A dynamic phosphorus transport model CATCHLOAD: the case study of Lake Burtnieks, Latvia

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Abstract

Eutrophication of lakes is one of the most serious environmental problems. The aim of this study was to use a method developed for assessing dynamic phosphorus transport from large drainage basins and also to assess the effects in the target lake. The CATCHLOAD model consists of two compartments: a runoff model and a nutrient transport model. It is possible to use different kinds of runoff models in the CATCHLOAD. The statistical transport model calculates the transport as a multiplication of runoff and concentration separately for forested and agricultural areas of the catchment. The concentrations for forested and agricultural areas are obtained using empirical functions. The CATCLOAD simulates only the diffuse loading (agriculture and basic loading from forest) of sub-catchments and for that reason the point and sparse population loading were added to this simulated loading. The different versions of CATCHLOAD have already been used successfully prior to this study.

In this study the runoff model METQ98 was used. The calibration results of CATCHLOAD were rather accurate. To assess a loading simulation in the future, different scenarios were formed. The main contributor to the loading is agriculture and it is assessed that in the future the main changes in loading happen only in agriculture due to the fertilization. The climate change scenarios were also simulated and generally it can be noticed that the annual effect of climate change on nutrient loading is smaller than the annual effect of calculated agriculture scenarios on nutrient loading.
Keywords: nutrient loading, modelling, phosphorus, catchment, climate change, CATCHLOAD.

1 Study area

Lake Burtnieks is the fourth largest lake in Latvia. Its surface area is 40.06 km^2 and an average depth of the lake is 2.2m. The inflowing rivers of Lake Burtnieks are the River Rūja, the River Seda, the River Briede and 27 smaller rivers (fig. 1). The only outflow is the River Salaca. It is 95 km long and discharges into the Baltic Sea. The total drainage basin of Lake Burtnieks is 2215 km^2 Tidriķis [1]. Agricultural land covers 40 % of the catchment area of Lake Burtnieks. The area includes arable land and other heterogeneous agricultural areas. Wetlands cover about 3 %, forests (mostly mixed and coniferous) about 45 % and scrubs about 8 % of the drainage basin. The percentage of lakes is less than 3 %.

Catchment areas play a great role in the chemical composition of the water in lakes and rivers. In the 1990s economical activities have decreased and many of the above mentioned sources of point pollution have stopped. At the end of the 1990s it was found that Lake Burtnieks is starting to recover and self-purification processes are going on.

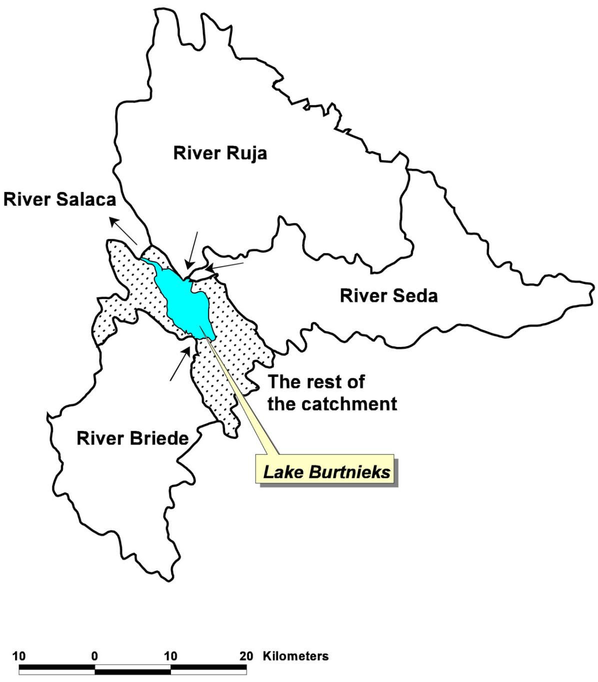

Figure 1: The drainage basin of Lake Burtnieks.

2 CATCHLOAD model

The conceptual model of catchment dynamics consists of two components: a runoff model and a nutrient transport model, CATCHLOAD, presented roughly e.g. Bilaletdin *et al.* [2]. There are several different hydrological models available. In our studies, we have mainly used a Finnish version of the HBV [3]. In the present study, the runoff model METQ98 by Ziverts and Jauja 1999 [4] was used. The model METQ98 applied is a mathematical model for the simulation of daily runoff and evaporation for the rivers with different catchment areas. Input data for the model are daily mean values of air temperature, precipitation and vapour pressure deficit. The model METQ98 has 22 parameters. However, most of the parameters are physically based and the rest of the parameters could be estimated by calibration. The model simulates runoff separately for fields and forested areas.

