Ecological Indicators 46 (2014) 1–10

Contents lists available at ScienceDirect

Ecological Indicators

journal homepage: www.elsevier.com/locate/ecolind

Lake ecoregions and nutrient criteria development in China

Shouliang Huo [a,*], Chunzi Ma [a], Beidou Xi [a,**], Rutai Gao [a], Xiangzhen Deng [b], Tiantian Jiang [a], Zhuoshi He [a], Jing Su [a], Feng Wu [b], Hongliang Liu [a]

[a] State Key Laboratory of Environmental Criteria and Risk Assessment, Chinese Research Academy of Environmental Science, No. 8 Anwai Dayangfang, Beijing 100012, China
[b] Institute of Geographic Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing 100101, China

ARTICLE INFO

Article history:
Received 20 March 2014
Received in revised form 23 May 2014
Accepted 10 June 2014

Keywords:
Lake nutrient ecoregions
Nutrient criteria
Stressor–response models

ABSTRACT

China has numerous lakes that have suffered water quality deterioration and decreasing area. Based on climatic, geographic, and ecosystem differences, this study scientifically proposes that national lake ecoregions provide a spatial basis for nutrient criteria development in China. Moreover, ecoregional nutrient criteria were established to support policies for national eutrophication control. China was divided into eight separate lake ecoregions, and the differences in nutrient effects for different lake ecoregions were analyzed. National nutrient criteria were developed for seven lake ecoregions using the stressors–responses models. Due to local variations in water chemistry and lake depth, the range of nutrient criteria exhibited significant differences within certain nutrient ecoregions. The establishment of ecoregional nutrient criteria will provide technical support and implement water quality standards, thereby avoiding the under-protection of lakes in China. To reduce future lake eutrophication, China needs an ecoregional control strategy that integrates measures to comply with regional water quality standards.

1. Introduction

Nutrients such as nitrogen and phosphorus are not toxic to aquatic organisms or humans in small concentrations (Lamon and Qian, 2008). However, they are harmful when they promote the growth of algae and bloom outbreaks that lead to the death of aquatic life and the damage of aquatic ecosystems and water uses (Liu et al., 2011). Hence, a nutrient criterion is defined as the numeric value that supports a particular designated beneficial use beyond which abrupt changes in quality, property, or aquatic ecosystem phenomena exist (US EPA, 1998). Numeric criteria are essential to a water-quality-based approach to pollution control and serve as a critical basis for assessing the attainment of designated uses and measuring progress toward meeting the water quality goals (US EPA, 1998, 2000, 2008).

Currently, many countries and regions have formulated lake ecoregions to establish regional nutrient criteria and meet their requirements of lake management. The process of identifying geographic divisions (i.e., regionalization) is part of a hierarchical classification procedure with the purpose of grouping similar lakes together (Gibson et al., 2000). Initially, the continental United States was divided into 14 separate lake ecoregions of similar geographical characteristics based on perceived patterns of causal and integrative factors that included land use, land surface form, potential natural vegetation, and soils. Moreover, the United States EPA recommended an ecoregion-based national strategy for establishing nutrient criteria (Gibson et al., 2000; Omernik, 1987). In Europe, the water framework directive (WFD) requires bodies of water to be differentiated into types based on geographical differences in catchments (e.g., biogeography of species, geology, and altitude) and lake factors (e.g., depth, area, and water color), and to derive type-specific reference conditions for appropriate ecological quality elements (Cardoso et al., 2007; Carvalho et al., 2008).

The US EPA recommends three types of scientifically defensible empirical approaches for setting regional numeric nutrient criteria: the reference condition approach, mechanistic modeling, and stressor–response analysis (Gibson et al., 2000; US EPA, 2000, 2010). The stressor–response analysis is an appropriate approach for deriving numeric criteria to address nitrogen/phosphorus pollution when minimally affected sites cannot be identified and paleoecological or historic data are not available (Bowman and Somers, 2005; Stoddard et al., 2006; Huo et al., 2013).

China has numerous lakes with rich cultural, ecological, and economic importance (Jin et al., 1990; Ma et al., 2011). Although

* Corresponding author. Tel.: +86 10 8493 7970; fax: +86 10 8491 3805.
** Corresponding author.
E-mail addresses: huoshouliang@126.com (S. Huo), xibeidou@263.net (B. Xi).

http://dx.doi.org/10.1016/j.ecolind.2014.06.014
1470-160X/

the number of lakes is numerous, their spatial distributions are extremely unbalanced. In general, the eastern monsoon region, especially the middle and lower regions of the Yangtze River, is the largest freshwater lakes of China, and the lakes in west are concentrated in the Qingzang Plateau region, mainly inland salt lakes. Over the last 3 decades, significant changes in the number, size, and quality of China's lakes have occurred due to the great increase in human influences on these lakes accompanied by economic and technological development (Ma et al., 2010; 2011). The nutrient standards in the Environmental Quality Standards for Surface Water (2002) do not reflect regional diversities or the lack of constraints on lakes with regional differences. Lake eutrophication management has been under-protected due to the lack of ecoregional nutrient criteria for a scientific basis of eutrophication control (Liu, 2011). Therefore, regional nutrient criteria must be developed that are appropriate for each geographic and climate area and that consider ecoregional variations to better protect lake water quality in China. Therefore, the objectives of this study are: (1) to evaluate the status and trend of Chinese lake eutrophication; (2) to delineate lake nutrient ecoregions of China; (3) to analyze the differences of nutrient effects in different ecoregion lakes; (4) to determine the nutrient criteria of different ecoregion lakes; (5) to discuss the policy implications of regional nutrient criteria.

