INTEGRATED MODELLING OF PHOSPHORUS FLUXES AT THE CATCHMENT SCALE

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ABSTRACT

A model (HBV-P) is developed for calculations of present P status, fluxes through the river system, source apportionment, and the combined effect at the catchment-scale of several nutrient reduction measures (e.g. changed agricultural practices, buffer zones, and constructed wetlands). HBV-P is based on the hydrological rainfall-runoff model HBV. The model is dynamic, using a daily time-step. Models of agricultural leaching, lake and river/river bank processes are integrated in the catchment model, as well as diffuse leaching from forests and urban areas, and emissions from point sources. Agricultural leaching estimates are based on the ICECREAM model, which is a field scale model that at present is being further developed by including macoropore flow to tile drains. Upscaling of sediment transport and surface runoff from agricultural land are made in a GIS-environment. Lake processes are simulated with a simple lake module. Processes in the river have been included, and also a routine for streambank erosion. Routines for reduction in buffer zones and wetlands will soon be added to the model.

KEYWORDS: Catchment modelling, dynamic modelling, phosphorus, remedies, source apportionment

INTRODUCTION

In Sweden, the annual average (1985-1999) transport of phosphorous (P) from land to surface waters is approximately 6700 t. About half of this transport is the natural background from land, and the other half is caused by human activities. Of the anthropogenic part, about 50% can be linked to agricultural activities, and the to clear-cutting in forests, storm runoff from urban areas, rural households, wastewater treatment plants and industries. P loads from industries, wastewater treatment plants and agricultural point sources have significantly decreased since the 1970s, whereas the reduction of loads from agricultural fields has been less pronounced. This is partly due to lack of knowledge of best management practices, and insufficient communication about available knowledge.

For nitrogen, there is a relatively satisfactory knowledge about the impact of various remedies on leaching from agricultural land. In Sweden, models of leaching from agricultural land have been applied on scales varying from plot up to the national level (e.g., Jonsson et al., 2002).

Research with regard to diffuse loads of P has been more limited. A significant proportion of the P is bound to soil particles, with the actual amount depending on chemical characteristics of soils and sediments. Consequently, a high proportion of the annual transport can take place during a very limited time frame, usually in connection to high water flow.

There is also a lack of knowledge about the mechanisms responsible for shifting between various phases and soil pools of P. Evidently, these uncertainties in process descriptions make it difficult to construct models that are useful for quantification of the effects of various remedies for reduction of P loads from agricultural fields.

Also P movements into and out from constructed wetlands are strongly event-related. Large changes in concentrations and flows might occur within hours influencing the processes in the wetland. The fate of P is depending not only on the magnitude of the streamflow changes, but also on catchment specific characteristics determining what forms of P that are reaching the wetland.

Establishment of buffer zones is often is suggested as a remedy to reduce the transport of P to water courses. From a literature survey of P reductions after introduction of buffer zones, it was concluded that there are very few field studies on the impact of grass covered buffer zo nes under natural precipitation conditions. The survey points out that the empirical evidence of P reduction due to buffer strips, linked to site specific conditions, is very uncertain (Ulén, 2002).

There have been indications that the P concentration (and transport) in runoff from entire catchments often exceeds the concentration in runoff from single fields within the catchment (e.g., Andersson et al., 2002). Bank and bed erosion in streams within the catchment has been proposed as a potential mechanism responsible for the differences in concentration, as the mobilised fine sediment particles have P attached to them (e.g., Kronvang et al., 1997; Ulén, 1998).

In addition, the moving of water in rivers and streams plays a larger role in the P cycle than just merely transport. Due to the highly reactive nature of P there are numerous processes affecting the retention and several of these are currently only partially understood (Wörman, 1998).

Despite the limitations in the full understanding of relevant processes, a new model for integrated modelling of P fluxes at the catchment scale is under development within the Swedish Water Management Research Programme (VASTRA). This project aims to provide increased knowledge and practical tools that significantly contribute to an efficient and socially acceptable solution to the problem of eutrophication at the catchment scale. The model will be used to simulate the effect and cost of various remedies on P, including scenarios of changed agricultural practices, construction of buffer zones and artificial wetlands, improved treatment of effluents from rural households and emissions from point sources, and biomanipulations in lakes. The modelling system will be generally operational by using the national databases. This means that most input data is available for model application in the whole of Sweden.