The basic idea of the statistical transport model CATCHLOAD is that the transport is calculated separately for agricultural and forested areas. The catchment is divided into several sub-catchments in the model. Nutrient transport is calculated as the product of discharge and concentration.

$$M = Q_f\, c_f + Q_a\, c_a + M_s + M_w \tag{1}$$

where
M = nutrient transport ($M\ T^{-1}$)
Q_f = discharge from forested areas, using the runoff model described above (LT^{-3})
c_f = nutrient concentration of the waters coming from forested areas ($M\ L^{-3}$)
Q_a = discharge from agricultural areas, using the runoff model described above ($L\ T^{-3}$)
c_a = nutrient concentration of the waters coming from agricultural areas ($M\ L^{-3}$)
M_s = nutrient loading of sparsely populated areas ($M\ T^{-1}$)
M_w = point loading ($M\ T^{-1}$)

The principle of forming the equations used in calculating the concentrations (c_f and c_a) is that standard concentrations referring to certain catchments and certain standard situations are corrected using empirical functions. The functions are designed so that in the standard situation the values of the functions are equal to one and some of the functions increase and some decrease concentrations (tables 1 and 2):

$$c_f = c_{stf}\, f(L)\, f(A)\, f(R)\, f(F)\, f(S) \tag{2}$$

and

$$c_a = c_{sta}\, f(L)\, f(A)\, f(R)\, f(F)\, f(P) \tag{3}$$

where
c_{stf} = standard nutrient concentration in waters from forested areas ($M\ L^{-3}$)
c_{sta} = standard nutrient concentration in waters from agricultural areas ($M\ L^{-3}$)
$f(L)$ = correction function for lake percentage
$f(A)$ = correction function for the area of the catchment
$f(R)$ = correction function for runoff
$f(F)$ = correction function for soil frost
$f(S)$ = correction function for slope
$f(P)$ = correction function for 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. The CATCHLOAD simulates only diffuse loading (agricultural and basic loading) of river basins and for that reason the point source loading and sparse population loading have to be added to this simulated loading.

Table 1: Standard situations of the empirical functions and directions of the effects on changing circumstances.

Standard situation	Change	Effect on loading
lake percentage low	more lakes	decreasing
small catchment area	area grows	decreasing
mean runoff	runoff grows	increasing
no soil frost	soil frost	decreasing
slope low	slope grows	increasing
plant cover type	no plants	increasing

Table 2: The forms of the empirical functions.

Name of the factor	Form	Variable	Constant	Notice
f (lake percentage)	$e^{(a\ pl)}$	p_l	a	
f (catchment area)	A^b	A	b	A (km^2)
f (runoff)	$(q / Mq)^c$	q, Mq	c	(q / Mq)>1
f (soil frost)	d SF + 1	SF	d	SF = 0 (no soil frost)
				SF = 1 (soil frost)
f (slope percentage)	$(1 + SL)^f$	SL	f	
f (plant cover type)	g PT + 1	PT	g	PT = 0 (plants, soil frost)
				PT = 1 (no plants, no soil frost)

3 Application of the model

3.1 Calibration

For the calibration of the runoff model, four discharges and one water level of the lake hydrological stations have been used [5]. The calibration periods differed from 5 to 8 years. For such a basin, the observation points, as well as the calibration periods are sufficient. The time series of four river discharge and one water level of the lake stations have sufficiently good data for a successful calibration of the distributed rainfall-runoff model for the drainage basin of Lake Burtnieks.

The dynamic nutrient transport model CATCHLOAD simulates only nutrient loadings from forested and agricultural areas. Seasonal variations of point loading and loading of sparsely populated areas have been taken into account separately. In this application [5], slope and plant cover type of the field did not correlate with nutrient loading. The drainage basin of Lake Burtnieks is relatively flat. Also a large part of agricultural areas are meadows at present and, therefore, both empirical functions in question do not indicate a great increase in the loading. In the nutrient transport calibration (figs. 2 and 3) the only observed water quality information was from River Rūja. In order to get as good result of the calibration as it was possible, all the observed years were used. The calibration period was from the beginning of the year 1994 to the end of the year 1997. The observed values were explained using the constants of the nutrient transport model CATCHLOAD (tables 3 and 4). Because the goal of the simulation is to estimate nutrient transport, it was not considered important to have very accurate estimates of concentrations per se during flow periods e.g. in summer.

