Dynamic nutrient modelling of a large river basin in Finland

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Abstract

The Baltic Sea is one of the most eutrophied European seas. High nutrient input mainly via river discharges and leaching from agriculture along with the reduced water exchange with the open ocean have, during past decades, led to enhanced growth and biomass of primary producers. Characterized by a large catchment area, pollution that originates from land finally ends up in the Baltic Sea. The nutrient loading from the Kokemäenjoki river basin (27000 km²) was simulated by applying different mathematical models. Phosphorus and nitrogen loading from the Kokemäenjoki river basin to the estuary was estimated by calculating nutrient loading from point and diffuse sources using the CATCHLOAD model and by calculating retention in rivers and lakes using the CHAIN-LAKE model. Simulated nutrient fluxes are finally the input data for an estuary model. Two nutrient reduction scenarios, based on requirements of the current environmental policy have been carried out: 1) waste water scenario which is based on the implementation of the EU directive for N removal from inland wastewater treatment plants, and 2) diffuse pollution scenario from agricultural areas which is based on good management practices of the Finnish Agri-Environmental Programme. In the waste water (WW) scenario, N removal efficiency on the major waste water treatment plants of Tampere would rise from 40% to 70%. In the agricultural scenario (AGRI), total P load would decrease by 20% and total N by 37% from fields to the river. The scenarios affected the annual nutrient output from the Kokemäenjoki river by reducing total N on an average by 4% (WW), and total N by 7% and total P by 6% (AGRI). If a total nitrogen reduction of 70% were required the loading of nitrogen to the Baltic Sea would not decrease much. From the point of view of Baltic Sea protection, special attention should be paid to coastal river basins, where water protection measures could be concentrated on selected land use forms with high nutrient loading.

Keywords: nutrient, loading, modelling, phosphorus, nitrogen, catchment, Baltic Sea.

1 Introduction

According to Wulff *et al.* [1] the unsolved eutrophication problems in the Baltic Sea are partly due to lack of knowledge on large-scale relationships and couplings between physics, biogeochemistry and ecological properties, and also due to lack of overall drainage basin-wide analyses on cost-effective measures. Eutrophication problems in the Baltic Sea can be solved by reducing nutrient loading from the external sources, i.e. from the catchments and from the atmosphere. In this respect understanding of the key processes influencing nutrient loading in catchment areas is essential for the management of the entire Baltic Sea. The NUTRIBA research project, “Nutrients from river basins – experimental and modelling approach”, as a part of the Finnish Baltic Sea Research Programme (BIREME), financed by the Academy of Finland through the years 2003–2006, aimed at increasing knowledge of the processes important for nutrient transport and dynamics in catchments and at improving the management strategies and tools that could help us to achieve the desired effects in the coastal waters.

2 Study area

The study area, Kokemäenjoki river basin, is the fourth largest catchment in Finland and it finally ends up in the Baltic Sea (figs. 1 and 2). Its total surface area is 27 000 km² and the average water discharge is 230 m³ s⁻¹. The land use in the area varies from intense agriculture to almost totally forested areas. The Kokemäenjoki river basin is characterized by a high proportion of lakes (11% of total area). Most of the lakes are small (< 5 km²) and humic; the colour of water typically varies between 30 and 90 mg Pt l⁻¹. The population density varies from sparse (<10 inhabitants km⁻²) in remote rural areas to city densities, with Tampere being the largest one with its ca. 200 000 inhabitants. The industry is variable, big pulp and paper mills being historically the most critical for the development of the present trophic status in surface waters in many areas of the river basin. Nutrient loading from point sources to rivers and lakes and further to the Baltic Sea has decreased since the early 1970s due to the improved wastewater purification of municipalities and industry (2, 3). Today, the main challenge in Finland for controlling eutrophication is diffuse nutrient loading which originates from agriculture, forestry and scattered settlements (figs. 3 and 4). According to the Finnish Environment Institute, in 2004 the shares of total N and total P from diffuse sources to inland surface waters in were estimated to be 59% and 80%, respectively. The most fertile soils used for agriculture are located usually in lower parts of the catchments, close to the streams, rivers and lakes. The role of these areas is important due to their vulnerability with respect to extreme events such as spring floods or heavy rains. Future changes in climate and land-use are anticipated and thus we should improve our understanding of the key biogeochemical and hydrological processes in lake basins and river reaches, and their role in retention, removal and transport of nutrients.

