Modelling diffuse nutrient flow in eutrophication control scenarios

B. Arheimer*, L. Andersson*, M. Larsson, G. Lindström*, J. Olsson* and B.C. Pers***

* Swedish Meteorological and Hydrological Institute (SMHI), SE-601 76 Norrköping, Sweden

** Dept. Soil Sciences, Swedish University of Agricultural Sciences (SLU), Box 7072, SE-750 07 Uppsala, Sweden

Abstract The Swedish Water Management Research Programme (VASTRA) focuses on the development and demonstration of tools for more efficient eutrophication control when implementing the EU water framework directive in Sweden. During the first half of the programme, models for nitrogen flow were developed, and at present, similar models for phosphorus are under construction (e.g. HBV-P). The programme is interdisciplinary, and scientists are collaborating in actor-games and focus group evaluations including scenario analysis. The scenarios modelled in VASTRA phase I, show that (i) changed agricultural practices can be the most effective and least expensive way to reduce nitrogen transport from land to the sea; (ii) constructed agricultural wetlands may only have small impact on riverine nitrogen transport in some regions, due to natural hydrometeorological dynamics; (iii) removing planktivorous fish may be an efficient way of reducing the algal concentrations in lakes without the undesired side-effect of increased nutrient load to the down-stream river system. In VASTRA phase II, one of the highlights will be interdisciplinary scenario-modelling of different measure strategies in a pilot catchment of southern Sweden (Rönne å).

Keywords Catchment; lake; modelling; nitrogen; phosphorus; scenarios; VASTRA

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Introduction

Eutrophication in lakes and the coastal zone is considered a serious environmental problem. It causes a greater production of plankton algae (sometimes poisonous), excessive growth of macrophytes and macroalgae, which leads to oxygen deficiency and fish kills. It also results in reduced biological diversity and the so-called "bottom death" of water bodies. The problems are mainly caused by excessive load of phosphorus (P) and nitrogen (N) in freshwater. The nutrient load origin is from point-source emissions and diffuse sources. The load from point sources (e.g. wastewater treatment plants) has been successfully reduced in Sweden starting in the 1970s (especially for P). However, water quality problems still remain due to diffuse leaching from arable land and from sediment loading.

Measures have been undertaken to reduce the agricultural leaching in Sweden during the 80s and 90s (Johnsson and Hoffmann, 1998), although their net influence on the large-scale transport from the agricultural sector is still rather small (Arheimer and Brandt, 2000). Reduction of nutrients from diffuse sources is difficult to achieve as the sources are difficult to monitor and the nutrients constitute a natural part of the soil and water environment. Moreover, the measures requested more directly affect people's lifestyle and livelihood. To achieve changed agricultural practices, new policies including catchment-based management plans for farmers have been suggested. Nevertheless, catchment-based solutions of nutrient problems demand catchment-based knowledge of nutrient transport processes and appropriate tools for landscape planning, which may not be available at present.

Water management in Sweden is now going through dramatic changes related to the adoption of the EU Water Framework Directive, the new Environmental Code and the new and revised National Environmental Quality Objectives. This new scene of water resources management will have a significant impact on authorities and stakeholders trying to adapt to new policy instruments, organisational structures and implementation schemes. The Swedish Water Management Research Programme, VASTRA, is a multidisciplinary, solution-oriented research programme, scheduled to run during 1997–2004. The overall objective is to develop tools for more efficient eutrophication combat, and VASTRA is just entering its second phase.

VASTRA has in its first phase applied a broad perspective on water management strategies, including sub-programmes on (1) reducing fluxes of nutrients from land to aquatic systems, (2) improving the potential for multiple uses of surface water resources, (3) safeguarding groundwater resources, (4) databases, model development and systems analysis, and (5) interactive catchments studies. The second and concluding phase of the programme covers three core problem-areas, which can be illustrated by the following questions:

- What would be a suitable set up of organisational structures and incentives to get a positive co-operation from stakeholders, e.g. farmers, in water management strategies that can solve the eutrophication problem in a catchment area?
- How will measures to control nutrient transport, both N and P, from land to aquatic systems in catchment areas, contribute to "good water status"?
- How can various measures to control nutrient transport from land to aquatic systems be integrated into a tool-box that – in the hands of stakeholders – has the power to produce well balanced action plans to solve the eutrophication problem on catchment scale?

