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Integrated 3D Modelling of Water Circulation and the Dynamics of Phytoplankton; the Effects of a Planned Reservoir

Key words: modelling, nutrient cycles, phytoplankton, reservoir, Kemijärvi, Vuotos

Abstract

The FINNALGA model has been used to assess the effects of a planned reservoir, Vuotos, on a downstream lake, Kemijärvi, in northern Finland. The model is based on 3D calculations of water currents and water quality. The simulation results are compared with the measurements and the effects of Vuotos on the present situation are assessed. The assessments on increased nutrient inputs are based on the earlier experiences of an existing similar reservoir at Porttipahta. Many scenarios were made to obtain as versatile assessment as possible. According to the model simulations, the average concentrations of algal biomass will increase by 20 - 60 %, while the maximum concentrations will double during the first years of the reservoir Vuotos. The effects will be most appeared in the northern part of the lake, near the estuary of Kemijoki. In the eastern parts of the lake the effects will be smaller, because it is not on the through flow route of Kemijoki.

1. Introduction

There has been notable interest in the effects of reservoirs in Finland during the past decade, because it has been considered necessary to assess the effects of the planned reservoir Vuotos as accurately as possible. The development of water quality in the Finnish reservoirs and their effects on the downstream water systems were studied by mathematical modelling during 1988-1992 (VIRTANEN et al., 1994). Additional studies have been made during 1994-96, when eutrophication processes were estimated by advanced models.

This paper will briefly describe the study area, lake Kemijärvi and the model used, FINNALGA. The results of the calibration and the validation runs will be presented and discussed. The aim of the study was to assess the effects of the planned reservoir on the eutrophication of the downstream lake. Different scenarios were calculated and the results will be presented at the end of the paper.

2. Material and Methods

2.1. Lake Kemijärvi

Lake Kemijärvi is situated in Finnish Lapland near the Arctic Circle. The water level of the lake has been regulated since 1966 with an annual amplitude of 7 meters. This oligotrophic lake is mainly loaded by the inflowing water of the river Kemijoki. Other important loads come from airborne depositions and point sources, such as a pulp mill, the town of Kemijärvi and fish farming. The river and point loads were measured quite frequently, but airborne depositions had to be assessed at the Sodankylä station (about 100 km north from the lake). The nitrogen deposition in the Kemijärvi area is approximately 50 % of the total dissolved nitrogen load.

Water quality is most frequently monitored at point 147 in the southern part of the lake (Fig. 1). This point represents quite well the state of the lake, because the Kemijoki river flows via the area and there is enough time to fix nutrients from the river and the other big point sources from the northern parts of the lake. As an addition to the nutrient and algal biomass measurements, chlorophyll-a measurements were used in the comparisons. The relation between chlorophyll-a and the algal biomass was assessed by simultaneous measurements using the least squares method. The ratio of algal biomass to chlorophyll-a was 115.

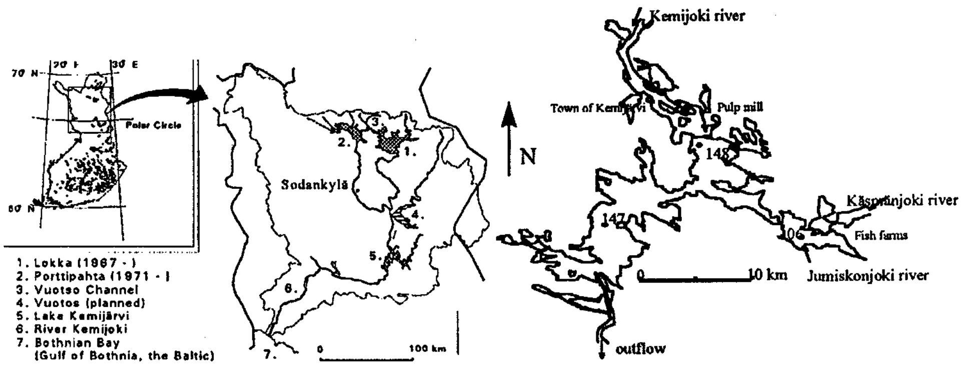

Figure 1. The reservoirs of northern Finland and the study area with its measurements points and greatest load sources.

2.2. Model

The dissolved nitrogen is fixed by algae (Fig. 2). The detritus nitrogen is formed by dead algae or zooplankton grazing. The detritus is settled and sedimented on the bottom or mineralized to ammonium by bacteria. Ammonium can be nitrified to nitrite or fixed again by algae. The cycle is complete. The cycle of bioavailable phosphorus is modelled very similar to N. The exact equations and parameters of the model were presented in INKALA et al. (1997).

