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ENVIRONMENTAL QUALITY BENCHMARKS FOR PROTECTING AQUATIC ECOSYSTEMS

Development of aquatic life criteria in China: viewpoint on the challenge

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Abstract While more developed countries have a well-established systems to develop water quality criteria (WQC), little research has been done on the adequacy of the current WQC to protect endemic species of China. In order to maintain the health of aquatic ecosystems in China, a series of projects to establish national WQC based on regional characteristics has recently been initiated. However, the establishment of a completely novel methodology would be costly and time consuming. Also, due to the similarities in physiologies and natural histories of classes of aquatic organisms, there is no reason to believe that WQC would not be sufficient to protect unique species in China. This review was undertaken to identify key outstanding issues regarding establishment of aquatic life criteria (ALC) to be applied in China, including prioritization of chemicals, test species, mode of action, field/semi-field data, and methods of aggregating the information and calculating the ALC. This was used to identify the principle issues that need to be addressed in order to better understand the methods for development of criteria for the protection of aquatic life and provide a reference to China and other developing countries committed to the establishment of their own WQC system.

Keywords Water quality criteria · Prioritization of pollutants · Representative species · Adverse outcome pathway analyses · Ecological risk assessment · Asia

Introduction

Water quality criteria (WQC) are defined as levels of individual characteristics or descriptions of conditions of a water body which, if met, will generally protect the designated use(s) and water quality standards (WQSs) (USEPA 1985). These can include both physical parameters, such as temperature, and chemical characteristics, such as various pollutants. While more developed countries have a well-established WQC system (USEPA 1985; OECD 1995;

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CCME 1999; RIVM 2001), thus far, in China, WQSs had been based primarily on WQC developed by other jurisdictions (Xia et al. 2004). For this reason, little research has been done on the adequacy of the current WQC in China. Aquatic life criteria (ALC) were only derived for few compounds as a case study, such as heavy metals (Wu et al. 2012), nitrobenzene (Yan et al. 2012), tetrabromobisphenol A (Yang et al. 2012), and chlorophenols (Jin et al. 2011, 2012a, 2012b). In order to maintain the health of aquatic ecosystems in China, a major project to establish, de novo, a set of national WQC that is based on regional characteristics and current conditions has been initiated (Wu et al. 2010).

Development of methods for deriving WQC for protection of aquatic life from adverse effects of both acute and chronic exposures to chemical and physical stressors can provide a technical basis for development of China's WQC. However, establishment of completely novel methodology would be costly and time consuming. Also, due to the similarities in physiologies and natural histories of classes of aquatic organisms, there is no reason to believe that WQC would not be sufficient to protect unique species in China (Jin et al. 2011). However, this has never been investigated and is thus an uncertainty for government regulators and environmental managers. There is urgency on the part of the central and provincial governments to manage the quality of aquatic environments and minimize further degradation and where possible remediate and or restore environments that were previously degraded. The purpose of the present research is to select ALC methodologies, from those currently used throughout the world, which can be efficiently and effectively employed to develop WQC for Chinese ecosystems.

At the core of most methods for derivation of criteria lies ecotoxicological effects data (Wheeler et al. 2002). Ideally, criteria should be based on data of adequate taxonomic diversity that assure protection of most taxa. ALC should be based on science and existing data and models in order to ensure the most effective aquatic life methodology. However, some existing methodologies are not generally suitable for the situation in China (Jin et al. 2009). One must consider the potential toxicity of an increasing number of chemicals to meet new legislative mandates while reducing uncertainty introduced during collection of data calculations based on the various models and procedures used in methods to derive ALC (Bosker et al. 2010). It is recommended that information on the effects of target chemicals with a range of mechanisms of on representative species be used in derivation of ALC. In addition, to basing ALC on appropriate data, it is equally important to select an appropriate conceptual model and method of aggregation and portraying information. Since these concepts are the basis for the derivation of ALC, the objective of the present review is to provide an overview of the state of water quality criteria in China with an emphasis of prioritization of chemicals, test species, mode of action, field/semi-field data, and methods of calculation of ALC.

