Limnologica 64 (2017) 38–45

Contents lists available at ScienceDirect

Limnologica

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

Identifying the relationships between trophic states and their driving factors in the Shihmen Reservoir, Taiwan

Wen-wen Liu[a,b], Enmin Zhao[a,b], Yi-Ming Kuo[a,b,*], Cheng-Shin Jang[c]

[a] School of Environmental Studies, China University of Geosciences, Wuhan 430074, China
[b] Laboratory of Basin Hydrology and Wetland Eco-restoration, China University of Geosciences, Wuhan 430074, China
[c] Department of Leisure and Recreation Management, Kainan University, Luzhu, Taoyuan 338, Taiwan

ARTICLE INFO

Keywords:
Dynamic factor analysis (DFA)
Classification and regression tree (CART)
Eutrophication
Trophic state index (TSI)

ABSTRACT

Eutrophication has become a crucial issue for water resource management in recent years. In addition, reservoir trophic states are varied with environmental and water quality variables. The objectives of this study were to apply the DFA model to examine which water quality variables significantly affect variations of trophic state index (TSI) factors (i.e. total phosphorus (TP), chlorophyll-a (Chl-a), and Secchi disk transparency (SD)) and use classification and regression tree (CART) to determine the trophic states of the Shinmen Reservoir based on the levels of TSI factors during spring 2001–winter 2009. Results showed that the optimal DFA model contained one common trend (the underlying processes influencing trophic states, which can be rainfall intensity or runoff volume) and 7 explanatory variables. Turbidity (TB), pH, and dissolved oxygen (DO) influence concentrations of TP, while ammonium nitrogen (NH_3-N), organic nitrogen (O-N), and nitrate nitrogen (NO_3-N) control variations of Chl-a, and TB is related to SD. The CART model can specify trophic states only using two dominant driving factors, i.e. TP and Chl-a. The results of the CART illustrated that eutrophication could be occurred in the Shihmen Reservoir if TP is greater than 31.65 μg/L or if Chl-a is greater than 5.95 μg/L while TP concentration is less than 31.65 μg/L. Runoff nonpoint source pollution resulted from heavy storms may be the important factor affecting reservoir trophic states. Establishing vegetative filter strips along the riparian zone may able to effectively reduce this pollution in a reservoir. The integrated DFA and CART serves as good-fit relationships among trophic states, TSI factors, and water quality variables and provide control strategies for managing water quality in the Shihmen Reservoir.

1. Introduction

Eutrophication or algal bloom in lakes and reservoirs has been a major water quality issue in many parts of the world (Smith et al., 1999; Kuo et al., 2006; Qiang et al., 2012). Nutrient enrichments from point and nonpoint source pollutants discharged into water bodies frequently cause algal blooms, decrease dissolved oxygen (DO), and consequently inhibit the growth of aquatic organisms (Karul et al., 2000). In addition, algal bloom can reduce transparency (Havens, 2007; Yang et al., 2012) and increase facility costs associated with water purification (Chou et al., 2007; Shen et al., 2011). Therefore, understanding the factors reflecting the trophic states and reducing the probability of eutrophication occurrence has become an important concern in water resource management (Smakhtin, 2001).

The trophic state index (TSI), based on the calculation of total phosphorus (TP), chlorophyll-a (Chl-a), and Secchi disk transparency (SD), is a composite measurement for evaluating the healthy status of water bodies (Carlson, 1977). TSI provides an effective method to classify the trophic states (oligotrophic, mesotrophic, or eutrophic) of a reservoir in a scale of 0–100. However, factors (such as hydrological, abiotic, and biotic variables) affecting trophic states or algal blooms of a reservoir are complicated (Kuo and Wu, 2016). We still need to investigate which factors relate to the variations of TSI factors (i.e. TP, SD, and Chl-a) for well managing trophic states.

