Sustainable Environment Research 26 (2016) 243–248

Contents lists available at ScienceDirect

Sustainable Environment Research

journal homepage: www.journals.elsevier.com/sustainable-environment-research/

Original research article

Reconstructing nutrient criteria for source water areas using reference conditions

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A R T I C L E I N F O

Article history:
Received 29 September 2015
Received in revised form
29 January 2016
Accepted 7 March 2016
Available online 24 May 2016

Keywords:
Reference conditions (RCs)
Nutrient criteria
Source water protection
Land disturbance

A B S T R A C T

Nutrient concentrations are of concern in most watershed areas that serve as source water for public drinking water due to the high cost of nutrient removal treatment. Yet all nutrients criteria for source watersheds in Taiwan are identical for quality standards and the specific conditions of each source watershed were not considered. Nutrient RCs estimated by statistical methods and land disturbance modeling were applied to the Tamsui River in Taiwan. The results were then used to evaluate the nutrient status of Taipei Water Source Domain, which is located near the upstream portion of Tamsui River. The estimated RCs of NH_3-N, TP, and Total N were 0.03–0.04, 0.019 to 0.036, and 1.22–1.50 mg L^{-1}, respectively. Comparing with current criteria of NH_3-N (0.1 mg L^{-1}), the estimated reference conditions are lower and the criteria could be stricter to maintain sufficient water quality. However, the reference condition of TP estimated by the disturbance modeling (0.03 mg L^{-1}) is higher than current criteria (0.02 mg L^{-1}), leading to a possible loosening adjustment.

1. Introduction

For surface water supplies of drinking water, watershed protection approaches have provided an integrated framework to improve the identification of the highest priority problems and to focus water pollution control effects on the protection of drinking water supplies [1,2]. Many countries have developed assessment tools for protecting watersheds that supply drinking water [2,3] or further established water quality criteria for regulating source water [4]. In Taiwan, two water quality standards, the “Surface Water Classification and Water Quality Standards (hereinafter, Taiwan Surface Water Standards)” and the river pollution index (RPI) [5], can be applied to regulating the water quality of rivers and are also used to evaluate the water quality in watersheds that supply drinking water. However, the water quality in the source water protection area may exhibit different features depending on the specific geographical locations where the watersheds are situated. The uniform criteria for all drinking water protection areas that do not consider the geographical characteristics may not actually reflect the water quality status [6]. In particular, for the nutrient management that results in eutrophication problems, exploring the nutrient background concentration and defining the amount from anthropogenic activities are critical to establish watershed protection plans and prevent increasing the load in water treatment processes for water supply.

The reference conditions (RCs) that are used to provide the biological integrity in biological assessments have been taken to determine the natural background nutrient concentrations in streams [6–12]. Nutrient RCs have been estimated using two main approaches: percentile analysis and disturbance modeling. Percentile analysis identifies nutrient concentration based on analysis of data frequency distributions. Disturbance modeling examines the relationships between nutrient variables and disturbing factors, such as land use type and population density, to establish non-disturbance background concentration [13]. USEPA [12] outlined approaches for establishing the RCs, including the 75th percentile of reference sites and the 5 to 25th percentile of total population. Thereafter, several researchers have used the percentile methods to determine the river nutrient criteria [14–17]. Furthermore, Sánchez-Montoya et al. [18] also used the percentile approach to establish the physio-chemical RCs in Mediterranean streams according to the European Water Framework Directive.

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Peer review under responsibility of Chinese Institute of Environmental Engineering.

http://dx.doi.org/10.1016/j.serj.2016.05.002

In addition to the percentile approaches, disturbance modeling has also been used to establish RCs of river nutrients [6,7,19]. The disturbance modeling is a model of multiple linear regressions for evaluating the statistical relationship between river nutrient concentrations and human disturbance [7]. The conditions of the basin environment can return to the undisturbed conditions, which are regarded as the RCs, when the human disturbance is completely removed [20,21]. The disturbance modeling can predict the background nutrient concentrations without abundant reference-site data. Dodds and Oakes [6] used regression models to analyze the relationship between the nutrient concentrations and the disturbance variables (anthropogenic land uses and population densities) to estimate the background concentrations of TN (sum of NO_3^--N, NO_2^--N, and total Kjeldahl nitrogen) and TP in 14 ecoregions. Herlihy and Sifneos [7] applied road densities, population densities, anthropogenic land uses, and riparian disturbance indices as disturbance factors to evaluate the background TN and TP concentrations in three ecoregions.

In northern Taiwan, the Taipei Water Source Domain (TWSD) located upstream of the Tamsui River is the most important source water protection area. According to the monitoring data in the past six years (2005–2010), the nutrient concentrations in the area often exceeded the Taiwan surface water standards. However, current standards are not established specifically to source water areas; nor do they consider the geographical features for each watershed. This study uses the TWSD as a case study to evaluate the source water quality by comparing with the nutrient RCs which were estimated by percentile and disturbance modeling methods. Additionally, the results provide suggestion for revising the current water quality standards.