Prioritization of chemicals

The extensive and intensive use of chemicals in our developed, highly technological society includes more than 100,000 chemical substances. It would be impossible to experimentally assess the toxicity of all of these chemicals or develop WQC for all of these chemicals in a timely manner (Snyder et al. 2000; Mitchell et al. 2002). Thus, some type of prioritization or ranking is required in order to allocate monitoring efforts towards relevant target compounds (Ela et al. 2011; Guillén et al. 2012). A number of prioritization methods have been proposed for and applied to rank different organic compounds (Arnot and Mackay 2008; Muñoz et al. 2008; Kumar and Xagoraraki 2010; Murray et al. 2010; Daginnus et al. 2011), and a detailed review was provided by Bu et al. (2013).

However, for a long time in China, most research on toxic substances was based on methods developed in other countries. There are large quantities of data for toxicities of organochlorine, organophosphorus pesticides, polycyclic aromatic hydrocarbons, and other persistent organic pollutants, but less research on priority pollutants in China (Jin et al. 2009). Based on the experiences of more developed countries, an attempt was made to rank priority pollutants in China using 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. In China, a "black" list of 68 priority pollutants was developed for regulatory purpose. Based on this list, regional priority pollutants were selected in Beijing (Wang et al. 1991), Tianjin (Song et al. 1992), and Zhejiang (Fang and Hu 1991). These lists in China were mainly based on the existing priority lists in USA and Europe. These ranking approaches should be further developed for different situations covering different geographical regions, climates, demographics, and cultural backgrounds and should be designed in such a way that they account for the use practices, complex fate processes, and the specific modes of action associated with many chemicals (Boxall et al. 2013; Bu et al. 2013).

Representative species

In natural ecosystems, there is a range of species with different natural histories and in different feeding guilds that might be differentially exposed or have different sensitivities to stressors. Therefore, the USEPA guidelines state that only wildlife species distributed throughout North America can be used as test species to derive the WQC, such as criteria continuous concentration, for the protection of freshwater and marine ecosystems (USEPA 1985). In Australia, species sensitivity distributions (SSDs) and protective concentrations for 95 % of local species are being used to derive water quality guidelines for toxicants (Hose and Van den Brink 2004). It is commonly thought that different ecosystems contain different biological constituents, and a concentration threshold that would be harmless in one ecosystem may lead to irreversible toxic effects on others. The potential use of toxicity data for nonnative species to derive WQC is controversial, due to the fact that it is sometimes questioned whether criteria based on species from one geographical region provide appropriate protection for species in a different region (Maltby et al. 2005; Kwok et al. 2007). However, this uncertainty could not be resolved previously in large part due to the paucity of toxicity data applicable for local species. In particular, toxicity data, especially for chronic effects on resident species in China, are sparse, and selection of resident species for use in the development of ALC values is confounded by variations among ecosystems throughout China.

Comparisons of sensitivities between native and nonnative species for limited chemicals, such as 2,4-dichlorophenol and pentachlorophenol (Jin et al. 2011; Jin et al. 2012a), revealed that values derived by use of nonnative species values were protective of native species when a safety factor was included. However, closer examination of native and nonnative dataset reveals consistent differences in the species included in the two groups, such that there was deemed to be a lack of parity. Generally, lesser taxonomic diversity is seen in toxicity data for native species. Under such circumstances, bias could be introduced as a result of the presence of more sensitive taxa. A related consideration is representativeness of the available datasets, which is the extent to which the species for which toxicity data are available reflect the natural taxonomic diversity of site-specific water body (Leung et al. 2001). Although there is considerable potential for use of both native or endemic and nonnative species (Maltby et al. 2005), to avoid bias, species parity and representativeness need to be examined for each chemical substance (Leung et al. 2001; Kwok et al. 2007). The objective of the development of China's ALC is to protect treasured and endemic species in China. Because of the lack of information on species characteristic of China's aquatic ecosystem, such as the model fish, the rare minnow (*Gobiocypris rarus*) (Zha et al. 2007, 2008), it is important to develop standardized test methods for local model species in future ALC research.