Dynamic factor analysis (DFA) has been used to analyze the relationships between time series data of multivariate water quality and environmental variables (Kuo and Chang, 2010; Kuo et al., 2013, 2014; Kuo and Wu, 2016). DFA is a dimension reduction technique that can estimate common patterns, identify interactions between multivariate time series, and capture the effects of explanatory time-dependent variables (Zuur et al., 2003; Muñoz-Carpena et al., 2005). DFA was initially developed to analyze economics studies, but was later extended to apply in studies of groundwater levels and quality (Muñoz-Carpena et al., 2005; Ritter and Muñoz-Carpena, 2006; Kaplan et al.,

* Corresponding author at: School of Environmental Studies, China University of Geosciences, Wuhan 430074, China.
E-mail address: airkuo@ntu.edu.tw (Y.-M. Kuo).

http://dx.doi.org/10.1016/j.limno.2017.04.004
Received 16 July 2016; Received in revised form 5 December 2016; Accepted 25 April 2017
Available online 19 May 2017
0075-9511/

2010; Kuo and Chang, 2010), aquatic ecology (Zuur and Pierce, 2004; Kuo and Lin, 2010; Kuo et al., 2013), and $PM_{2.5}$ and ozone pollution (Yu et al., 2002; Kuo et al., 2011a,b; Kuo et al., 2013). Recently, Kuo and Wu (2016) used DFA model to point out that water temperature, electrical conductivity, water level, nutrients (total phosphorus, NO_3-N, and NH_3-N), and macro-zooplankton were the key factors affecting the abundances of predominant phytoplankton in the Shihmen Reservoir.

Classification and regression tree (CART) can be used to illustrate nonlinear relationships between variables (Crichton et al., 1997). The CART, a data mining tool (Williams, 2011), can explore and analyze large data sets in search of meaningful patterns (Hurwitz et al., 2013). CART may also provide a valuable tool for uncovering the hidden interactive structure of water quality and revealing an enhanced influence mechanism of environmental variables on water quality (Atkins et al., 2007). The CART algorithm has been applied to predict the scour below ski-jump bucket spillways (Breiman et al., 1984; Lamon and Stow, 2004), discuss the critical submergence for different clearance bottoms (Qian and Anderson, 1999; Veronika et al., 2014), and classify the potential distribution of various gullies statements (Lin et al., 2011).

This study applied DFA and CART models to assess the relationships between the trophic states and dominant water quality variables during spring 2001 to winter 2009 in the Shihmen Reservoir, Taiwan. The DFA model is applied to examine the most responsible water quality variables affecting the temporal changes of TSI factors (i.e. SD, TP, and Chl-a) and to identify the meaning of common trends that represent any unexplained variability in the TSI factors. The CART is applied to determine the trophic states of the Shihmen Reservoir based on the levels of SD, TP, and Chl-a variables. The integrated approach identifies key factors affecting the levels of SD, TP, and Chl-a variables and provides applicable management strategies for controlling the eutrophication in the Shihmen Reservoir.

2. Material and study area

2.1. Study area

The Shihmen Reservoir, located in the northern Taiwan (Fig. 1), was completed in 1964 to provide irrigation, public water supplies, power generation, and flood control. The Shihmen Reservoir greatly contributes to the agricultural and industrial developments in northern Taiwan and prevents calamities such as floods and droughts (Wu et al., 2004). The Reservoir has a 763 km^2 catchment area with 16.5 km in length, covering Taoyuan, Hsinchu, and Ilan counties. Its highest water level (highest capacity) and lowest water level (dead water level) are at 245 m and 195 m, respectively. The reservoir watershed has a subtropical monsoon climate with the annual average temperature as 19 °C, and average annual rainfall ranging from 2200 to 2800 mm. During typhoon seasons, subtropical storms frequently attacked Taiwan and substantially increased sediment and nutrients in this reservoir (Tsai et al., 2012; Chen et al., 2010).