Three sub-programs (SP) have been designed to provide the knowledge required for answering these questions. SP1 is the overall integration and synthesis of knowledge for eutrophication control in catchments, which is demonstrated in the pilot catchment Rönne å in southern Sweden. SP1 (Figure 1) includes a database and tool for scenario analysis; definition and calculation of management scenarios; Ph.D. training program; program synthesis and stakeholder test of the VASTRA tool-box (the "focus group" approach); and a leap into the future (the "think-tank" approach). SP2 deals with selecting policy instruments, institutions and conflict solution mechanisms for sustainable catchment management. SP3 deals with nutrient flow and modelling in landscape elements (arable land, buffer zones, wetlands, lakes, rivers) and integrated catchments. SP2 and SP3 feeds into SP1, in which the new tools are applied in the pilot area in close co-operation with local and regional

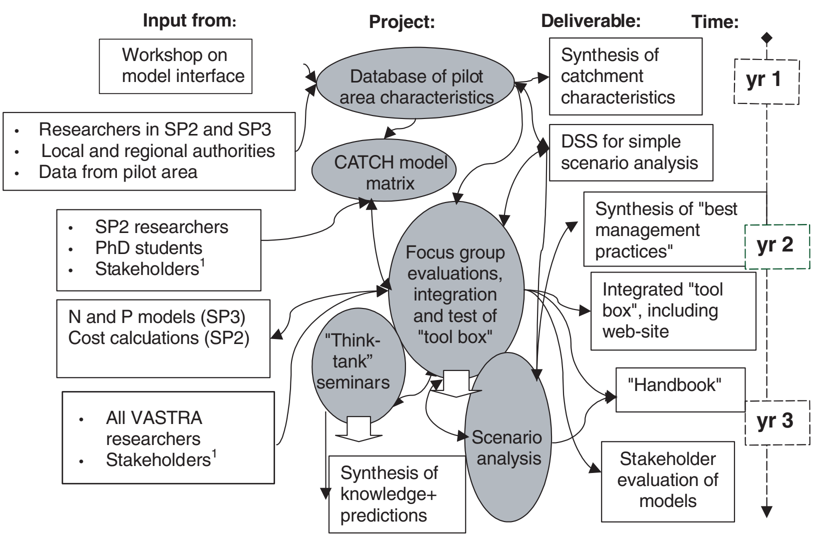

Figure 1 Schematic structure of Subprogram 1 in VASTRA, its input, projects, deliverables and time frame (*www.vastra.org*)

stakeholders. This paper presents the VASTRA nutrient-modelling tools for the catchment scale and lakes, and some of the scenario results achieved so far.

Methods

Catchment modelling of N flow

VASTRA uses the dynamic HBV-N model, which has recently been used for estimation of Swedish N-load from rivers to the Baltic Sea (Arheimer and Brandt, 2000). HBV-N is based on the rainfall-runoff model HBV (e.g. Bergström, 1995), which calculates the water balance in coupled subbasins of the landscape. In the N-routine, leaching concentrations are assigned to the water percolating from the unsaturated zone of the soil to the groundwater reservoir of the HBV model (Figure 2). Different concentrations are used for the categories: forest, urban, arable and other land. The arable land may be further divided based on soil type, crops, and management practices, for which root-zone concentrations are achieved from the SOILN model (Johnsson *et al.*, 1987). In addition to soil leaching, N is also added from rural households and point sources, such as industries and wastewater treatment plants. Atmospheric deposition on water surfaces is also added, while N-deposition on land is included in the soil leaching.