METHODS

The model developed (HBV-P) models particulate phosphorus PP and soluble reactive phosphorus SRP. The structure of HBV-P is shown in Fig. 1. The hydrological part of the model is based on the HBV-model (Lindström et al., 1997). The model is dynamic, driven by daily air-temperature and precipitation that is areally weighted for each sub-catchment. Soil moisture, evaporation, groundwater response and routing are described conceptually, using a limited number of parameters and monitored streamflow data for validation, if available. Routines for nitrogen (HBV-N) were added during the 1990s (Arheimer and Brandt, 2000).

Contributions to P loads

For other land categories than agriculture, static ”typical values” of concentrations compiled and used within the so-called TRK-project (Brandt and Ejhed, 2003) are used. Also for point sources, the concepts are taken from TRK.

Diffuse losses of P through the soil is calculated with the ICECREAM model (Tattari et al., 2001). Since preferential flow through macropores is an important pathway for both dissolved and particulate P through structured soils (e.g. Sharpley & Rekolainen, 1997), a description of macropore flow and transport was included in the ICECREAM model (Fig. 1).

The macropores are treated as a rapid transport pathway where transformation of P and root uptake are assumed negligible. Particle bound P is transported to the tile drains without interactions with other P pools in the soil, while the dissolved P is transported through the macropores and mixed with the dissolved P percolating out of the micropores before discharging through the tile-drains.

In the coupling between ICECREAM and HBV-P, concentrations are calculated for selected combinations of soils, vegetation, and management practices with a geographical aggregation that reflects variations in agricultural practices and climate. The outputs are provided as averages over a selected time-period (e.g., for individual months or seasons). The calculations of soluble and particulate P concentrations from tile drains are then mixed into the upper of the ground-water storages in the HBV-P model. Matrix flow of soluble P is added to the lower of the groundwater boxes in HBV-P (Fig. 1). Since this component of the P transport from agricultural fields is highly dependent on local topographical conditions and distances from water courses, a GIS-driven model component was developed to consider this geographical heterogeneity (Hellström, 2002). The model is driven by sub-catchment values of daily rainfall and snowmelt, soil moisture and soil temperature, derived by the HBV-model. The model use curve numbers to estimate overland flow generation. Several agricultural non-point source models including ICECREAM use this method due to its simplicity and the possibility of obtaining parameters from simple descriptive indicators of the vegetation cover and soil characteristics of the basin. Estimates of soil loss are based on a modification of USLE. In earlier applications, the routines of ICECREAM were coupled with the outputs from the GIS-based calculations of surface runoff and sediment transport. However, these routines will be substituted by simplified equations.

Artificial wetlands and buffer zones

The wetland component of HBV-P is developed using data for a number of small wetlands receiving agricultural drainage water in southern Sweden. As in Arheimer and Wittgren (2002), a completely mixed batch reactor model with a high temporal resolution will be used to account for the varying water flow. The quality of the inflowing water will be separated into dissolved and particulate P, given by the stream flow component of the catchment model. Dissolved P can be incorporated into organic forms (plant uptake) and released from sediments during low flow and warm periods. For particulate P a simple sedimentation/resuspension equation will be used (Braskerud, 2001).

No physically-based model routine of the impact of buffer zones on reduction of surface runoff of P will be included in HBV-P until there is more empirical research available that can quantify the impact of the buffer zones, depending on local conditions. Instead, only a certain percentage of reduction will be assumed to take place, and the range of uncertainty in these estimates will be presented.

Streambank erosion

Presently, a GIS-based approach is being tested for incorporation in HBV-P (Evans et al., 2002), in which a range of catchment characteristics besides the dominating soil type is investigated as explanatory variables for (monthly) in-stream erosion (e.g., topographic slope, animal density and soil erodibility).

