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Simulation of plankton dynamics and internal nutrient fluxes in a eutrophic shallow lake.

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Summary (in English)

In the present study a numerical water quality model has been developed which simulates the nutrient and plankton dynamics in shallow lakes: StoLaM (Stoichiometric Lake Model). The basis for model development and validation of simulation results is a three-year survey of the succession of plankton and nutrient dynamics in a eutrophic lake. The focus is on the quantification of the processes, which control the nutrient dynamics during summer with special emphasis on the internal nutrient loading.

StoLaM is appropriate for temporary thermally-stratified shallow lakes as well as for deeper lakes. It takes into consideration the sediment-water interactions, more important in shallow lakes due to the low volume-surface ratio, as well as the vertical gradients in shallow and deep water bodies. A one-dimensional vertical hydrodynamic module (HyLaM) allows high resolution of the lake internal conditions (e.g. temperature, light, and turbulence) both in time and space using weather data at 10 minutes intervals. This makes possible a realistic simulation of the physical environment required for modelling the nutrient and plankton dynamics in detail.

Besides the oxygen concentration and water temperature, several zooplankton and phytoplankton groups are used as state variables in StoLaM. In addition, closed nutrient cycles of phosphorus, nitrogen and silicon within the water column have been mathematically formulated. And because their stoichiometric ratios have a strong influence on the nutrient uptake and regeneration by planktonic organisms, they have been included in the model. The quantity and ratio of dissolved nutrients in the water are affected by external loading and internal processes (e.g. release from the sediment, excretion by benthivorous fish, sedimentation, dinitrogen fixation and denitrification). The uptake rate of dissolved nutrients by phytoplankton is as defined by Monod kinetics, and the phytoplankton growth depends on their internal nutrient contents in accordance with the Droop equation. The growth and nutrient excretion of the zooplankton is determined by their nutrient requirements as well as the stoichiometry of nutrients in the food. The impact of both fish zooplanktivory on the zooplankton as well as the nutrient release from the sediments into the water column by benthivorous fish is described by a special fish module.

The small eutrophic Lake Alsdorf, located near Aachen, Germany, served as a model lake due to its morphometric and stratifying characteristics: In spite of an average depth of only 2.6 m and a maximum depth of 4.1 m, stable thermal stratification evolves during the summer months. In the years 1995 to 1998, nutrient and plankton dynamics were investigated. Additionally, in 1997, a nutrient balance was calculated including independent calculations of inflow and outflow, deposition, sedimentation, aerobic and anaerobic sediment release, nutrient loading by benthivorous fish, and dinitrogen fixation by cyanobacteria.

The nutrient budget in 1997 showed that resuspension events were responsible for the major part of phosphorus turnover in the water column of Lake Alsdorf with 137 kg P. In contrast, in the same year, all other rates for phosphorus turnover achieved approximately 110 kg P. Here, the external phosphorus loading (34 kg P) was more than double the internal phosphorus supply (79 kg P).

The main focus of the food web analysis is the feeding ecology of omnivorous roach (*Rutilus rutilus*), which dominates the fish community in Lake Alsdorf. This present study has shown that the switch from zooplanktivory to benthivory during summer of even small roach with a body length of 8-10 cm predominantly depends on the population size structure of their zooplanktonic prey and this also takes place at high zooplankton densities (mainly *Bosmina longirostris*). From June to August, benthivorous roach were responsible for 40% of the total internal phosphorus load during summer by translocating sediment bound phosphorus to the water column. During this period, the resulting phosphorus loading by roach (6.5 mg P $m^{-2} \cdot day^{-1}$) achieved a similar order of magnitude as the biochemical phosphate release from the sediment (6.9 mg P $\cdot$ $m^{-2} \cdot day^{-1}$). With a portion of the total annual phosphorus load of 27 %, roach play an essential role in the internal nutrient mobilization due to their high turnover of benthic food.

StoLaM was able to simulate the general patterns of the nutrient fluxes and plankton dynamics comparably with the three-year field survey of Lake Alsdorf. Despite the low water depth, the temperature stratification as well as turbulence-dependent vertical oxygen and nutrient gradients have been precisely predicted by the hydrodynamic module HyLaM. Due to the high temporal-resolution of the vertical physico-chemical gradient dynamics, the development of bloom-forming summer phytoplankton could be analysed under simulated semi-natural conditions. Simulations of the vertically migrating dinoflagellate *Ceratium hirundinella* demonstrated that in the nutrient-rich Lake Alsdorf an optimal utilisation of the radiation is of greater importance than the utilisation of additional nutrients from deeper layers of the lake. Nevertheless, diurnal vertical migration reduces the probability of phosphorus limitation for *C. hirundinella* even under eutrophic conditions. Field measurements revealed that grazing pressure by the omnivorous rotifer *Asplanchna priodonta* was the most significant factor affecting the mortality rate for *C. hirundinella* during mass occurrences. This finding is also quantitatively confirmed by simulation. In addition, model calculations show that filamentous cyanobacteria (*Aphanizomenon flos-aquae*) considerably increased the total nitrogen concentration by dinitrogen fixation in late summer of 1997. Although StoLaM was able to describe the population dynamics of *C. hirundinella* and *A. flos-aquae* for individual years with high accuracy, the dominance pattern of these competing summer algae, however, could not be reliably predicted. The competitive strength of both algae probably depends crucially on the starting densities of their populations in early summer and can, for example, be influenced by zooplankton grazing.

The water quality model StoLaM can be further used as a prognostic tool for other vertically stratified shallow and deep water bodies. By taking into consideration the principles of ecological stoichiometry, the influence of changing nutrient ratios on the plankton dynamic is demonstrable. In future, this model may be usefully employed in the process-oriented analysis of lakes as well as in the evaluation of proposed management concepts for standing waters.

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