The HBV-N model simulates N residence, transformation and transport in groundwater, rivers, lakes, and surface-flow wetlands (ponds). A time-step of one day is used. The equations used to account for N-retention processes are based on empirical relations between physical parameters and concentration dynamics. The model is calibrated step-wise against observed time-series of water flow and concentrations (Pettersson *et al.*, 2001). Source apportionment for the riverine load is achieved by adding sources of different categories in the catchment. This is made separately for gross and net load to illustrate the influence of retention processes. Net load is the remaining part of the gross load, which eventually reaches the sea after N removal in sinks downstream of a specific source and subbasin (Wittgren and Arheimer, 1996).

Catchment modelling of P flow

The model development of VASTRA phase II aims at developing a similar tool for P as for N. It will be adapted to climatological and hydrological conditions in the Nordic countries,

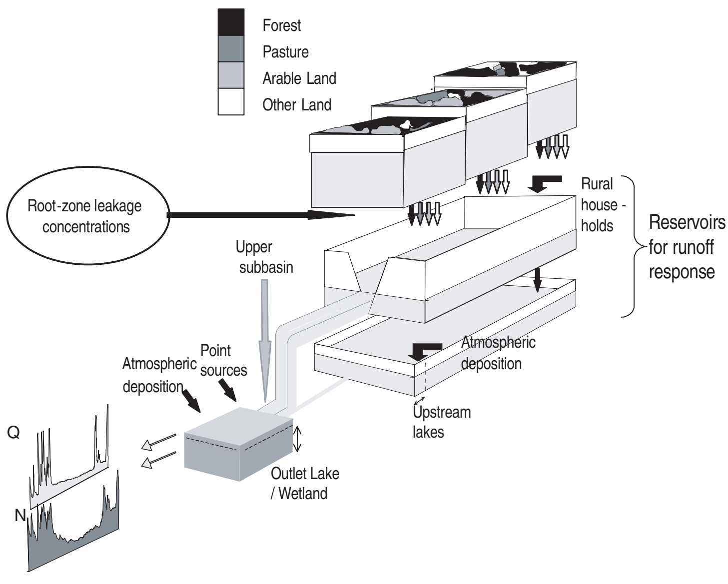

Figure 2 Schematic structure of the catchment model HBV-N. Modified from Pettersson *et al.*, 2001

and quantify transport of P from various sources in a catchment, transformation in rivers and lakes, and further transport to the sea (Figure 3). The overall objective is to link different scales, sources and transports of nutrients into a scenario tool at the catchment scale. The following sub-models that will be integrated with the catchment model: (i) P-transport from fields (surface, and subsurface pathways through the soil matrix and through macropores), (ii) sedimentation/erosion processes in riverbanks and the streambed, (iii) internal processes in lakes, (iv) retention in buffer zones and wetlands. Contributions from other land types than agricultural, and point sources will mainly be based on empirical data or achieved from the national TRK project (Brandt and Ejhed, 2003). To be applicable for large river basins, the model will only depend on regionally available databases of driving variables and geographical data.

The model development has started with P losses from arable land based on the ICECREAM model (Rekolainen *et al*., 1998), but the hydroclimatological compartments have been replaced with sub-routines from the catchment-scale model HBV. So far, this coupled model has been tested at three agricultural field-sites in different climate regions of Sweden. In most cases ICECREAM performed better when driven by hydroclimatological routines from HBV, compared to when driven by the original hydroclimatological routines in ICECREAM (Persson *et al*., 2001). The Soil Conservation Service (SCS) curve number procedure is used for estimating surface runoff from agricultural land from daily runoff. The surface runoff routine is driven by soil moisture, soil frost and rain/snowmelt estimates from the HBV-model. To assess spatial variability of erosivity, we use concepts from a GIS-assisted version of the Universal Soil Loss Equation (Reinelt *et al*., 1989). For calculations of soluble particulate P with surface runoff, catchment estimates of surface runoff and sediment loads for different combinations of land use and soils are used as input to the ICECREAM model, and then returned to the catchment GIS-system, where the total transport of P from agricultural land (dissolved P from soil leaching, dissolved and particulate P from surface runoff) are calculated.