2. Methods

2.1. Lake nutrient ecoregion delineation

Ecoregions are a mapped classification system of ecological regions, that is, regions with assumed relative homogeneity of ecological characteristics (Omernik, 1987). Lake nutrient ecoregions are developed to define broad areas, within which there are general similarities in natural and anthropogenic characteristics that affect nutrient effects (Gibson et al., 2000). The delineation of lake nutrient ecoregions is the preliminary step for regional nutrient criteria development. China is a vast territory characterized by significant regional variations in climate, geography, and geological conditions. The spatial variations in geographic phenomena that cause or reflect differences in nutrient effects within lakes must be considered to establish meaningful nutrient criteria and better serve the needs of scientific research and policy making.

The approach for defining lake nutrient ecoregions in this study is based on the hypothesis that lake ecosystems display regional patterns that are reflected in spatially variable combinations of causal factors for nutrient effects. These causal factors include climate (precipitation and temperature), physiography (elevation and geomorphology), and moisture index (Gibson et al., 2000), which are the major factors that explain the difference of regional lake nutrient effects. These causal factors causing regional variations in lake nutrient effects were examined to delineate national lake nutrient ecoregions. The interrelatedness of many of the factors is an advantage in defining ecoregions because it reinforces the distinctiveness of particular areas (Omernik, 1987). Lake elevation has great influence on the lake nutrient effects in China, which is significantly negatively related to the TLI index (Cao et al., 2011). With the increase of elevation, the observably decreased temperature will inhibit the growth of algae, resulting in the decline of eutrophication state. Light and a suitable temperature are the necessary conditions for algae growth. In addition, precipitation not only has a dilution effect on lake water, but it also carries nutrients into lakes.

Based on the background data of high spatial resolution, these data of causal factors were converted into spatial data and imported into ArcGIS platform using the sampling analysis and spatial statistics analysis methods. Spatial cluster analysis of ArcGIS was applied to every causal factor to produce thematic maps. The five thematic maps as precipitation, temperature, elevation, geomorphology and moisture index thematic maps were compiled at a same level of generality to delineate the national lake nutrient ecoregions (Fig. 1). The five most important thematic maps were firstly analyzed together to sketch out regions that were relatively homogeneous in their precipitation, temperature, elevation, land surface form and moisture index. Secondly, the thematic maps were overlaid and the levels of generalization of each map were evaluated. The K-means cluster analysis was used on attribute data extracted from these thematic maps to define ecoregion classification. Finally, considering the climate, environment and political boundaries, the national lake nutrient ecoregion boundaries were revised to reflect the conditions that typified each ecoregion.

1.2. Stressor–response models

Stressor–response models including simple linear regression (SLR) and multiple linear regression (MLR), are used to estimate and interpret for deriving numeric nutrient criteria to address nitrogen and phosphorus pollution (US EPA, 2000, 2010). SLR provides an estimate of the linear relationship between a response variable and a stressor variable such as the concentration of Chl *a* and TP or TN. The results of SLR are two coefficients specifying the intercept and slope of a straight line representing the modeled relationship between the two variables. To provide reliable results, the two coefficients estimated using SLR require the use of at least 20 independent samples when fitting the model (US EPA, 2010).

MLR is the extension of SLR to provide an estimate of the linear relationships between one dependent variable and two or more independent variables. It is useful in cases in which other environmental factors in addition to the nutrient variable influence the response, or in cases in which the effects of different nutrients must be modeled together.

In this study, TN and TP were chosen to represent the stressor variable and Chl *a* was selected as the biological response variable. The annual mean data of lakes were applied to build stressor–response models. Prior to analysis, log-transformation ((base 10)) was considered for all the variables to symmetrize the distribution (Tamhane and Dunlop, 2000).

1.3. Data sources and data quality

Nutrient data throughout the national lakes were obtained from the environment agencies and scientific institutes, including ambient monitoring network supported by the Department of Provincial Environmental Protection of China. The obtained data consist of measurements for stressor variables such as total nitrogen (TN) and total phosphorus (TP), and response variables such as chlorophyll a (Chl *a*).

The final dataset was rather heterogeneous as some lakes were sampled every month over 20 years whereas others were sampled only once or three times per year. In this study, we only used those lakes sampled on at least three surveys (in three water periods) in separate years over this time interval and averaged these data for every year for a given lake. The final dataset contained a total of more than 170 lakes identified for this analysis. The water quality parameters were measured according to the standard methods (PRC EPA, 1988). Each integrated water sample was a mixture of two sub-samples from 0.5 m below the surface and from 0.5 m above the bottom, respectively. All water samples were analyzed for different physico-chemical