpoint selection affect WQC research.

(1) Data acquisition and screening. Data acquisition and screening are critical factors in WQC research, and mainly involve the selection of test species and screening of toxicity test methods. Test species should be selected according to the characteristics of target regions and biota differences. Many countries have a requirement for the number of test species. The WQC derivation in USEPA requires at least three phyla and eight animal families [19]. The EU requires that statistical extrapolation should include at least 10 NOECs for at least eight taxonomic groups [28]. Canada requires the coverage of at least six species, including the common aquatic life species in North America [22]. Australia and New Zealand have different requirements for data size according to the reliability of the trigger values to be calculated [27]. With respect to toxicity testing, WQC research needs to be supported by systematic test standards, which can be established only by repeated validation. Currently, China has developed test standards only for limited species (i.e., daphnia, zebra fish, Scenedesmus, and luminescent bacteria) and this coverage needs to be expanded. Data screening is an important procedure following data acquisition. The quality of acquired data should be evaluated according to their reliability and relevance using relevant standards, as required by the EU, UK, Canada, Australia, New Zealand, and the Netherlands. Klimisch et al. [79] classified toxicity data into four categories according to reliability, relevance, and adequacy. Categories 1 and 2 are usually acceptable for WQC research. Moreover, WQC derivation also requires uncertainty analysis. Current methods for uncertainty analysis include Monte Caro sampling [80], interval analysis [81], and methods based on probability and fuzzy theories [82]. Selection of appropriate probability evaluation methods (e.g., traditional confidence-level

**Table 2** Comparison of aquatic-life WQC for China and the USA [a)]

| Pollutant | Criterion for China (μg $L^{-1}$) | | Criteria for the USA (μg $L^{-1}$) | |
|---|---|---|---|---|
| | Acute criterion | Chronic criterion | Acute criterion (CMC) | Chronic criterion (CCC) |
| Zinc [65] | 89.70 | 34.50 | 120 | 120 |
| Cadmium [5, 63] | 2.10–7.30 | 0.21–0.23 | 2 | 0.25 |
| Copper [66] | 30.0 | 9.44 | 12.0 | 9 |
| Mercury [74] | 1.743 | 0.467 | 1.4 | 0.77 |
| Nitrobenzene [64] | 572.0 | 114.0 | 3145 | 878 |
| Acrylonitrile [67] | 2156 | 575 | – | – |
| Sodium thiocyanate [68] | 1350 | 253 | – | – |
| Acetonitrile [69] | 1145000 | 413000 | – | – |
| 2,4-dichlorophenol [70] | 1250 | 212 | – | – |
| 2,4,6-trichlorophenol [48] | 1010 | 226 | – | – |
| Pentachlorophenol [75] | 25 | 3 | 19 | 15 |
| Ammonia nitrogen [76] | 403–38900 | 66.4–3920 | 299–57000 | 37.1–2240 |
| Tributyltin [77] | 0.43* | 0.002* | 0.42* | 0.0074* |

a) – indicates no data available; * indicates a criterion for saltwater aquatic life.

methods and Bayesian analysis [83]) is also important in generating valid criterion values.

(2) SSD. SSD features are crucial to WQC research. WQC are derived from sensitive species, and are thus strongly dependent on their toxicity data. Species react to different pollutants with different sensitivities. Conversely, species at different trophic levels react to the same pollutant with different sensitivities. These differences affect WQC. For example, an SSD study found that crustaceans are more sensitive than fish to zinc [65], whereas fish are more sensitive than invertebrates, such as crustaceans, to pentachlorophenol [84]. Therefore, different pollutants are associated with different SSDs, which leads to variations in WQC.