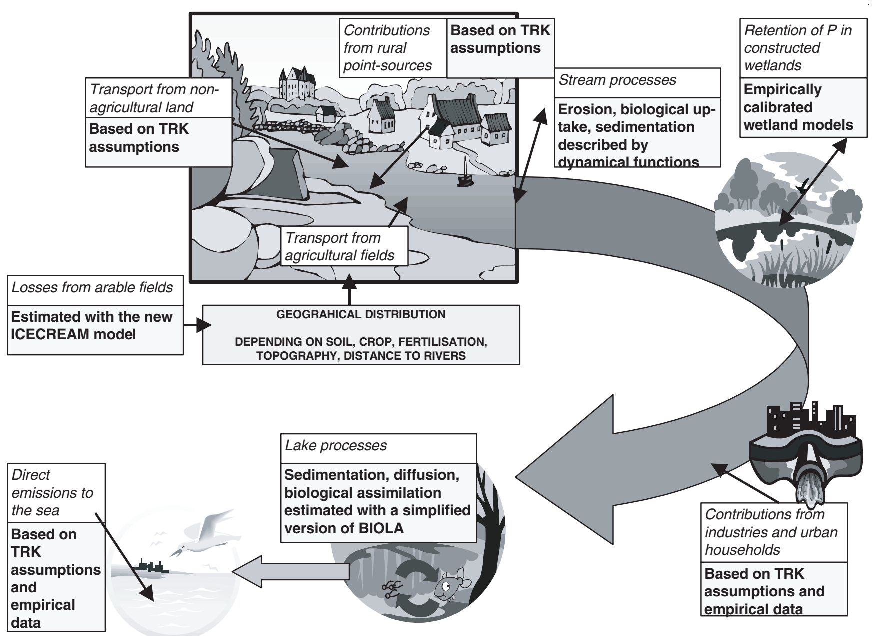

Figure 3 The VASTRA nested catchment-model approach, which combines scales and links sources, transport and fate of P from various landscape elements. (TRK is a Swedish project for estimation of transport, retention and source apportionment at the national scale.)

The coupling of HBV with a detailed, field-scale model such as SOILN and ICE-CREAM constitutes an attractive approach to accommodate nutrient flux variability and transport over a range of scales. The implementation of HBV-P, however, is likely to be more complex than HBV-N due to the more uncertain and ill-defined pathways of P transport. Modelling catchment transport of P is indeed challenging, but recent attempts support the feasibility of such efforts (e.g. Cooper *et al.*, 2002). Important considerations will be the balance between model complexity and data availability, and the description of elusive but potentially very important processes such as surface runoff, bank erosion and in-stream P transformations.

Biogeochemical lake modelling

The BIOLA model (Pers, 2002) was developed during VASTRA phase I, to evaluate combinations of measures and their improvement of water quality in specific lakes. BIOLA may be used for simulation of different management scenarios and help to understand why lakes react differently. The model is linked to a hydro-dynamic lake model, because temperature and mixing/stratification are important for lake ecology. A time step of 10 minutes, 3 h-interval meteorological forcing and daily inflow/outflow records are used. The biogeochemical module simulates the changes in nutrient and biological state with time resolved over depth. The primary response variables are dissolved inorganic nitrogen (DIN), phosphate (PO_4) and algae. These variables are often the ones most critical to control. Blue-green algae were separated from other phytoplankton because some genera are able to fix atmospheric N, and because their presence is sometimes a nuisance. Totally 14 variables are modelled and the processes modelled are illustrated as flows between the state variables in Figure 4. At set up, initial values of all variables are given, but these are sometimes changed later to get a relatively stable concentration level. Some parameters of the model are then calibrated against observations. Parameters are tested sequentially during calibration. The visual appearance of the time series compared to observations was used