Adverse outcome pathway

Survival, development, and reproduction are traditional measurement endpoints in ecotoxicity tests. Because these effects can be readily linked to population-level effects, they are favored for derivation of ALC that protect aquatic organisms. Non-traditional endpoints, such as modulation of the endocrine system, induction or inhibition of enzyme activities, alterations of behavior, changes in histology, upregulation of the expression of stress proteins, changes in RNA or DNA incidences of mutagenicity, or carcinogenicity, are often more sensitive than the traditional endpoints, but few relationships between these "biomarkers" links have been established with more apical measures of response that have ecological relevance at either level of the individual, population, community, or ecosystem (Zhang et al. 2008; Fedorenkova et al. 2010). Nevertheless, biomarkers such as vitellogenin, secondary sexual characteristics, gonadal somatic index, concentrations of steroids in blood plasma, and gonadal histology are considered "signposts" in the environmental risk assessment of endocrine-disrupting chemicals (EDs) (Hutchinson et al. 2006), and detection of such signposts determines priority for the chemical and biological analysis for water, sediment, and biota. The potential to use biomarkers as signposts was evaluated by determining the occurrence of false negatives and false positives (Hartung 2009; Bosker et al. 2010) and it has been suggested (Lin et al. 2005) that effects at the molecular or hormonal level will not necessarily be transmitted to higher level ecological effects because of the innate ability of organisms to repair damage or adapt physiologically to the effects (damage) caused by stressors. By contrast, if a population is affected by toxicity of a chemical, then the functions and structures of the ecosystem could also be affected (Lin et al. 2005). Maintaining the viability of populations of plants and animals is a key focus of environmental regulation. For this reason, non-traditional endpoints are rarely used for derivation of ALC, instead population-level endpoints are proposed for the development of ALC. More recently, adverse outcome pathway (AOP) has been proposed to fill in the gap by utilizing individual-level endpoints to predict population responses (Ankley et al. 2010). An AOP is a conceptual construct that portrays existing knowledge of the link between a direct molecular initiating event, such as an interaction between a xenobiotic and a specific bimolecular and an adverse outcome at a biological level of organization relevant to risk assessment. It is critical to select the appropriate individual-level endpoint in data collection for deriving ALC. By using the AOP approach, it is possible to identify endpoints of regulatory concern and to ask which toxicity mechanisms are most likely to lead to adverse outcomes. This is especially invaluable for emerging pollutants with less or no animal toxicity data.

Field/semi-field data

The introduction of the USEPA (1985) methodology notes that it would be ideal if we could determine no-effect concentrations for water bodies by adding various concentrations of a chemical of concern to several clean water bodies and the highest concentration that causes no effect. However, the most abundant, reliable, and easily interpretable toxicity data are from single-species laboratory tests. All of the other types of studies are criticized for lack of standardization, lack of replication, and difficulty of interpretation. Sanderson (2002) reviewed the replicability of micro- and mesocosms and found that coefficients of variation averaged 45 %, with a large, outdoor mesocosms averaging 51 %. Due to these problems and given the relative cost-effectiveness, reproducibility, and reliability of single-species toxicity tests, most methodologies do not utilize multispecies data for criteria derivation.

Hose et al. compared the species sensitivity between laboratory-generated single-species data and semi-field (mesocosm) data based on acute LC50 data for the organochlorine pesticide endosulfan. The findings of this study suggest that the exclusion of natural environmental factors (such as light, temperature, habitat suitability, shelter, etc.) in laboratory tests does not significantly affect the outcome of risk assessments (Hose and Van den Brink 2004). The HC_5 value derived from laboratory data was less than that derived from the mesocosm data and was thus protective of those populations. Versteeg et al. (1999) provided a detailed discussion of why organisms in laboratory studies are likely to be more sensitive than those in mesocosm studies. Differences in water quality and availability of habitat or shelter between laboratory and semi-field studies are also likely to favor greater sensitivity under laboratory conditions, and this can be corrected by assessment factors (e.g., water effect ratio) to get final WQC (Rand and Clark 2000; Welsh et al. 2009). Although there is a tendency to use field data in deriving ALC, it similarly needs more research about its standardization, reproducibility, and reliability in China.