2. Materials and methods

2.1. Study area

The TWSD, a source water protection area delineated in 1984 and managed by the Taipei Water Management Office (TWMO), is located in northern Taiwan (Fig. 1). The Feitsui Reservoir, which provides drinking water to approximately 5 million people in the Taipei metropolitan area, is situated within this domain. The area of the TWSD is 717 km^2. Over 92% of the area is forested, 2% is agricultural land, and approximately 1% is urban and transportation uses. The activities of land-use, mining, forestry and recreation are strictly limited in the area. As a result, the nutrients status in this area is better than that of the midstream and downstream regions in the Tamsui River. The average concentrations of TP and NH_3-N in the TWSD are 0.023 and 0.02 mg L^{-1}, which are lower than the average concentration of TP and NH_3-N in the Tamsui River Basin (0.162 and 0.98 mg L^{-1}, respectively). We adopted the monitoring sites in the TWSD as reference sites to estimate the background nutrient concentrations for the Tamsui River and later compared the derived criteria with the current water quality standards and monitoring data to discuss the suitability of the requirements of the regulations.

The Tamsui River is 159 km long and has an area of 2726 km^2, whose main source is situated at the latitude 24°26′11.3″ N and at the longitude 121°15′56.6″ E in the northern Taiwan. The average annual precipitation in the Tamsui River Basin can vary from 2100 mm in the estuary to 5000 mm in the mountains. The fluctuating flow condition obtained from a hydraulic station in the central part of the basin is shown in Fig. 2. Most peak flow occurred during the typhoon season from July to September. There are approximately 9 million people, 39% of the overall population in Taiwan, living in the basin. Approximately 70% of the area is forested; 17% of the area is for urban and transportation uses; 6% is for agricultural use.

2.2. Data collection

The data used to establish the RCs of the nutrients came from two sources. The first source was from the 38 sites of Taiwan EPA's monitoring sites distributed in the Tamsui River Basin, and the other source was from the 23 sites monitored by the TWMO (Fig. 1). Because the area managed by TWMO is assumed pristine or the least-disturbed upstream watersheds, the water quality there is classified into Category A according to the Surface Water Standards and classified into the unpolluted or slightly polluted class according to the Taiwan RPI (Table 1).

The RCs of NH_3-N, TP, and TN were analyzed in this study. The NH_3-N and TP concentrations were monitored monthly from 61 sites (Taiwan EPA and TWMO) from 2005 to 2010. The TN was monitored monthly from 38 Taiwan EPA sites from 2002 to 2006. If any monitored record is reported as "not detected", half of the detection limit is used to replace the record for further analyses. The detection limits of NH_3-N, TP were 0.1 and 0.006 mg L^{-1}, respectively.

2.3. The percentile values from the monitoring sites

The 75th percentile of the reference sites is one of the reference-site approaches for establishing the background nutrient criteria. The USEPA [12] suggested that authorities could use the 75th percentile values of the nutrient concentration distribution in reference streams as the standards for regulating river nutrients. This approach was adopted in this study to determine the candidate criteria of the NH_3-N and TP concentrations in the Tamsui River with the data from the 23 reference sites. Because Taiwan EPA did not monitor TN for the reference sites, no TN criterion was suggested by this 75th percentile approach.

When the reference sites are few or not available, the USEPA [12] provided the 5 to 25th percentiles of the total population sites as a surrogate instead of the 75th percentile of the reference sites. This approach chooses one percentile from the 5 to 25th percentiles of the nutrient concentration distribution of the general sites as the candidate nutrient criteria. In this study, the 5 to 25th percentiles of the population was calculated with the data of 61 sites (from the entire basin and from the reference sites) to estimate the NH_3-N and TP background concentrations. However, the TN criterion was suggested by the data of the 38 Taiwan EPA sites.

2.4. Disturbance modeling

Disturbance modeling establishes the statistical relationship between the river nutrient concentrations and the human disturbance levels to predict the natural background nutrient concentrations. The median of the monthly nutrient concentrations monitored from 61 sites was modeled with multiple linear regressions as a function of the disturbance variables [7]. All the nutrient concentrations were log transformed for normal distributions (Kolmogorov-Smirnov test, $p > 0.05$) and to avoid negative intercepts that lead to negative concentrations [6]. The intercepts of the regression models represent the nutrient concentrations in the absence of anthropogenic land uses and other human disturbance variables.

The disturbance factors used in this study include the percentage of paddy land, upland, orchard land, husbandry land, urban land, transportation land, and the population densities; however, one variable was deleted if any two variables were highly correlated ($r > |0.80|$) to avoid collinear problems. The multiple linear