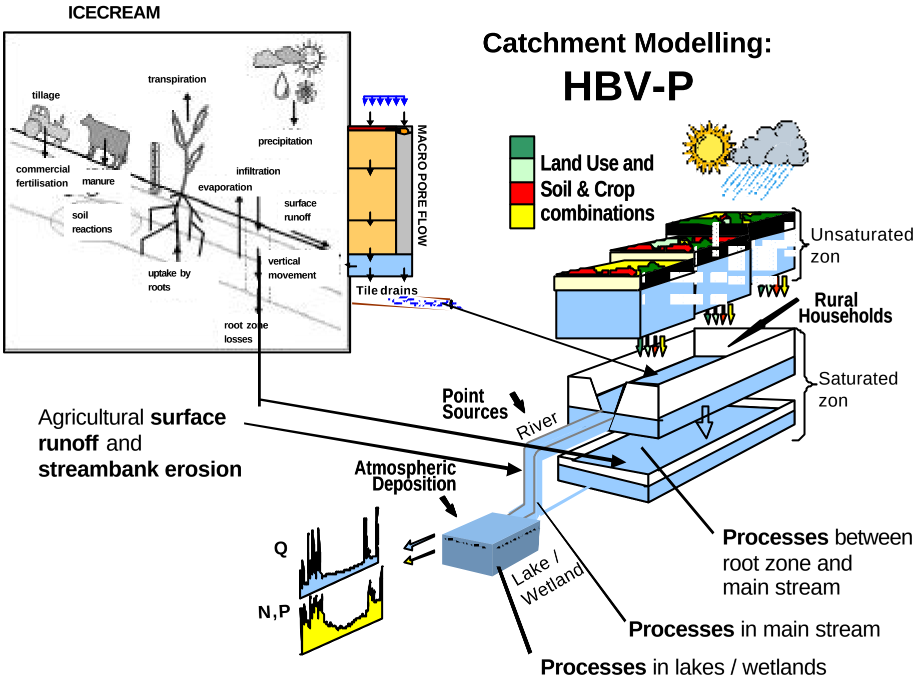

Figure 1. *The HBV-P concept.*

P concentration from five fields and their surrounding catchments were compared in order to find out if there were additional sources to the catchment sediment and PP load than the field deliv eries. Surface runoff from the fields was hypothesised to be transported to the tile drainage system, mainly through stormwater wells. From the catchments, data were available during approximately 10 years, and consisted of daily runoff (Q) as well as concentrations of suspended sediments (SS) and P fractions sampled on an approximately biweekly basis. From the fields, annual runoff and flow-weighted mean concentrations were available, and to make comparison possible the catchment data were converted correspondingly. The data have been collected within the Swedish environmental monitoring program (see, e.g., Ulén, 2001).

Processes within the river

The HBV-P model has been equipped with several sub-models to simulate the separate channel processes included in this modelling approach.

Sedimentation is calculated as a part of suspended P according to a logarithmic equation (Lidén, 1999). The resuspension is calculated according to a similar equation but reversed and taken as a part of the accumulated sediment. Bankfull discharge is used for the upper limit for these processes. Currently this process does not cover any morphological change of the channel. The buffer effect is driven by the concentration gradient of SRP between model timesteps (e.g., Lijklema, 1993). This process is also thought to be covering the exchange of P with periphyton and macrophytes although this might be replaced with later modules. PP is simulated as being in equilibrium with current concentration of soluble P according to a distribution coefficient. The water temperature controls the growth and decay of suspended biological matter, mainly algae. Due to the variability of covering foliage and uncertainty of cloud cover models/observations, especially along the stretch of an entire river, the light dependency of this process was transformed into an extra dependency on temperature.

The constants of the included equations were combined into three model parameters that will be calibrated to observed values in each major basin where the model is applied. Also, to provide the necessary data for the computation, the HBV model was expanded with sub-models providing the velocity and depth of the water flow at any given point along the channel. Both these sub-models are regression models calibrated using extensive series of observations from SVAR (Swedish Water Archive) on velocity, depth and width on watercourses in all of Sweden. To improve these models the data was divided into eleven groups according to which geomorphologic zone they originated from. The R^2 values of these regression fits range from 0.49 to 0.79.

PROCESSES IN LAKES

The most important processes were assumed to be retention (e.g. assimilation by phytoplankton) or release from the sediments for SRP and sedimentation for PP. These processes were assumed to depend upon lake surface area (A_L), lake temperature estimated as a thirty day mean of air temperature ($\overline{T_{30}}$), lake eutrophication level in the form of a typical SRP concentration (c_{orig}), and the present P concentration in the lake (c). Each equation has a parameter that can be calibrated (k_n). The process equations in the lake module are:

$$\Phi_{SRP\_L} = k_4 * c_{orig} * 0.86^{\left|\overline{T_{30}} - 15\right|} * A_L \quad (1)$$

$$\Phi_{PP\_L} = k_5 * c * A_L, \quad (2)$$

Three different temperature functions were tested ($\overline{T_5}$, $1.07^{\overline{T_{30}}-20}$ and $0.86^{\left|\overline{T_{30}}-15\right|}$, where $\overline{T_n}$ = n-day-mean air temperature). With a completely mixed lake the equations are applied to the whole lake volume, but if a division into an active and a passive lake part is used, the equations are only applied to the active part. Two parameters determine the relative volume of the active and passive parts and the relative contribution of each to the outflow. The passive (upper) part of the lake can be seen as if part of the inflow takes a more direct route through the lake without mixing with the larger part of the lake water volume. The water flows and volumes were taken from HBV, but as input to the lakes observations of concentrations of SRP and TP in the inflows were interpolated and used. In addition P loads from point sources and atmospheric deposition have been added to the lakes.