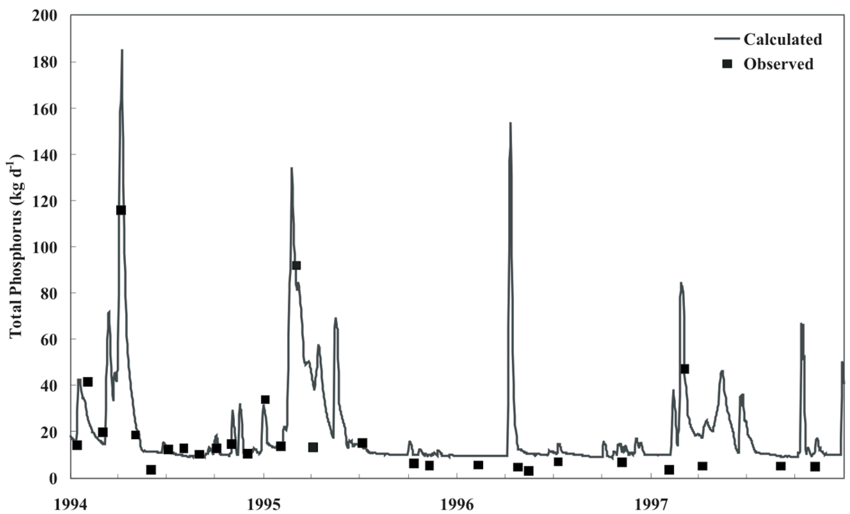

Figure 2: Total phosphorus loading calibration result from Rūja drainage basin. Calibration period 1994-1997.

3.2 Scenarios

3.2.1 Nutrient loading scenarios

To assess a loading situation in the future, for a period of about 10-20 years, different scenarios were formed (table 5). The main contributor to the loading is agriculture and it is assessed that in the future the main changes in loading happens just in agriculture due to the rise of fertilization. On the other hand it is possible to decrease point source loading and loading of sparsely populated areas. Other loading contributors were considered to be constant in the near future.

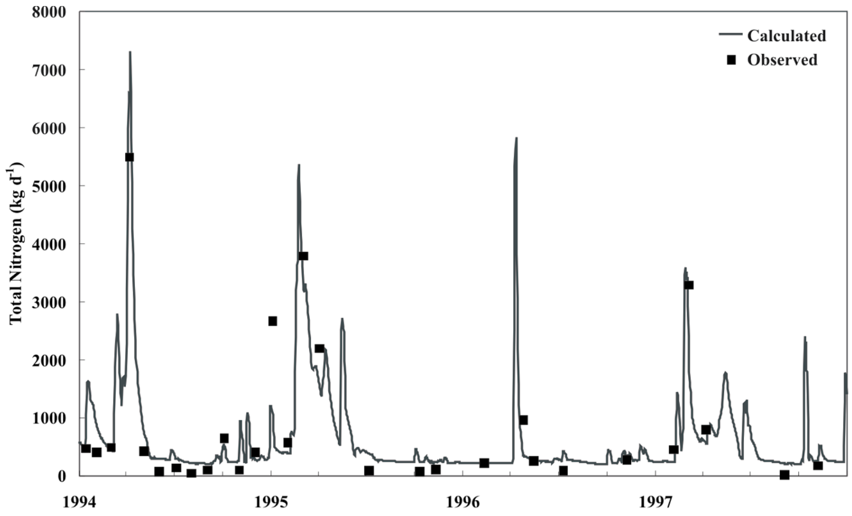

Figure 3: Total nitrogen loading calibration result from Rūja drainage basin. Calibration period 1994-1997.

Table 3: Calibration results of the constants of the empirical phosphorus functions.