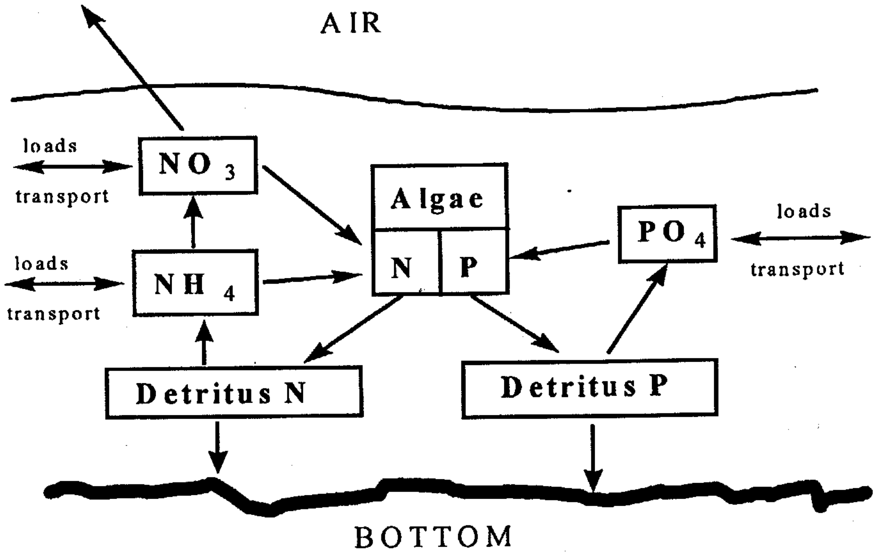

Figure 2. Flow diagram of the FINNALGA model.

The model is 3-dimensional. The transportation of the model is based on the Simons multilayer model (SIMONS, 1980), which has been developed further (KOPONEN et al., 1992). The water mass is treated as horizontal layers. The horizontal model area is subdivided into rectangles with arbitrary mesh intervals in both directions. Explicit finite-difference schemes are used for the numerical solution of flow velocities and water level elevations.

3. Results and Discussion

3.1. Calibration

The model was calibrated in the conditions of the year 1994, which was hydrologically close to the long-term average, but quite warm. At the beginning of the simulation the concentrations of dissolved nutrients were mainly determined by the concentrations of the inflowing river Kemijoki, because the residence time during the spring flood is only several days. Both nitrogen and phosphorus can be limiting nutrients, because the ratio of DIN:DIP typically varies from 4 to 8. The results of the calibration simulation are presented in Fig. 3.

The algal spring bloom achieved its maximum at the beginning of June, after which the concentrations of algal biomass were more or less constant. The concentrations of dissolved nutrients were rather low, however neither nutrient was completely used by algae.

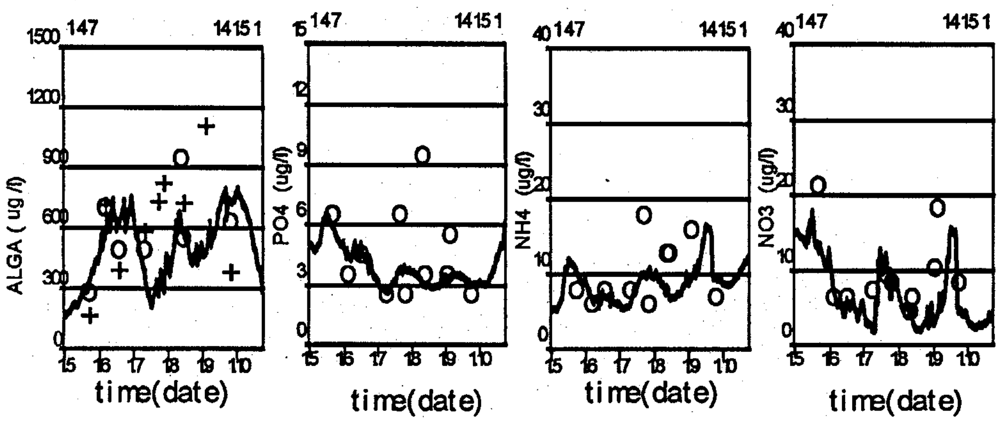

Figure 3. Calibration simulation and measurements (circles: measured values, crosses: chlorophyll-a) from point 147 depth 0-1 m from May 1 till October 30, 1994.

The model was able to simulate the measured dynamics of algae and nutrients quite well. The simulated levels of concentrations also correlated with the measurements. Some measurements of nutrients were made at the end of July and August, when simulated concentrations were lower. This has an effect on the algal biomass concentration too. The reason for the differences might be related to the internal loading. It was assumed in the simulations that the loss rates will transcend the internal load, which may be a good assumption in the long run, but there might be some seasonal fluctuation. In August, the internal load might be clearly greater than the loss rate of dissolved nutrients.