RESULTS

Differences in PP transport from fields and catchments

For all the five investigated field-catchment combinations, the PP concentration was higher or substantially higher in the catchment outlet (Fig. 2). The difference ranges between 0.01 and 0.07 mg l^{-1}, being on average ~0.05 mg l^{1}. As for the actual concentration levels, the field-catchment difference generally increases with increasing clay content of the catchment. Despite the uncertainties involved, from e.g. field-catchment differences in soil types and the unclear representativity of the fields for the surrounding catchments, the results indicate a significant influence of streambank erosion. Preliminary tests of the GIS-based method by Evans et al. (2002) indicate a satisfactory performance also at a daily time step.

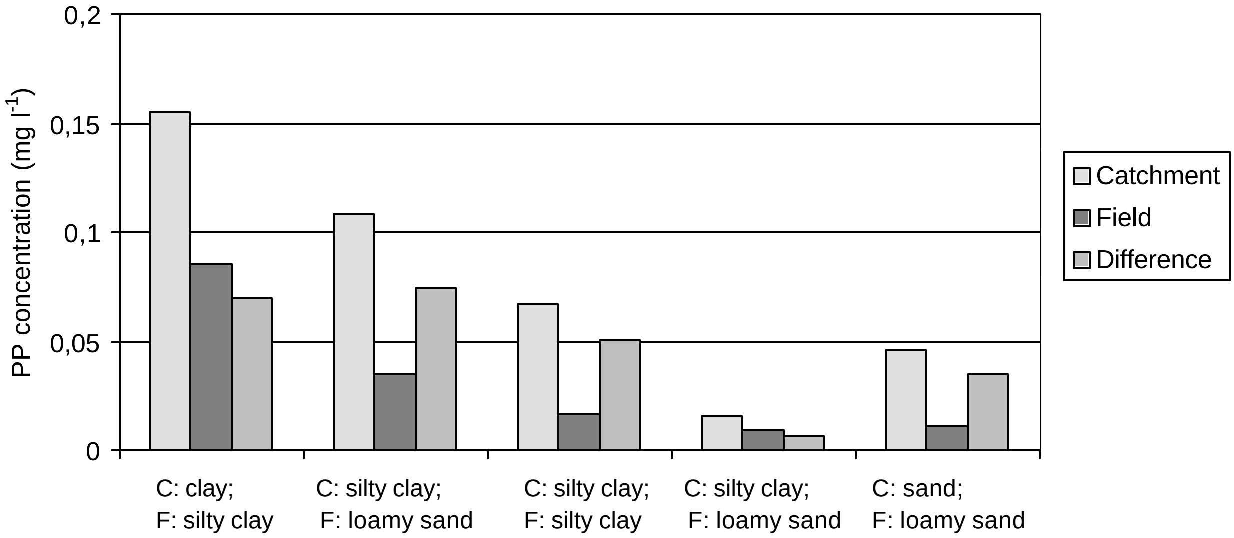

Figure 2. *Long-term average PP concentrations in the runoff from five field (F) - catchment (C) combinations with different dominating soil types.*

The impact of lake processes

Fig. 3 shows the observed and simulated TP concentration in Lake Ringsjön from the concurrent calibration with nitrogen, and simulation with process parameters equal to zero (i.e. only considering variations in the contribution from upstream sources).

The impact of processes within the river

In Fig. 4, preliminary results from the river module of HBV-P are shown for a catchment containing few lakes or urban areas, and consiststing of several upstream sub-catchments that mainly are forested and therefore well suited for isolating and testing the river processes. Unfortunately the frequency of the available observations are not fully adequate to catch the dynamics of the phosphorus concentration. However in observation series of higher frequency (e.g., Svendsen et al., 1992), process dynamics similar to the simulated values can be seen. The dynamics of the 'No model' curve are due to the diluting effect of the water discharge.