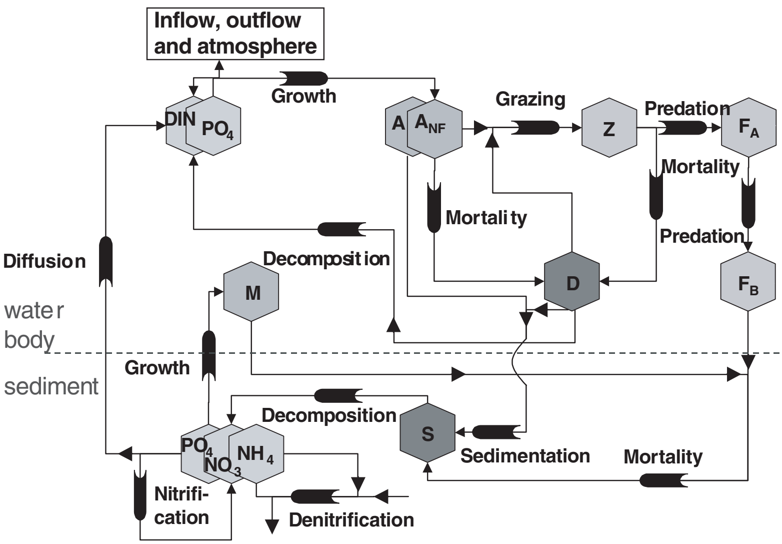

Figure 4 Schematic structure of the biogeochemical lake model BIOLA (Pers, 2002). The model is classified as: dynamic, one-dimensional, process-based, mechanistic. The model calculates the state variables in the water-body in each layer (normally every metre) with a 10 minutes time-step. The compartments in the figure illustrate the storage of the following variables: DIN = dissolved inorganic nitrogen; PO_4 = phosphate; A = autotrophs (i.e. phytoplankton); Z = zooplankton; F_A = planktivorous fish; F_B = predator fish; D = detritus; S = sediment; M = macrophytes; NO_3 = nitrate; NH_4 = ammonium

for choosing the best parameter values. This is based firstly on the level, and secondly on the seasonal variation of the state variables.

Results and discussion

Scenario modelling in VASTRA phase I

Management scenarios to reduce riverine nitrogen load were constructed in an actor game (i.e. role-play) for the Genevadsån catchment in southern Sweden (Wittgren *et al.*, 2001). The game included stakeholders for implementation of a loading standard for maximum N transport at the river mouth. Scenarios were defined after negotiation among involved actors and included changes in agricultural practices, improved wastewater treatment, and establishment of wetlands. The VASTRA models were used to calculate the N reduction for different measures in each scenario. An index model (Hoffmann *et al.*, 1999) calculated the root zone leaching of N from crops at four type farms. This generated input to HBV-N and farm economics. The economic impact of different sets of remedial measures was evaluated for each type farm and then extrapolated to the catchment.

The results from scenario modelling indicate that possible changes in agricultural practices (such as tuning, the timing of fertilisation and ploughing, changed crop cultivation) could reduce the N load to the sea by some 30%, while wetland construction could reduce the original load by some 5%. Changed agricultural practices were also found to be much more cost-effective in this region with high livestock density. The constructed wetlands were found to be less effective for N removal than expected (Arheimer and Wittgren, 2002). The biochemical processes resulting in N reduction in the wetlands are most effective during summer when the load is low. High flow conditions coincide with low retention capacity (Figure 5), which gives a low annual impact. However, the scenarios were restricted to topographically realistic siting of 40 wetlands covering in total 0.92 km^2, which would be easy to construct without raising the groundwater level too much. This figure corresponds to 0.4% of the total catchment area. If it would be accepted to have more land waterlogged the wetland impact would also be higher.