Ecological risk model

Two basic methods for derivation of ALC are in use or proposed for use throughout the world. These include the assessment factor method and the statistical extrapolation methods, such as SSD approach. Single-point assessment factors are recognized as a conservative approach for dealing with uncertainty in assessing risks posed by chemicals. Yet, current applications of safety factors are based on policy rather than on empirical scientific evidence and that they result in values that are protective, but not predictive (Chapman et al. 1998).

The present paper focuses on the derivation of ALC using the SSD method because it can deliver greater statistical confidence into the risk assessment process when compared to the single-point approach. Yet, the extrapolation approach based on single-species toxicity test data has been criticized for their underlying assumptions, which contribute to uncertainty of risk (Jagoe and Newman 1997). For example, species interactions which may have a large impact on effect concentrations are not taken into account in a single-species toxicity testing. In addition, in a single-species toxicity test, the direct effect of a chemical on a one species is usually evaluated under controlled laboratory conditions that do not necessarily mimic environmental conditions. For example, physiochemical properties like the dissolved organic carbon concentration and temperature have been shown to considerably alter the magnitude of direct effects of chemicals (Ke et al. 2007). Multiple species toxicity tests, often termed microcosm or microcosm experiments, have features that promote their use as a realistic way of assessing chemical-induced stress and enable observation of the indirect effects of chemicals caused by interactions among species and physicochemical factors (Giesy and Odum 1980).

Therefore, with increasing awareness of the importance of cost-effective and efficient methods for assessing higher tiered risk assessment of chemicals, population and ecosystem models can be used to evaluate the consequences of exposure to chemicals. An ecological model, which can be defined as a simplified representation of a specific ecological system, may be the only option for assessing chemical effects under circumstances where field experiments cannot be conducted (Naito et al. 2002). One advantage of the use of ecological models in chemical risk assessment is that the models are capable of characterizing process-level relationships between exposure and ecological impacts. Furthermore, indirect effects of chemicals caused by interactions among species can also be characterized by ecological risk models. Therefore, an ecological model used in a regional ecological risk assessment can supply a more reasonable effect concentration compared to extrapolations based on single-species toxicity test. At present, a number of ecological models have been developed and reviewed for potential use in the ecological effect assessment of chemicals. One of them, AQUATOX, has been used to assess the potential ecological risk posed by chemicals in regional aquatic ecosystems (Park et al. 2008). Because the ecological risk model can characterize the indirect effects of chemicals caused by interactions among species, it should be implemented in future derivation of ALC and ecological risk assessment in order to efficiently and accurately produce WQC for China.

Conclusions

We have demonstrated that prioritization of chemicals, test species, mode of action, field/semi-field data, and calculation model all influence analyses to a greater or lesser extent of ALC. This was used to identify the principle issues that need to be addressed in order to better understand the methods for development of criteria for the protection of aquatic life. Aquatic life criteria are mainly based on ecotoxicity studies, but the lack of research in this field cannot fully explain why ALC based on China's domestic aquatic species have not been considered previously. Moreover, China's research in the field of ecotoxicity has been rapidly developing, and currently, the magnitude and quality of studies equal or in some cases exceed than those in more developed countries such as the USA, European Union, Germany, France, Denmark, Spain, Canada, South Africa, and other countries in the development of their ALC. The fact that China has not developed their own WQC is more due to passive strategy for prevention of water pollution and neglect of water quality standards. Protecting aquatic environments requires development of a strategy to prevent pollution of surface waters in our country. This will require recognition of the importance of development and establishment of scientific water quality criteria in China.

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