2.2. Analyses of physico-chemical data

Fig. 1 shows the sampling site of this study. Water samples of one designated were collected seasonally from spring 2001 to winter 2010 at a depth between 0.5–1.0 m below water table. Water samples were then preserved and transported to the laboratory and analyzed within 24 h of sampling. Water temperature (TEMP), pH, and electrical conductivity (EC) were measured on site. Turbidity (TB), suspended sediment (SS), chemical oxygen demand (COD), organic nitrogen (O-N), total hardness (TH), total alkalinity (Alk), ammonium-nitrogen (NH_3-N), nitrate-nitrogen (NO_3-N), DO, TP, SD, and Chl-a were analyzed by the APHA standard method (APHA, 2000).

3. Methods

Fig. 2 shows the framework how the integration of DFA and CART was used to determine factors controlling reservoir trophic states. DFA was used to quantify the temporal relationships between TSI factors (SD, Chl-a, and TP as response variables) and their driving factors (other variables as explanatory variables). The CART was applied to classify the trophic states of the Shihmen Reservoir based on TSI factors. In this study, data of TSI factors and environmental variables from spring 2001 to winter 2009 were used for DFA and CART analyses, while data of the TSI factors in 2010 were used for verifying the accuracy of the CART training process.

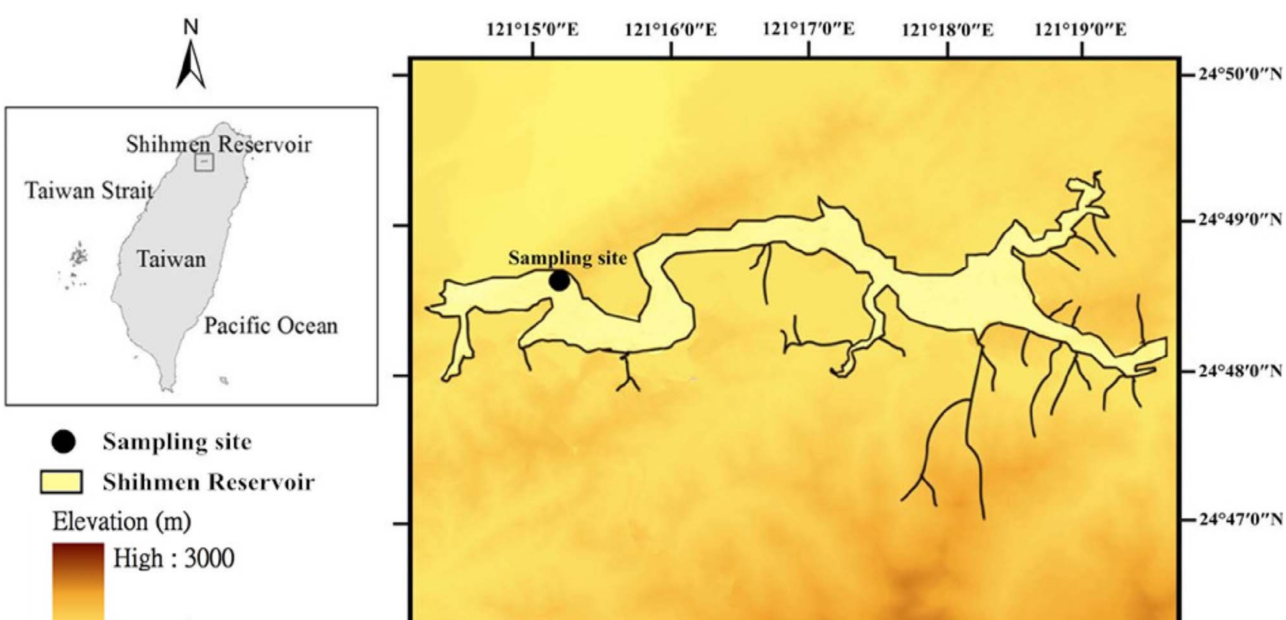

Fig. 1. Study area in the Shihmen Reservoir, Taiwan.