Name of the factor	*Constant*	*Forested area*	*Agricultural area*
standard concentration	c_0	30	70
f (lake percentage)	a	-0.07	-0.07
f (catchment area)	b	-0.08	-0.08
f (runoff)	c	0.15	0.15
f (soil frost)	d	-0.10	-0.10

Table 4: Calibration results of the constants of the empirical nitrogen functions.

Name of the factor	*Constant*	*Forested area*	*Agricultural area*
standard concentration	c_0	1110	2000
f (lake percentage)	a	-0.036	-0.036
f (catchment area)	b	-0.05	-0.05
f (runoff)	c	0.15	0.15
f (soil frost)	d	-0.10	-0.10

Table 5: The agricultural and point source loading scenarios concerning nutrient loading to Lake Burtnieks during the forecasting period.

Scenarios
Agriculture, present
Agriculture, 50 % increase
Agriculture, 80 % increase
Point source loading and loading of sparsely populated areas, 50 % decrease

3.2.2 Climate change scenarios

The climate scenarios of the Finnish Research Programme on Climate Change SILMU Carter *et al.* [6] and the results of a climate generator were used as a base values for climate change scenarios of Latvia. The climate generator was used to produce meteorological data sets, needed in the model, for both present and changed climate. Scenarios account for two major uncertainties concerning future greenhouse-gas emissions and climate sensitivity. They give air temperature, precipitation and cloudiness changes for Finland concerning central, low and high emissions and sensitivity. The scenarios used in the weather generator called CLIGEN are summarised below in table 6. Humidity was calculated as a regression of temperature and cloudiness. The regressions were calculated from 30-year (1961-1990) weather statistics from Pirkkala airport. Wind speed values were normalized from observed weather data by calculating the deviation of the study period's daily wind speed values and 30 year's wind speed daily mean values. This deviation was the added to the observed wind speed values. In the model scenario values in the present climate, as well as in year 2010, 2030 and 2060 were used. The SILMU policy oriented scenarios have been tuned to the circumstances of Latvia by the University of Latvia, Hydrological Department of the Agricultural University.

Table 6: The scenarios of seasonal temperature and precipitation change over Latvia. Rates are assumed to be linear.

Season (initials of months)	Temperature (°C/decade)			Precipitation (percent/decade)		
	Central	Low	High	Central	Low	High
Spring (III-V)	0.4	0.1	0.6	0.5	0.125	0.75
Summer(VI-IX)	0.3	0.8	0.45	1.0	0.25	1.5
Autumn (X-XII)	0.4	0.1	0.6	1.0	0.25	1.5
Winter (I-II)	0.6	0.13	0.75	2.0	0.42	2.5
Annual	0.4	0.1	0.6	1.0	0.25	1.5

4 Results of the scenarios

4.1 Phosphorus loading

The dynamic loading scenarios were produced for water quality modelling in Lake Burtnieks. Because phosphorus is a limiting factor of algae growth in Lake Burtnieks, only phosphorus results are presented here.

The nutrient loading scenarios were calculated to the four sub-catchments of Lake Burtnieks (Rūja, Seda, Briede and the rest of the catchment). The effects in the different sub-catchments are very similar. During high discharge periods, the nutrient loading increases clearly and produces mainly a rise of the loading, fig. 4. The annual effects on total phosphorus loading to the Lake Burtnieks using presented scenarios are remarkable due the great division of arable land: 28% (AGRI150), 45% (AGRI180) and -9% (SP50).