3.2. Validation

The validation of the model was made relative to the measurements of the following year. The year 1995 was hydrologically very different compared to the calibration year. The spring flood was extensive and the average flow during the simulation period was about 35 % greater. The highest temperature observed in the water column was 17 ^{o}C during both research years.

The measured nutrient concentrations were at the same level as in the calibration year, but the biomass concentration was clearly higher. Also, the dynamics of algal biomass was different with three separate production peaks.

The simulated nutrient concentrations were at the same level with the measurements, with the exception of the lower concentration around August. The unknown internal load possibly was the reason for this as in the case of the calibration year. The high peaks in the nitrate concentrations were due to the heavy rains, which also caused the airborne deposition to the surface layer to be especially high.

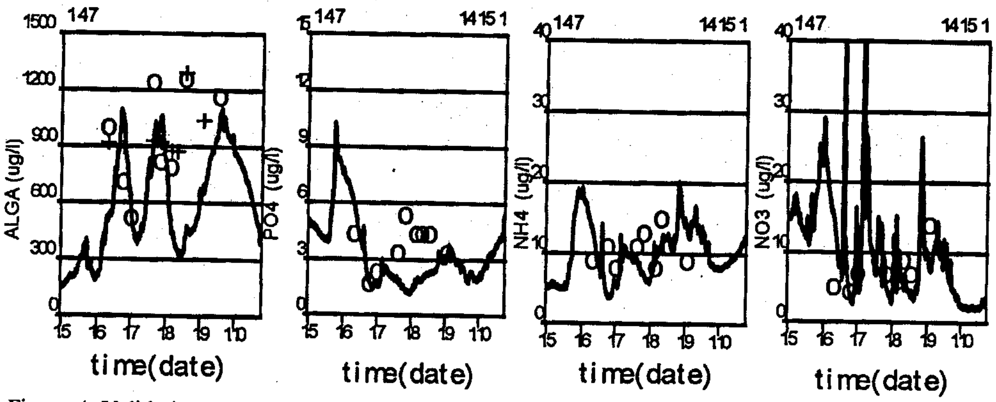

Figure 4. Validation simulation and measurements (Circles: measured values, crosses: chlorophyll-a) from point 147 depth 0-1 m from May 1 till October 30, 1995.

During extensive spring floods the residence time of lake Kemijärvi is less than a week and the concentrations were also strongly affected by the river Kemijoki. The simulated spring bloom was delayed by two weeks because of too strong influence of the flood in the model. The simulated concentrations around August were also lower than the measured ones, which was a direct implication of the lower nutrient concentrations. However, the model was able to describe similar dynamics with measurements. It can be assessed that the validation simulation was equally successful as the calibration.

3.3. Effects of Vuotos

The reservoir of Vuotos is planned to be build about 50 kilometers upstream from Kemijärvi. The amplitude of water level fluctuation will be 8 meters and the volume of the lake will vary between 0,150 and 1,307 km^3. The potential load of Vuotos on the total phosphorus concentrations was assessed by VIRTANEN el al., 1993. The loading of dissolved nutrients was assessed from the measured concentrations of the similar reservoir at Porttipahta by ITKONEN (1995). Due to the irregular relationship between total phosphorus and dissolved nutrients, eight different scenarios were determined (Table 1).

In the scenarios 1-5, only nutrients have been added as a river load. Scenario 3 is the most probable. However, the distance from Vuotos is short and it was postulated that algal biomass will also be carried to the river. The scenarios 6-8 were therefore added to the study.

Point 147 is situated in the southern part of Kemijärvi and it shows the quality of outflowing water (Fig. 1). Additional loading will increase the average algal biomass by 10-30 %. Kemijärvi lake is oligotrophic and hence cannot feed the additional algal concentration (scenarios 6-8). The changes in the average algal concentrations are slighter than in the maximum concentrations.

Table 1. The loads (kg d^{-1}) and the average flow (m^3 s^{-1}) from the river Kemijoki and the scenarios used.

Scenario	Ptot	PO_4	Pdet	Ntot	NO_3	NH_4	Ndet	Algae	flow
Kemijoki 1994	330	250	15	7500	230	230	150	5000	300
Kemijoki 1995	630	200	27	12300	180	210	270	8700	410
Vuotos 1	170	10	1,7	850	80	40	17	-	
Vuotos 2	170	20	2,4	1200	170	70	24	-	
Vuotos 3	170	40	3,4	1700	250	100	34	-	
Vuotos 4	170	55	4,0	2000	340	170	40	-	
Vuotos 5	170	80	5,4	2700	550	210	54	-	
Vuotos 6	Vuotos 3 + Algal biomass in Kemijoki river							500 mg m^{-3}	
Vuotos 7	Vuotos 3 + Algal biomass in Kemijoki river							1000 mg m^{-3}	
Vuotos 8	Vuotos 3 + Algal biomass in Kemijoki river							2000 mg m^{-3}	

Point 148 is situated near the estuary of the Kemijoki river, which means that the additional nutrients will be fixed here (Fig. 1). The relative effects are clearly the highest 30-200%. The additional load can also maintain the higher algal biomass concentrations, which was used in the last three scenarios.