The BIOLA model was applied in two eutrophic lakes in VASTRA phase I. Scenario modelling was performed to evaluate the potential impact from various eutrophication control measures on biogeochemical cycling, algal growth and nutrient out-flow. It was stated that reduced nutrient load on the lakes would significantly improve the lake-water quality. However, various in-lake measures to reduce the algal concentration showed some unexpected side effects. For scenarios in Figure 6A and 6B the algae were removed all right, but with the undesired side effect of increased nutrient load to the down-stream river system. In

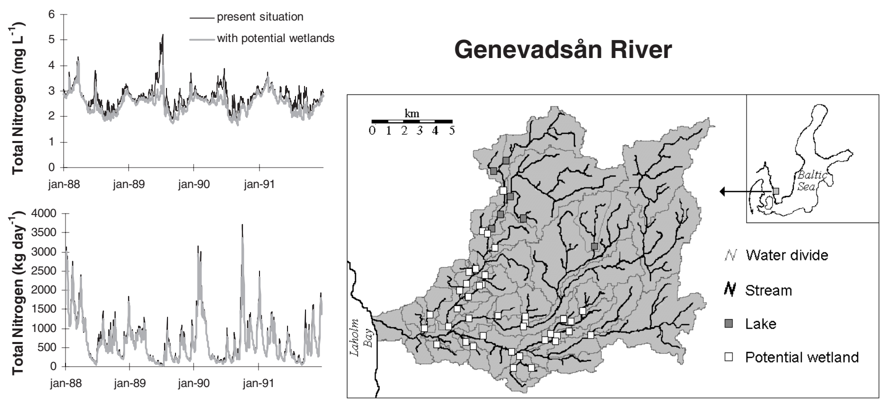

Figure 5 Scenario simulation of the influence of potential wetlands on riverine N concentrations and load at the mouth of the Genevadsån River in southern Sweden. Modified from Arheimer and Wittgren, 2002

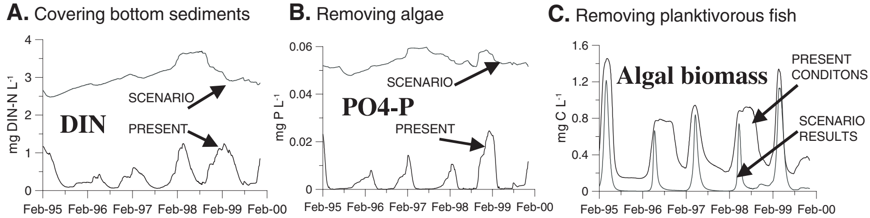

Figure 6 Scenario modelling by using BIOLA for analysing the effects of different in-lake methods to reduce the algal concentration (Pers *et al*., to be published)

scenario 6C the algae were reduced, but without significant side effects on nutrient concentrations (Pers *et al*., to be published).

Scenario modelling in VASTRA phase II

In order to facilitate co-operation and communication between both the researchers from different disciplines within VASTRA, and researchers and stakeholders, a pilot catchment in common has been selected for phase II. This 1,900 km^2 catchment of the Rönne å River is located in southern Sweden and drains out to the Skälderviken bay (Figure 7). More than 50% of the catchment is forested, 3% is lake area and the rest mainly agricultural or urban areas. The catchment was chosen because it has a history of eutrophication, it comprises a wide range of land uses and stakeholders, and it has good sources of data. From the first estimates of source apportionment, the arable land dominates the N load considerably, and the natural retention capacity during the transport from sources to the coast is low (Figure 7).

P scenarios have not yet been produced within VASTRA. So far, the HBV-P has only been tested against observations in a few small agricultural catchments (10 km^2) after contributions from point sources and other land have been added (Figure 8). HBV-P scenarios will not be available until 2004.

The scenarios in SP1 will not be based on another actor-game, but on focus group evaluations, where different actors and stakeholders in the catchment will be interviewed about their attitudes and expectations of eutrophication, nutrient loading and countermeasures. These discussions will end-up in realistic scenarios, which are judged to have the best potentials for acceptance and efficient implementation in the region.