(3) Selection of a toxicological endpoint. WQC studies are based on toxicity data for pollutants, and these data are affected markedly by the choice of toxicological endpoints. For example, studies on the toxicity of estradiol (E2) to Japanese medaka [85] found a lowest observed effect concentration of 1000 ng $L^{-1}$, when using a change in body length as the endpoint, compared with 8.66 and 0.94 ng $L^{-1}$ respectively when using the offspring sex ratio and vitellogenin induction as the endpoint. Moreover, the regular experimental exposure of zebra fish embryos to diclofenac found $LC_{50}$ to be 480 μg $L^{-1}$ [86], whereas morphological studies indicate that 1–5 μg $L^{-1}$ diclofenac affects liver and kidney cells/tissue [87]. A study observed that EE2 produces irreversible reproductive toxicity in vertebrates (e.g., fish) at nanomolar concentrations and causes death at microgram-per-liter levels [51]. These case studies indicate that appropriate toxicological endpoints need to be selected according to toxic effect of pollutants in WQC research. Studies on common pollutants usually require data for toxicological endpoints such as growth inhibition, respiratory inhibition, motor inhibition, and lethal effect. In comparison, for endocrine disruptors such as estrogen, studies may generate much greater WQC than actual protective thresholds if the lethal effect is considered alone, thus failing to protect against other hazardous effects. For these pollutants, different endpoints should be examined and more-sensitive endpoints (e.g., genotoxicity, endocrine disruption, and aromatic hydrocarbon receptor effect) should be used to derive WQC.

(4) Pollutant selection. The selection of target pollutants requires consideration. There are a wide variety of pollutants in the environment with substantially different properties, such as heavy metals, nutritional elements, and toxic organics. Pollutants are associated with different environmental concentrations, hazard severities, actions sites, and acting mechanisms. Pollutants neglected in other countries may require careful attention in China and, conversely, key pollutants in other countries may not necessarily be priorities in China. Target pollutants should be selected on the basis of their nature, toxicity, and priority. Meanwhile, official pollutant lists may serve as a good reference for such selection. Finally, methods of screening risk pollutants (e.g., the quotient method) should be developed to aid the selection [88].

(5) Model selection. Model selection is critical to WQC studies as it directly affects the determination of WQC. The pattern of the toxicity data distribution should be analyzed before selecting the most suitable model for WQC derivation. Differences in data and model selection lead to different criterion values. In data processing, model suitability should be assessed according to statistical parameters, such as the coefficient of correlation ($R^2$), residual distribution, and mean-square deviation [89]. Statistical analyses should use methods such as probability assessment and avoid point assessment. Studies on heavy metals that are sensitive to environmental factors may need to evaluate bioavailabilities using the BLM. Internationally, studies have begun applying the BLM to predict WQC for metals such as zinc, copper, and nickel [90–92]. When joint effects from pollutants cannot be ignored, joint toxicity models may be used to evaluate their overall effects on life. Pollutants with the same action mechanisms can be treated with a simple additive model, and those with different mechanisms need to be examined with more complex tools such as the independent-action model [93]. In addition, applying an ICE to criterion prediction has been justified as a valid option and become a promising direction for WQC research [58, 59].

(6) Regional differences. Regional differences are another factor in determining WQC. As WQC are determined according to the environmental behaviors and ecotoxicological effects of pollutants, biota-related differences can result in substantial regional differences in WQC [78]. Different regions host different local sensitive species and can produce different toxicity and WQC data. To resolve this complication, WQC studies should include toxicity data for local species whenever possible and only carefully include data for exotic species, provided they represent ecological characteristics of the target region.

## 6 Trends of WQC research in China

China is endeavoring to develop water quality standard systems, but has not initiated comprehensive research on WQC systems so far. There is an urgent need to develop WQC systems suitable for the regional and socioeconomic characteristics of China by learning from proven international practices. The development should focus on the following issues.

(1) WQC study for the emerging pollutants. Studies on WQC for common pollutants primarily consider growth inhibition, motor inhibition, and death. New pollutants such as polybrominated diphenylethers, endocrine disruptors (e.g., estrogens), pharmaceuticals, and personal-care products may have special toxicological effects, including genetic toxicity, endocrine disruption, and aromatic hydrocarbon receptor effects. Consequently, these new pollutants

require special attention.

(2) Integration of acute/chronic criteria with environmental management. WQC studies usually give both acute and chronic criteria. In comparison, current Chinese water quality standards specify a single value for each water function. Considering the guiding roles of WQC for water quality standards, environmental protection departments may design separate short- and long-term standards for emergency and regular environmental management respectively.

(3) The effect of joint toxicity on WQC. Pollutants may have joint toxicity (e.g., antagonistic, synergistic effects) to life, a phenomenon commonly observed for heavy metals. Therefore, joint effects of multiple pollutants should be considered in WQC studies.

(4) WQC theories and methods. Basic theories and methods are fundamental to WQC research. Systematic studies should be undertaken to focus on important scientific problems related to WQC. It is urgent for us to establish WQC system suitable for China to support the formation of environmental standards and serve the environmental management.

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