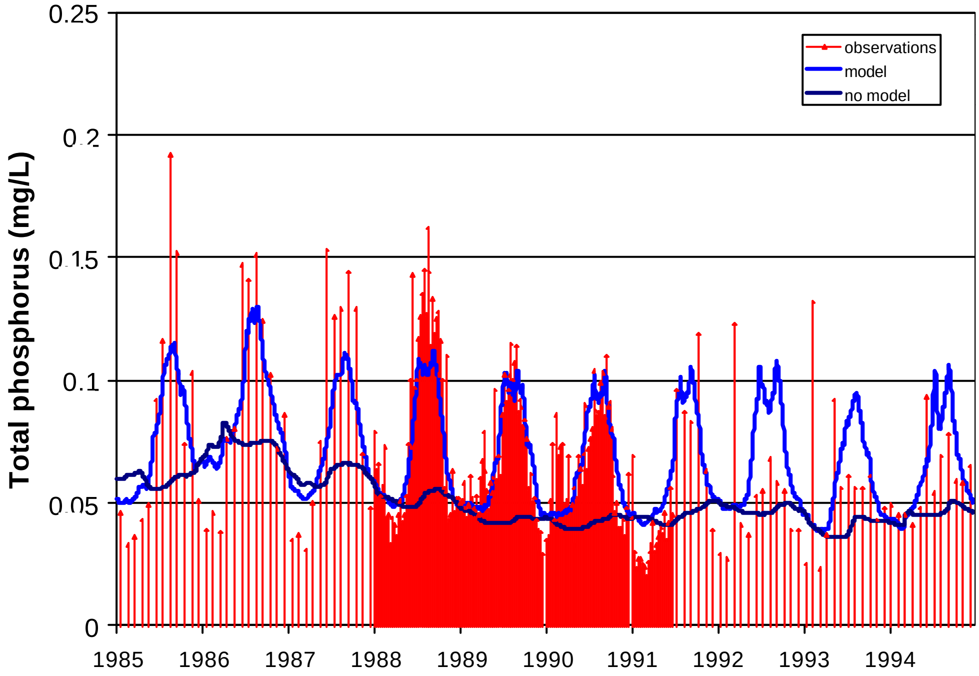

Figure 3. *Simulated and observed total phosphorus in Lake Ringsjön. Concurrent calibration of nitrogen and phosphorus 1985-1994 and without the new lake module (parameter values equal to zero).*

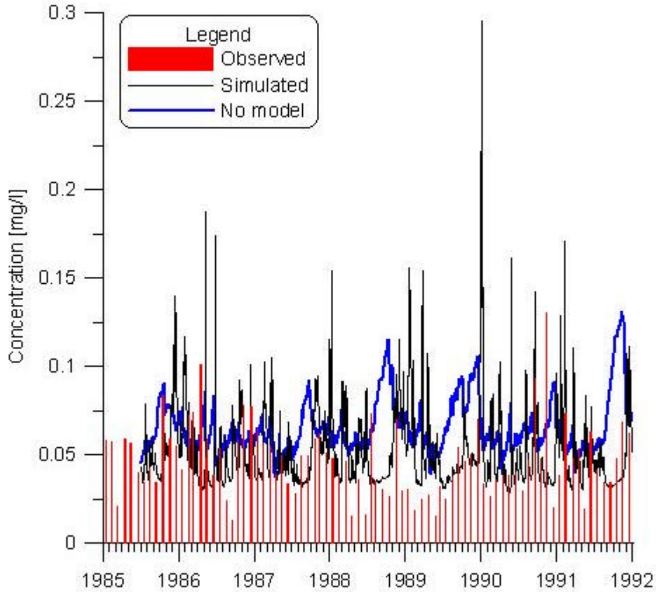

Figure 4. *Simulated tot-P concentrations for the Pinnå catchment, with and without consideration to the instream routine.*

CONCLUDING REMARKS

The HBV-P model will be applied for scenario analyses for various remedies within VASTRA´s pilot basin Rönne å (southern Sweden) during late 2003. It will be used for evaluation of which remedies that are most efficient in the basin, both with regard to acceptance, costs, and their contribution to reducing P loads in accordance to the water framework directive. From model development made this far, it can be concluded that we do capture most processes with some level of correspondence to what can be seen from monitored concentrations and transports. However, it must be emphasised that there are large uncertainties, both with regard to the impact of various remedies, the impact of lack of certain data (e.g. a satisfactory soil-data base), and due to parameter uncertainty. Uncertainty analyses will be a vital part of work within VASTRA, and such analyses will also be presented during stakeholder panel discussions, in order to assess the impact of such uncertainties in decision making.

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