Figure 1: The study area of the Kokemäenjoki river basin and the catchment area of the Baltic Sea.

Figure 2: The modelling area of the Kokemäenjoki river basin.

Figure 3: Essential total phosphorus mass flows (kg a^{-1}) in the dynamic modelling area.

Figure 4: Essential total nitrogen mass flows (t a^{-1}) in the dynamic modelling area.

3 Methods

3.1 Nutrient transport model CATCHLOAD

The conceptual model of catchment dynamics consists of two components: a runoff model and a nutrient transport model by Bilaletdin *et al.* [4]. In many Finnish applications it is possible to use the discharges calculated by the Finnish version of the HBV by Vehviläinen [5] and Vehviläinen *et al.* [6] and also in this case this procedure was used. The basic idea of the statistical transport model CATCHLOAD is that the transport is calculated separately for agricultural and forested areas. In the model the catchment is divided into several sub-catchments. Nutrient transport is calculated as the product of discharge and concentration. The principle of forming the equations used in calculating the concentrations of forest and field areas is that standard concentrations are corrected using empirical functions. The main state variables in correction functions are runoff, area of the catchment, lake percentage, soil frost, slope and plant cover type. The model must be calibrated against observed values of nutrient transport at the sampling site of the outlet of the catchment. It must be stressed that the standard concentrations are by no means universal but dependent on the catchment. However, they can perhaps be predicted by means of the geological regime of the region. CATCHLOAD simulates only diffuse loading (agricultural and basic loading) of river basins and for that reason the point source loading and sparse population loading must be added to this simulated loading.

3.2 Lake and river model CHAIN-LAKE

Lake and river modelling was made dynamically using daily input values of nutrient loading from different sub-catchments. To assess the transport and retention processes of nutrients in the river and lake system, the modelled area was divided into six river reaches and six lake basins. CSTR (i.e. continuously stirred tank reactor) approach was used in three lake basins and the one-dimensional advective-diffusive compartment approach for the rest of the lake basins and for all river reaches. The inlet and outlet of the compartments were linked advectively to other compartments. This kind of model application is called here the CHAIN-LAKE model. The system presentation of the Kokemäenjoki river basin is presented in figure 5.

4 Application of the integrated models

4.1 Calibration

The CATCHLOAD model was calibrated by using eleven sub-catchments of which water quality data was available. The calibration was made to total phosphorus and total nitrogen and the parameterization of the model was very similar as in other applications in Finland. The calibration period was 1998–

Figure 5: The system presentation of the Kokemäenjoki river basin.

2002. The calibration was made against the observed loading values. Because the goal of the simulation is to estimate nutrient transport, it was not considered important to have very accurate estimates of concentrations during low flow periods e.g. in summer.

A parameter estimation of the river and lake model CHAIN-LAKE was carried out by using water quality observations at seven sites. Modelled state variables are total phosphorus and total nitrogen. The calibration period was 1994–2000.

4.2 Scenarios

In the modelling approach, the scenarios for the regional development were first established to describe the possible future conditions for nutrient loading. We based the scenarios on EU water policy by the Council of the European Communities [7] and on expert judgment on the effect of agricultural water protection measures concerning diffuse loading. As a result, two scenarios were created. First it was assumed that reduction of N from one of the biggest point sources, the city of Tampere, will change from the present 40% to 70% and at the same time P reduction will remain at the present high level, i.e. > 95%. The second scenario was based on the assumption that protection measures in agriculture will decrease diffuse loading leading to a reduction of 37% in total N and 20% in total P loading. This scenario was applied in the Loimijoki catchment area that at present contributes roughly one third of the total P and one fourth of the total N loading flowing through the Kokemäenjoki River system into the Bothnian Sea (fig. 2).

4.3 Results

Based on the first scenario of improved N removal from wastewaters, the calibrated CATCHLOAD model showed that total N loading entering the Bothnian Sea could be reduced only by 4%. The second scenario showed that

reduction of diffuse loading from the Loimijoki catchment results in a total N reduction by 7% and a total P reduction by 6%, and would thus be more effective in preventing nutrient loading to the estuary than the improvement in wastewater treatment in Tampere (tables 1 and 2). At present, agriculture together with evenly growing dispersed settlements and forestry is responsible for the diffuse nutrient loading. Thus no single water protection action can significantly improve water quality in the estuary. Therefore to achieve the desired effects, the measures should be focused on all possible loading sources. The model chaining example highlights that special attention should be paid on the river basins with low lake percentage near the coast. There the water protection measures should be concentrated on selected land use forms with high nutrient loading.

