Journal of Environmental Management 145 (2014) 94–105

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Total phosphorus reference condition for subalpine lakes: A comparison among traditional methods and a new process-based watershed approach

Franco Salerno [a], [*], Gaetano Viviano [a], Elisa Carraro [a], Emanuela Chiara Manfredi [a], Andrea Lami [b], Simona Musazzi [b], Aldo Marchetto [b], Nicolas Guyennon [b], Gianni Tartari [a], Diego Copetti [a]

[a] *CNR – Water Research Institute (IRSA), Via del Mulino 19, Brugherio, MB, 20861, Italy*
[b] *CNR – Institute of Ecosystem Study (ISE), Largo Tonolli 50, Verbania Pallanza, VB, 28922, Italy*

A R T I C L E I N F O

Article history:
Received 10 February 2014
Received in revised form
28 May 2014
Accepted 11 June 2014
Available online

Keywords:
Export coefficient models
Phosphorus
Reference conditions
Morpho Edaphic Index
MEI
Hydrological transport model
Diatom inferred TP
Chlorophyll inferred TP

A B S T R A C T

Different methods for estimating the total phosphorus (TP) reference conditions of lakes have rarely been compared. This work tests the uncertainty and accuracy of the most frequently used approaches (Morpho-edaphic index -MEI-, export coefficient, diatoms and pigment-inferred TP models) for 35 subalpine lakes. Furthermore, we propose a new *process-based watershed approach* that was tested on a subalpine environment and consists of combining a space for time substitution with a space for space substitution. The possible presence of uncontaminated or less contaminated environments inside or next to the watershed can be exploited by training a hydrological transport watershed model according to the uncontaminated conditions and then applying the calibration to the entire watershed, which reconstructs a natural or semi-natural TP load scenario. We found that the root mean square error (RMSE) for the MEI is 4 $\mu g\ L^{-1}$. However, its application is limited for lakes that present with an alkalinity ≤ 1 meq L^{-1}. For lakes with a higher alkalinity, we observed a loss of predictive capability that results from the lower solubility of phosphorus under conditions of high calcium content. The export coefficient model was applied with a mean export coefficient and presents similar prediction capabilities as the MEI. The chlorophyll-inferred TP model shows a higher uncertainty (RMSE = 8 $\mu g\ L^{-1}$); however, it produced fewer underestimations and overestimations. With regards to the diatom-inferred TP model, we are only able to evaluate an uncertainty of 5 $\mu g\ L^{-1}$ at the European level. Finally, the proposed *process-based watershed approach* adequately predicted the reference condition of the selected lake and had an uncertainty lower than the other methods (2 $\mu g\ L^{-1}$). We conclude by revealing the potential and limitations of this approach in the field of ecological lake modelling more and more attracted by TP pristine load inputs in studies on the effects of climate change and eutrophication of lakes.

1. Introduction

Significant efforts have been taken to establish quality criteria and thresholds for classifying lakes according to their trophic status (e.g., Carlson, 1977; OECD, 1982; Buraschi et al., 2005). These criteria include nutrient (e.g., phosphorus and nitrogen) concentrations and physico-chemical (e.g., transparency and dissolved oxygen) and biological (e.g., chlorophyll) features. However, the role of phosphorus is generally recognised as a limiting factor in the process of eutrophication; therefore, it is widely used as a reference target to summarise the trophic condition of lakes (OECD, 1982; Schindler et al., 2008). The level of divergence between the current state and the natural or semi-natural reference condition

---

Acronyms: HYDRO, Hydrological Transport model; MEI, Morpho Edaphic Index; TP, Total Phosphorus; Chll-TP, Chlorophyll inferred TP model; DI-TP, Diatom inferred TP model; EXP-coeff-TP, Export coefficient TP model; MEI-alk-TP, Morpho-Edaphic Index; alkalinity, MEI-cond-TP; Morpho-Edaphic Index, conductivity; RMSE, Root Mean Squared Error; RMSEP, Root mean squared error of prediction; HA, High Alkalinity group; LM-A, Low-Medium Alkalinity group.

[*] Corresponding author. Tel.: +39 039 21694221; fax: +39 039 2004692.
E-mail address: salerno@irsa.cnr.it (F. Salerno).

http://dx.doi.org/10.1016/j.jenvman.2014.06.011

should be considered a crucial element in any ecological research and assessment programme (Bennion et al., 2005) because it provides a baseline for estimating human-induced lake changes with time, allows conclusions to be drawn as to the degree of the human impact to the current status and permits inferences to be made about potential future changes (Vollenweider, 1975; Vighi and Chiaudani, 1985; Cardoso et al., 2007; Lami et al., 2010; Pacini et al., 2013). Therefore, reference phosphorus concentrations are required to guide lake remediation strategies (Bennion et al., 2005). Phosphorus reference condition is referred here to a natural or semi-natural trophic state of a lake characterized by insignificant anthropogenic impacts (e.g., Anonymous, 2003; Cardoso et al., 2007; Salerno et al., 2014). A number of approaches have been proposed to establish phosphorus reference conditions (EPA, 1998), and a review can be found in the guidance on reference conditions documents of the Water Framework Directive (Anonymous, 2003; Solheim, 2005). In general, the approaches include 1) historical data analysis, 2) inferential models and 3) watershed models. In the absence of long-term monitoring data sets, the latter two approaches are the most frequently used.

