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Integrated water quality, emergy and economic evaluation of three bioremediation treatment systems for eutrophic water

Hongfang Lu[a], Yaguang Yuan[b], Daniel E. Campbell[c], Pei Qin[b,*], Lijuan Cui[d,**]

[a] Key Laboratory of Vegetation Restoration and Management of Degraded Ecosystems, South China Botanical Garden, Chinese Academy of Sciences, Guangzhou 510650, China
[b] Halophyte Research Lab, Life Science School, Nanjing University, Nanjing 210093, China
[c] US EPA, Office of Research and Development, National Health and Environmental Effects Research Laboratory, Atlantic Ecology Division, 27 Tarzwell Drive, Narragansett, RI, USA
[d] Institute of Wetland Research, Chinese Academy of Forestry, Beijing 100091, China

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A B S T R A C T

This study was targeted at finding one or more environmentally efficient, economically feasible and ecologically sustainable bioremediation treatment modes for eutrophic water. Three biological species, i.e. water spinach (*Ipomoea aquatica*), loach (*Misgurus anguillicaudatus*) and a pseudomonad (*Rhodopseudomonas palustris*), were combined in different ways: (A) water spinach–loach–pseudomonad; (B) water spinach–loach; (C) water spinach–pseudomonad, to construct three ecological engineering systems targeted at removing nutrients from the eutrophic water of Taihu Lake, PR China. An integrated water quality, emergy and economic evaluation of the three treatment systems was performed based on the observed changes in biomass, water quality, and other natural and economic inputs and outputs. The three ecological engineering treatment systems showed a different order of efficiency in removing nutrients (treatment A > B > C), produced different environmental loadings at the foreground (treatment B > C > A), background (treatment C = A > B) and whole system scales (treatment C > A > B), and had different economic feasibility (treatment B > A > C). Finally, after taking all direct and indirect environmental and economic impacts into account, treatment A was found to be the best choice at the foreground scale, followed by treatment C and then B, while at the background and whole system scales, treatment B was the best option followed by A and C. In this analysis, emergy evaluation was found to be an ideal ecological integration tool for quantifying both the environmental and economic characteristics of ecological engineering systems and processes at multiple scales, including pollution treatment systems. The complex results of this study obtained by considering water treatment efficiency, emergy indices of sustainability and loading on multiple scales besides economic output/input analysis can inform decision-makers about trade-offs that confront them in the management of eutrophic waters.

1. Introduction

Eutrophication, or more precisely hypertrophication, is a syndrome of ecosystem response to the addition of extremely large quantities of artificial or natural substances, such as nitrates and phosphates, to an aquatic system; for example, as through high volumes of fertilizer runoff or municipal sewage inflow (Schindler and Vallentyne, 2004). Accelerated eutrophication of lakes and reservoirs has become a world-wide environmental issue, and it represents a serious degradation of water quality that results in losses of ecological integrity, sustainability and compromises the safe use of aquatic ecosystems (Qin, 2009). China's prosperous economy and high population density are causing the eutrophication of lake water to such an extent that it has become one of the most important factors impeding sustainable development in the country (Le et al., 2010). According to the '2009 Report on the State of the Environment in China' (MEPC, 2010), among the 26 key lakes (and reservoirs) under eutrophication monitoring, 1 was heavily eutrophied, comprising 3.8% of the total number; 2 were under intermediate eutrophication, comprising 7.7%; 8 were under slight

* Corresponding author at: 22 Hankou Road, Nanjing 510650, Jiangsu Province, China. Tel.: +86 25 83592694; fax: +86 25 83592694.
** Co-corresponding author.
E-mail addresses: qinpei@nju.edu.cn (P. Qin), lkyclj@126.com (L. Cui).

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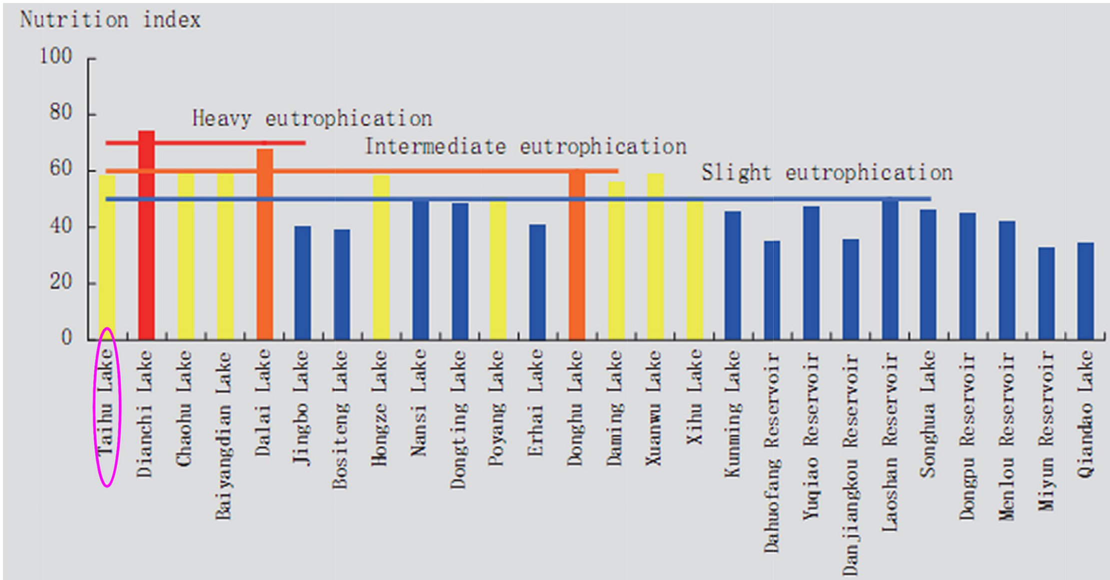