5 Discussion

In Finnish inland waters, growth of phytoplankton is mainly limited by phosphorus. The total concentration of biologically active phosphorus determines the amount of phytoplankton that can be reached in the water. For a short period of time, nitrogen or even some other nutrient may limit the growth but in that case the effect can be seen in the regulation of growth rate and not in the maximal biomass of phytoplankton. The situation is similar in estuaries, as it was earlier in the Gulf of Finland when excessive phosphorus loading converted the situation into nitrogen limitation.

In the Finnish water pollution control, main attention has been particularly paid to efficient removal of phosphorus from wastewaters. Efficient removal of

Table 1: The assessed decreases of total nitrogen loading (t a^{-1}) using different scenarios at the outlet of the Kokemäenjoki river basin during 1995–1999.

<i>Year</i>	<i>Reference</i>	<i>Tampere 40%</i>	<i>Tampere 70%</i>	<i>Loimi 63%</i>	<i>40To70</i>	<i>Loimi 63%</i>
1995	7570	7430	7220	7020	-3%	-7%
1996	5640	5510	5270	5240	-4%	-7%
1997	5780	5680	5470	5430	-4%	-6%
1998	7460	7310	7010	6990	-4%	-6%
1999	6820	6720	6500	6240	-3%	-8%

Table 2: The assessed decreases of total phosphorus loading (kg a^{-1}) using different scenarios at the outlet of the Kokemäenjoki river basin during 1995–1999.

<i>Year</i>	<i>Reference</i>	<i>Loimi80%</i>	<i>Decrease at the outlet of River Kokemäenjoki</i>
1995	347200	326000	-6%
1996	256700	241600	-6%
1997	253400	239700	-5%
1998	327400	308800	-6%
1999	312600	290700	-7%

phosphorus has improved the status of inland waters very effectively and thus the water pollution control policy in Finland has proved to be successful. If phosphorus removal had been less effective and more efficient removal of nitrogen had been carried out, our inland waters would be much more eutrophic and the effects on the Baltic Sea would be greater than today.

At present, nitrogen reduction of 70% is required in the effluent coming directly into the Baltic Sea ($PE > 10000$). In inland cities nitrogen reduction is today 30–40%. If it were raised to 70% the loading of nitrogen to the Baltic Sea would not much decrease. In comparison to agricultural loading, its significance is so small that it could remain in the margin of error in the estimation.

Nitrogen is retained in inland waters very effectively. The retention processes of nitrogen are sedimentation and denitrification. Majority of nitrogen, more than 90%, is retained in inland waters. Sedimentation removes nitrogen effectively but in certain cases the contribution of denitrification is also significant.

In lakes, concentrations of dissolved reactive nitrogen often decrease to a very low level and then conditions become favourable for intensive growth of nitrogen fixing blue-green algae (cyanobacteria), which can easily lead to harmful blue-green algal blooms. Nitrogen as an instantaneous minimum factor does not at all imply that primary attention should be paid to removal of nitrogen because also in that case the problem is too high a concentration of phosphorus the removal of which is the only sustainable solution. In other words, phosphorus must be made to be the minimum factor by means of water protection measures, just as it has been in Finland. The connection between blue-green algal blooms and a low nitrogen/phosphorus ratio has also been proved e.g. in Canadian lakes by empirical tests the results of which have been published in the authoritative journal *Science* by Schindler [8].

In spite of the water protection policy oriented to phosphorus removal, anthropogenic phosphorus loading in Finland is almost double compared to natural leaching whereas anthropogenic nitrogen loading is approximately equal to natural leaching. Human activities thus result in a distortion in the phosphorus/nitrogen ratio of lakes and enhance the appearance of blue-green algal blooms. Removal of nitrogen from domestic wastewaters does not necessarily improve the status of inland waters but may be even harmful.

Under natural conditions in a large drainage area of hundreds or thousands of lakes, the major nutrients are in theory completely processed along the water flow from the upstream parts of the catchment down to the estuary. Consequently, for the coastal ecosystems the impacts of nutrient transport from the catchment are of the greater importance the closer the source of nutrients is situated. In view of the Baltic Sea protection, special attention should be paid on coastal river basins, where water protection measures could be concentrated on selected land use forms with high nutrient loading.

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