Among the inferential models, the two main models are the morpho-edaphic index and paleolimnological reconstructions. The former exploits the positive correlation between the indicators of total ionic concentration (e.g., conductivity and total alkalinity) and TP concentrations found in water bodies with relatively undisturbed catchments (Battarbee et al., 2005; Cardoso et al., 2007), whereas the latter uses established relationships between total phosphorus (TP) concentrations and the diatom assemblage composition or chlorophyll content. TP inferences based on chlorophyll concentrations rely on the assumption that chlorophyll is proportional to nutrient levels and can be used as a proxy for algal biomass (Steele, 1962). This assumption directly leads to the well-known relationships between TP concentration and pigment concentration in water (e.g., OECD, 1982; Phillips et al., 2008) and sediment (e.g., Hall et al., 1997). According to Juggins (2013), the diatom-based method can only be used for inferring variables that directly affect diatom assemblage composition and is very sensitive to changes in other variables. TP is one of the most important variables controlling diatom composition, but the reliability of TP inferences in each specific lake should be carefully evaluated.

Of the wide range of watershed models, which are also defined as land-use models, the export coefficient approach is likely to have a wider practical application, particularly in the context of the Water Frame Directive (European Union, 2000), because it is simple to apply and requires little data. On the other hand, an innovative approach deals with the implementation of hydrological process-based models applied at the lake watershed scale. These models require specific input information regarding weather, soil properties, topography and vegetation but can simulate the dynamics of different processes occurring in the watershed, such as water movement, nutrient transport, vegetation growth and sediment movement processes (Solheim, 2005). Unlike the other approaches, the watershed models must be coupled with a supplementary model to convert the P-load to the mean in—lake TP estimates. The simplest approach consists of using the Vollenweider model (Vollenweider, 1975; OECD, 1982), in which the in—lake mean phosphorus concentration can be obtained from relatively simple data input, such as the water volume, lake hydraulic residence time, mean lake depth and phosphorus loading. Another approach is to implement a process-based lake model or a hydrodynamic and ecological model that includes a comprehensive representation of the biogeochemical processes occurring in lacustrine environments, with a substantial increase of data inputs (Carraro et al., 2012a).

The inferential models and export coefficient model are traditional models in which the estimates of TP reference conditions are unique synthetic values representing the annual mean natural or semi-natural external load and corresponding in—lake concentrations, whereas the process-based watershed approach is capable of developing dynamic scenarios tracing the hydrological and transport processes in the watershed under natural or semi-natural conditions. Coupling a process-based watershed approach with a process-based lake model allows or the development of ecological scenarios under simulated pristine conditions of the watershed; this type of integrated modelling is becoming increasingly common in the current scientific context (Mooij et al., 2010; Trolle et al., 2010), although few applications (Carraro et al., 2012b) have been developed for the simulation of natural or semi-natural lake-watershed conditions as well as their subsequent comparison with current conditions. With few exceptions (Heiskary and Swain, 2002; Bennion et al., 2005), the historical *P* values estimated by different modelling approaches have not been compared and no clear evaluation has been conducted of whether different models produce similar estimates of baseline TP concentrations.

To address these gaps, we compare the outputs of different approaches for a range of relatively undisturbed subalpine lakes with their mean TP in—lake concentrations. Lake Pusiano (North Italy) is a subalpine site for which an accurate account of the physical characteristics of the watershed and long-term direct chemical measurements of the lake exists; therefore, the traditional estimation methods were applied to Lake Pusiano and compared with the estimates of nutrient inputs to lakes under reference conditions by the process-based watershed model to evaluate the approach's accuracy, uncertainty, and potential application.

2. Data and methods

2.1. Watershed models

2.1.1. Export coefficient model

The export coefficient model can be used for estimating the historical TP in lake concentrations from relatively simple information on the catchment, including land cover and land cover specific TP export values. The export coefficient models apply a *space for time substitution* (Pickett, 1989; Fukami and Wardle, 2005) and operate under the assumption that the current anthropised environments would export the same quantity of TP that had been exported in the past under natural or semi-natural conditions once the original land cover was restored. This approach relies heavily on the accuracy of TP export coefficients, but these values are difficult to estimate because they depend on different catchment features, such as land-cover type, land use, climate, soil type, topography, agricultural practices, and erosion patterns (Johnes et al., 2007). Moreover, these coefficients are often site-specific and rarely transferable from their catchment of origin to another significantly different catchment, which indicates that they must be 're-validated' with measured data to fit new conditions (Solheim, 2005). Most of the derived studies are located in North America and Great Britain (Ferrier et al., 1996; Lin, 2004), but for the subalpine region in Italy, a unique generic TP export coefficient was calibrated (0.10 kg ha^{-1} y^{-1}) for uncultivated soil that includes forested and naked soils without any geographic and topographic differentiation (Barbiero et al., 1991; Marchetti and Verna, 1992). Compared to the coefficients reported in different studies that range on average from 0.05 to 0.30 kg ha^{-1} y^{-1} (Lin, 2004), the generic coefficient applied here represents an average condition for non-anthropic land covers.

To retrieve information for the error associated with the TP estimated using the export coefficient model, we used the same water bodies that were selected for evaluating the MEI capability, as described below (Fig. 1a). The TP load was calculated using the