Fig. 1. Nutrition index of major lakes and reservoirs in China.

MEPC, 2010.

eutrophication, accounting for 30.8% and the rest 57.7% posted a mesotrophic level of nutrients. Three of the five largest freshwater lakes in China are eutrophied, i.e. Taihu, Dianchi and Chaohu lakes (Fig. 1).

Taihu Lake with a surface area of 2338 km^2 is the largest freshwater lake in the Yangtze Delta, which is located in the eastern part of China. In this study, we chose Taihu Lake as a case study to examine the feasibility of establishing ecologically and economically sound treatment systems for eutrophic lake waters. Taihu presents a classic case of a eutrophic lake, because it is characterized by large and serious ecological and economic effects related to its trophic state (e.g., blue-algae blooms in summer, which directly threaten the drinking water security of cities near the lake's edge, like Wuxi and Suzhou, etc.). In addition, the Taihu Lake Basin is one of the most densely populated and most economically developed areas of China, contributing over 3%, 10% and 14% of China's population, GDP and government financial income, respectively (Mao et al., 2008; Gao et al., 2009).

Understanding how to control eutrophication and treat eutrophied lake water is an essential and urgent problem confronting not only the Chinese government, but also other countries and areas that want to promote more sustainable development. Many studies have been done and applications developed for this purpose during the past decade, based on physical, chemical, and biological methods (Schauser et al., 2003; Walpersdorf et al., 2004; Jobgen et al., 2004; Wauer et al., 2005; Le et al., 2010; Li et al., 2012). After physical methods of treating eutrophication, such as removing bottom mud, etc., were found to be too expensive, and chemical methods were found to have a high risk of secondary pollution; ecological techniques began to receive more interest. Ecological treatment systems have minimal side-effects and are relatively cheap to install and easy to operate for using the excess nutrients in eutrophic water bodies, through the cooperative metabolism of aquatic plants, microorganisms and animals, etc. (Mitsch et al., 2005; Song, 2007; Sierp et al., 2009; Li et al., 2009; Han and Li, 2012). Many ecological treatment methods have been developed (Zhao et al., 2010), but quantitative ecological–economic comparisons among them are still lacking, although knowing the relative efficacy of such methods is an essential precondition for effective planning and for choosing effective policies.

Many analytical tools are available for assessing environmental impacts and the sustainability of ecological economic systems, such as life cycle assessment (LCA), exergy analysis, and energy evaluation, etc. Among them, emergy evaluation has been found to be especially appealing, and as a result, it has been applied more and more widely in evaluating not only waste disposal and recycle systems (Björklund et al., 2001; Brown and Buranakarn, 2003; Grönlund et al., 2004; Giannetti et al., 2008; Mu et al., 2011), but also other ecological economic systems at different scales (Odum, 1996, 2007; Brown, 2009, 2011), due to its ability to compare different qualities and types of energy, material and information using a common unit, the solar equivalent joule. As a result emergy can account for the contributions of the environment to the economy and quantify economic activities on an equal basis.

Seeking environmentally efficient, economically feasible and ecologically sustainable bioremediation treatment modes for eutrophic lake water, three biological species, i.e. water spinach (*Ipomoea aquatica*), loach (*Misgurus anguillicaudatus*) and a pseudomonad (*Rhodopseudomonas palustris*), were chosen to construct a suite of ecological engineering systems for absorbing the nutrients in the eutrophic water of Taihu Lake. An integrated evaluation of water quality, emergy and economic aspects of the three treatment systems was done in this study, based on the observed changes in biomass, water quality, and other natural and economic inputs and outputs.

2. Methods

2.1. Materials

An aquatic plant, an aquatic animal and a microorganism were chosen in this study with the goal of assembling model treatment ecosystems with a closed food chain. The three species were chosen based on literature studies about them and their ability to contribute to the treatment of eutrophic water.

2.1.1. Plant

water spinach (*I. aquatica*) is a semi-aquatic plant that can be grown with remarkable ease in many areas as a leaf vegetable by rooting at the nodes. Water spinach stems are hollow so they can