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# Lake phosphorus dynamics and climate warming: A mechanistic model approach

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**Abstract**

Model results in this work indicate that lakes may respond very differently to climate change depending on their physical character. A physical lake model and a mechanistic phosphorus model are combined with two temperature scenarios generated by a regional climate model (RCM) in three sites in central Sweden—Lake Erken and two basins of Lake Mälaren (Galten and Ekoln). In the phosphorus model water mixing, mineralization, diffusion and biouptake are temperature dependent. In the simulations, Lake Erken is much more sensitive to climate warming than the two basins of Lake Mälaren, and the reason is shown to be the much longer water residence time in Lake Erken (7 years), stressing the importance of internal lake processes. In Galten and Ekoln the water residence times are less than 1 year, and the effects of water temperature changes are small. In Lake Erken the concentration of epilimnetic-dissolved phosphorus is almost doubled in spring and autumn in the warmest climate scenario. Since the lake is mostly phosphorus limited, this means that the potential for phytoplankton production is almost doubled. The implication would be that in Lake Erken, and in other eutrophic lakes with long water residence times, eutrophication problems may become serious in the future, and that managers may need to take action today in order to maintain good water quality in these lakes.


*Keywords:* Climate scenario; Phosphorus; Lakes; LEEDS-model; PROBE-model; Regional climate model; Eutrophication

## 1. Introduction

The widening consensus about an inevitable climate warming is forcing both decision makers and researchers to evaluate probable consequences. The bulk of literature on water management and climate change is dealing with hydrological problems in streams (e.g. Riebsame, 1988; Werritty, 2002) and lakes (e.g. Marsh and Lesack, 1996, and lit. therein) due to changes in evaporation and precipitation. However, there is a growing concern also that aquatic ecosystems function may be affected (e.g. Halpin, 1997; Schindler,

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1997). Science is called for to assess possible impact of climate change on ecology in order to guide management responses.

Naturally, a changing catchment hydrology has a large potential impact on lake ecosystems. Increasing or decreasing discharge may influence water levels, which, in turn, could change the extension of littoral zones, areas of sediment erosion/deposition and hydrological water residence time (e.g. Mortsch and Quinn, 1996). Timing and magnitude of inflowing nutrients can also be expected to change (e.g. Clair and Ehrman, 1996). However, since temperature is a key parameter in most biological systems, warmer water temperature may be as important in lake ecosystems as altered hydrology.

Modelling water temperatures in lakes is rather developed, and coupling of general circulation models (GCM; resolution larger than 300 km) to physical models in different types of lakes has been practised in a number of studies (Fang and Stefan, 1999; Small et al., 1999). Temperature models could be used for both qualitative and quantitative predictions of ecological effects (e.g. Stefan et al., 1993; De Stasio et al., 1996). Blenckner et al. (2002) applied a physical lake model (PROBE) in Swedish Lake Erken and found that the lake responded to a 2× carbon dioxide ($CO_2$) scenario with higher water temperatures, shorter periods of ice cover and longer and stronger summer stratification, and suggested a number of ecological consequences. For instance, spring blooming phytoplankton are likely to appear earlier in the season due to earlier ice-break (Weyhenmeyer et al., 1999), and the proportion of cyanobacteria may increase with higher temperature and altered mixing patterns (e.g. Robarts and Zohary, 1987; Zhang and Prepas, 1996). Predation pressure by zooplankton is known to be positively temperature dependent (George et al., 1990) and species at higher trophic levels, like fish, are possibly also affected (see, e.g. Sandström et al., 1995).

Water chemistry and biochemical reactions are directly influenced by temperature. The dynamics of phosphorus are of special interest since, in general, phosphorus is the limiting nutrient during most of the year in most lake ecosystems (e.g. Dillon and Rigler, 1974; Guildford and Hecky, 2000). With changing trophic interactions, the pathways of phosphorus between organisms would obviously be affected, with possible impacts on the whole phosphorus cycle. A change of water mixing and stratification due to high temperature may substantially affect the availability of phosphorus and other nutrients in the photic zone. In addition, processes of phosphorus release from sediments and mineralization are known to be temperature dependent (e.g. Kamp-Nielsen, 1975; Jensen and Andersen, 1992; Törnblom and Pettersson, 1998). In order to quantify and evaluate the possible impacts of climate change on lake ecosystems, predictive models may be powerful tools.

Existing phosphorus models differ in their structure with respect to modelling scales, driving variables, generality and overall complexity. In order to study responses to perturbations, dynamic theoretical models are preferred (Ahlgren et al., 1988). A set of processes appropriate for the problem formulation must be accounted for. Several phosphorus models based on theoretical descriptions of nutrient dynamics have been developed (e.g. Imboden and Gächter, 1978; Jørgensen et al., 1986; Chapra and Canale, 1991).

The LEEDS-model (lake eutrophication, effect, dose, sensitivity) is a dynamic theoretical phosphorus model, which includes several temperature dependent processes (Malmaeus and Håkanson, 2004). It is developed and tested with good results in a wide range of lakes and climate zones. Further, it is general and does not need calibration for individual lakes, which is an obvious advantage when studying scenarios that could potentially force lakes out of their original domains. In this work, the LEEDS-model is coupled with a physical lake model (PROBE) forced by two different climate scenarios (derived from two different future emission scenarios) for three lakes in central Sweden. The scenarios consider temperature changes only, and do not account for changes in water discharge or external nutrient load since predictions in these areas are yet very uncertain.

The aim of this paper is to quantitatively evaluate changes in lake function resulting from a climate warming in lakes of different morphometry and trophic status. To our knowledge, this is the first study connecting a regional climate model (RCM) with a physical lake model and a mechanistic phosphorus model to study effects of climate change. Specifically, phosphorus transport between model compartments and changes in total and dissolved phosphorus concentration will be considered.