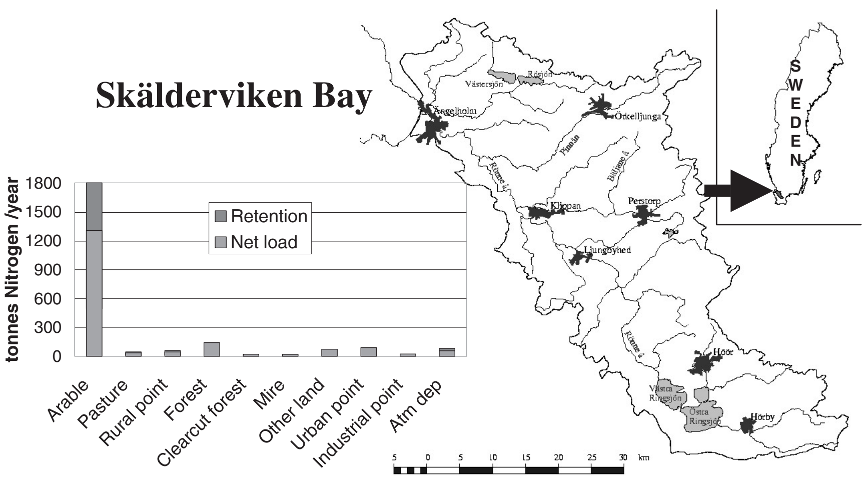

Figure 7 Source apportionment of N transport from the VASTRA pilot catchment of phase II (Rönne å)

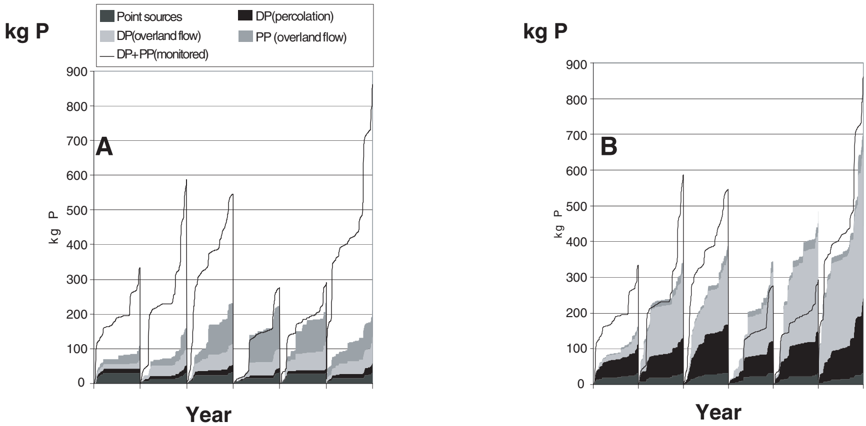

Figure 8 Simulated and monitored annual transport (1991–1996) of particulate and dissolved P in surface runoff, dissolved P in percolation and contributions from point sources. **A:** Hydrology/erosion from ICECREAM, **B:** Hydrology/erosion from HBV-P, alternative surface runoff routine (15% surface runoff). Modified from Andersson *et al.*, 2002

Conclusions

The overall successful development and application of HBV-N indicate that a conceptual hydrological model, such as HBV, is a sound basis of nutrient transport assessment in catchments. Thus, the HBV-P model is under development. The experience from the Swedish water management research programme (VASTRA) is that numerical models are useful tools in scenario analyses of the impact from measures to reduce diffuse pollution and coastal eutrophication. So far, the scenarios modelled show that (i) changed agricultural practices can be the most effective and least expensive way to reduce nitrogen transport from land to the sea; (ii) constructed agricultural wetlands may only have small impact on riverine nitrogen transport in some regions, due to natural hydrometeorological dynamics; (iii) removing planktivorous fish may be an efficient way of reducing the algal concentrations in lakes without the undesired side-effect of increased nutrient load to the downstream river system.

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