Point 106 is situated aside from the through flow of Kemijoki. The regulation of the reservoir Vuotos will also reduce the flow velocities during the summer. Thus, only a small part of the additional load will be transferred to the eastern part of Kemijärvi, where the effects on the algal biomass are markedly lower than elsewhere, being approximately 0-20%.

The concentration maps (Fig. 5) clarify the distribution of the effects on the algal biomass. The remarkable growth of the algal biomass will only be seen on the through flow area of Kemijoki (from NW to SW). The effects are greatest in the northern part of the lake, where the additional nutrients come from. The part of the nutrients will be used and sedimented before transferring to the south.

Table 2. Changes in the average and maximum algal biomass concentrations (mg m^{-3}) at three points of Kemijärvi in 1994.

	Average			Maximum		
Scenario	147	148	106	147	148	106
No Vuotos	604	385	644	795	1109	1080
Vuotos 1	+60	+115	+7	+145	+330	-127
Vuotos 2	+98	+213	+28	+216	+640	-113
Vuotos 3	+144	+324	+54	+301	+958	-98
Vuotos 4	+187	+433	+78	+384	+1275	-83
Vuotos 5	+280	+672	+126	+579	+1963	+3
Vuotos 6	+218	+925	+81	+554	+1220	-90
Vuotos 7	+343	+1406	+111	+860	+1501	+54
Vuotos 8	+605	+2117	+176	+1095	+2766	+407

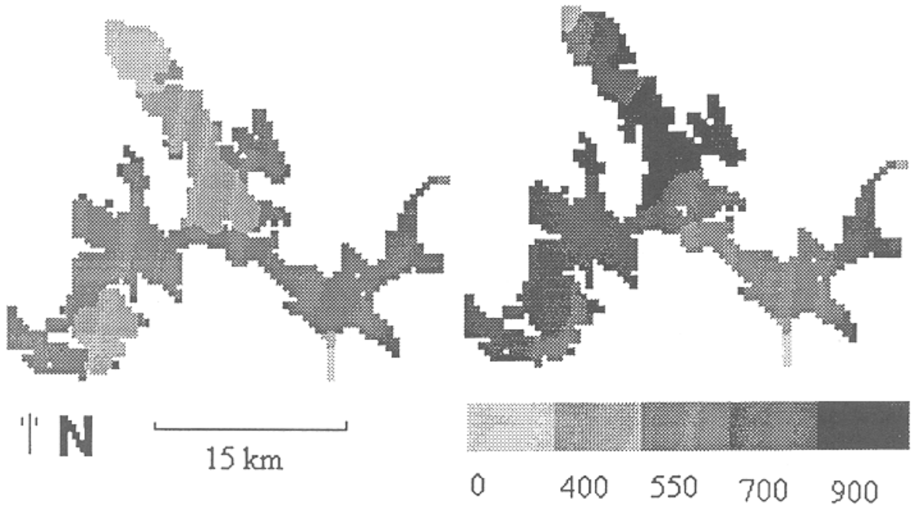

Figure 5. Average algal biomass concentrations (mg m^{-3}) in lake Kemijärvi in 1995. The left map presents the current situation and the right one the situation with the most probable scenario, Vuotos 6.

4. Summary

A 3-dimensional algal model was applied to lake Kemijärvi. The calibration and validation simulations were made and they indicate similarity with the measurements. The seasonal variation of the internal load was not included in the model, causing too low biomass values in August.

The effects of the planned reservoir Vuotos during its first year were assessed using several scenarios. According to the simulations the relatively greatest effects will appear in the northern part of the lake, near the estuary of Kemijoki. The effects in the eastern part of the lake will be slighter because this part is not on the through flow route of the Kemijoki.

The loads from Vuotos will cause on average increase of 100 - 300 mg m^{-3} (wet weight) in the algal biomass concentration. In normal situations, the maximum algal biomass of the lake will be under 2000 mg m^{-3}. Therefore, no marked eutrophication is expected to take place in the lake.

The application shows that quite a simple model was able to calibrate to the biological- and chemical data although the relations in nature are highly complex. Validation simulation indicates that the main processes in lake Kemijärvi has been included in the model equations.

5. Acknowledgements

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