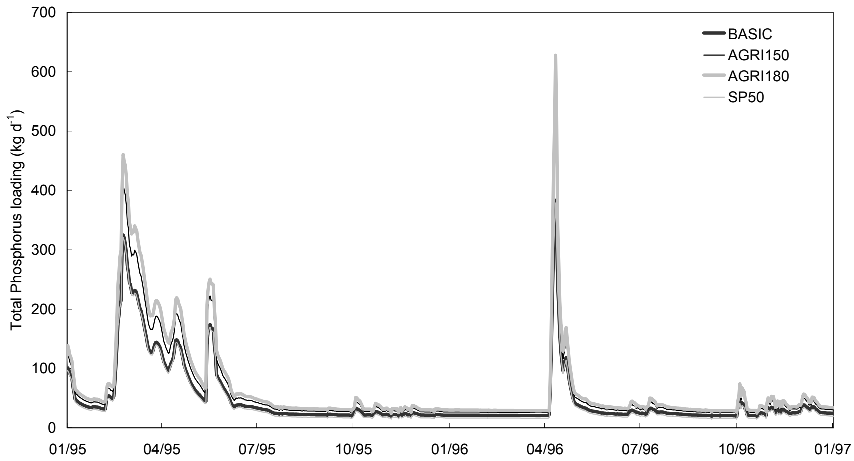

Figure 4: The dynamical effects of phosphorus loading scenarios on total phosphorus loading to Lake Burtnieks. BASIC = reference loading, AGRI150 = agricultural loading increased by 50%, AGRI180 = agricultural loading increased by 80% and SP50 = loading from sparsely populated area decreased by 50% and point source loading decreased by 50%.

4.2 Climate change

The hypothesis of climate change was used in the METQ98 runoff model and in the CATCHLOAD nutrient transport model (fig. 5). The observed years were the present, 2030 (C30) and 2060 (C60). On an annual basis the effects of climate change on runoff were only minor. Due to the increasing evaporation the increasing precipitation was not much reflected in runoff. Concerning the runoff scenarios, the relative annual sums of discharges comparing to the present situation were 1% (30 year) and 5% (60 year). Material transport follows closely the variation of runoff. The annual effects on total phosphorus loading to the Lake Burtnieks using presented scenarios are quite small: 05 % (30 year) and 4% (60 year).

Monthly effects are important for lake modelling. Monthly effects of climate change on nutrient transport can be described as follows: from January to

February transport increased and in April decreased. The rest of the year remains almost unchanged.

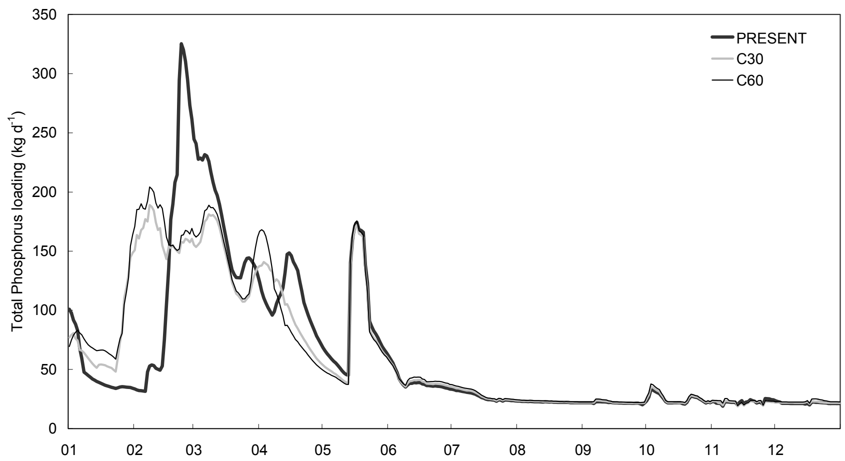

Figure 5: The effects of climate change scenarios on total phosphorus loading into Lake Burtnieks in the year 1995.

5 Discussion

Catchment (or watershed) models are used in the assessment of diffuse nutrient loading. They can be very detailed and sophisticated process-oriented models giving a realistic description of the formation of nutrient leaching. However, this kind of models cannot be used in calculating nutrient transport from large catchments. In this paper only a model applicable into large catchments is presented.

Models are the only possibilities in estimating nutrient leaching when catchments with no major rivers or brooks, often called as the nearest drainage basins referring to the fact that these parts of the catchment are in direct contact with the water area, are considered. Models are also needed in coupling the factors affecting the formation of nutrient loading with the actual loading. Thus, models can be utilized in predicting e.g. the effects of changing land use regime or agricultural practices, or global climate change.

There are both steady-state and dynamic catchment models available. Steady state models are suitable in cases in which information about long-term average values of nutrient loading are needed. Dynamic models must be applied in cases in which the temporal distribution of nutrient input must be considered. They are needed e.g. in more detailed impact assessments in which dynamic water quality models of lakes, rivers, coastal areas or seas are applied.

In this present study the dynamic catchment model CATCHLOAD was applied. An advantage of the CATCHLOAD is that it does not need very sophisticated data to achieve accurate estimates of nutrient loading in large catchments. Even though in this present application the input data could have been better, it was possible to get useful results for lake modelling.

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