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Water and phosphorus mass balance of Lake Tegel and Schlachtensee – A modelling approach

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ABSTRACT

Management models for aquatic systems can be used to determine which measures in the watershed or in the water body have been effective and/or which one should be used in future. The newly developed management models presented in the following for Lake Tegel and Schlachtensee are empirical and lake specific. The values for the unknown factors are estimated by an iterative process using optimisation routines and sensitivity analysis methods. The resulting models describe the water and phosphorus balance of each lake. The Lake Tegel water balance model calculates the unknown water inflow from the River Havel depending on the other main in- and outflows with very good validation results. The phosphorus models of both lakes quantify mixing of the upper and lower water body as well as sedimentation and release from the sediment as functions of measured variables. For Lake Tegel, management scenarios were run indicating effective management interventions. For Lake Schlachtensee, the phosphorus model captured the variations in the hypolimnion well but produced poorer results for the epilimnion because of unknown external phosphorus loads. For these the model indicated possible sources and magnitudes.

1. Introduction

A central question in lake restoration planning is whether external measures alone are sufficient to achieve restoration targets or whether internal measures are necessary as well. Assessing the external and internal P loads requires complete water and phosphorus (P) mass balances, but often, not all of the necessary data can be measured. A management model for a specific lake can help to fill data gaps in the water and nutrient balance. It is useful both for planning the measures, and for following the lake's restoration response, i.e. to assess which measures prove effective and which need to be changed or fine-tuned.

This paper describes the development and application of models for two lakes in Berlin which were subject to major restoration measures. The management models developed for Lake Tegel and Schlachtensee are simple mass balance models, empirical and lake specific. In contrast, most lake models are either dynamic (time dependent) process models which usually need to be calibrated for a given lake, e.g. Janse and van Liere (1995), Reynolds et al. (2001), or they are empirical models which can be generally applied, e.g. Vollenweider (1976), OECD (1982), Jensen et al. (2006). Simple static empirical models require the lake to be in steady state and cannot describe the transient phase after reduction of nutrient loading in combination with high internal load. They tend to underestimate the P content of a lake, particularly where internal loading prevails over a long time period (Sas, 1989; Søndergaard et al., 2003). Simple two-box models which combine a water phase and a sediment phase with sedimentation and sediment release (Nürnberg and LaZerte, 2004) mainly operate with 1-year time steps and cannot describe the

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Nomenclature

A_x	area of lake or hypolimnion [m^2]
C_x	concentration of x [$g\,m^{-3}$]
d_{level}	change in water level [m]
F_x	flux of x [$g\,mon^{-1}$]
k_{bi}	fraction of bank infiltration [–]
k_{mix}	mixing coefficient [$m^2\,mon^{-1}$]
Q_x	runoff of x [$m^{-3}\,mon^{-1}$]
q_x	factor for water flow depending on x [(unit of $x)^{-1}\,mon^{-1}$]
rl_x	factor for P release affected by x [(unit of $x)^{-1}\,mon^{-1}$]
sed_x	factor for P sedimentation affected by x [(unit of $x)^{-1}\,mon^{-1}$]
sig_x	factor for burial of P or Fe [mon^{-1}]
stability	stratification stability [–]
$Temp_x$	Temperature in x m lake depth [°C]
V_x	volume of lake or hypolimnion [m^3]
z_x	depth of lake or sediment [m]

seasonal variations of the TP-concentration in a deep, stratified lake (Jensen et al., 2006). Complex dynamic-process models can model seasonal changes of stratified lakes, but require in-depth investigations to quantify process parameters (Jørgensen and Mitsch, 1983). There are also some general process models (e.g. Janse, 2005; Håkanson and Boulin, 2002) which have a great value to predict long-term means because their predictive quality is higher than general empirical models and they can be applied without extensive calibration of parameters. However, they also poorly represent the seasonal and annual variability of measured values (Bryn and Håkanson, 2007), possibly because particularly P release from sediments is very difficult to describe with general parameter values (Mieleitner and Reichert, 2006). This drawback is particularly significant for lakes on the verge of moving from eutrophic, cyanobacteria-dominated, to mesotrophic with more diverse phytoplankton, because in these situations, seasonal patterns of P-maxima are critically important for determining phytoplankton patterns.

Empirical and dynamic lake-specific models (termed ''management models'' in the following) can combine the advantages of both approaches. They need less parameters than lake-specific process models, since they do not describe processes in detail, and they can model seasonal changes in a stratified lake with a multi-box approach. Their uncertainty is less than that of both empirical models and of general process models since they are calibrated for the lake in question. Such management models can help to understand the key factors driving the water and phosphorus balances better than static empirical models can, as they can be used to run scenarios to estimate the effects of lake management measures – both in retrospective and for planning further measures. While empirical lake-specific models are a simplified alternative to more complex lake-specific process models, both can also be used in combination: if values for a process parameter (e.g. sedimentation rates) are not available, a management model could be used instead of a lake-specific process model. If input data are not available (e.g. the P load from a certain source), a management model can quantify the missing data empirically using information about the drivers of the missing input variable. The key limit of lake-specific management models, however, is that in contrast to general models, they are not transferable to other settings. Like all lake-specific models their adaptation depends on good data sets in adequate temporal scale. The longer the time record for a lake, the more accurate is the evaluation of the unknown parameters, of the natural variability and of the effects of former measures for the lake's management.

The management models presented here were developed

1. to establish complete water and phosphorus mass balances over the past 20–25 years for Lake Tegel and Schlachtensee;
2. to quantify and understand the processes and key factors driving the phosphorus balance of each of these two lakes;
3. to identify effective further management options for further reduction of in-lake P concentrations.

Modelling was necessary to assess influences that were postulated to be important, but which are not amenable to direct measurement. Unknowns in the water balance of Lake Tegel were the River Havel inflow and the proportion of water exfiltrating through the abstraction of drinking water by bank infiltration. For Schlachtensee the unknowns were the inflow from the storm water overflows and diffusive surface water inflow. The latter may be a relatively important carrier of phosphorus. For both lakes, a main modelling target was to differentiate the external and the internal phosphorus load by establishing a phosphorus balance and using it to estimate sedimentation and release of phosphorus from the sediment, as these processes are very difficult to measure in situ.

1.1. *Characteristics of Lake Tegel and Schlachtensee*

Both lakes are situated in western Berlin, close to the River Havel. In response to intensive eutrophication problems, phosphorus elimination plants (German abbreviation: OWA) were installed at their main inflows in the early 1980s,

Table 1 – Morphologic lake parameters (Lake Tegel main basin, parameters provided by Büro Wassmann).

Parameter (unit)	Abbreviation	Lake Tegel	Schlachtensee
Area (km^2)	A	3.06	0.42
Area covered by hypolimnion (km^2)	A_{hypo}	1.47	0.13
Volume ($10^6\,m^3$)	V	23.15	1.97
Volume of hypolimnion ($10^6\,m^3$)	V_{hypo}	5.28	0.20
Maximum depth (m)	z_{max}	16	9
Mean depth (m)	z_m	7.56	4.69