Modelling of regional changes of riverine nitrogen flow in the Svartå River, Sweden

LOTTA ANDERSSON
Department of Water and Environmental Studies, Linköping University, S-58183 Linköping, Sweden
e-mail: lotan@lema.liu.se

BERIT ARHEIMER
Swedish Meteorological and Hydrological Institute, S-60176 Norrköping, Sweden

Abstract The HBV-N model was used to evaluate effects from changes (1885-1994) of land use, agricultural practices, N-deposition, food consumption, introduction of water closets, lowering of lakes, building of dams, and of climatic variability on N-transport from a river basin (1400 km²) in south central Sweden. Drainage of agricultural land had an overriding impact on N-load, compared to the effect of lowering of lakes and building of dams. This was because previously poorly drained areas had a geographical extension that was approximately 200 times larger than areas affected by alterations of open-water surfaces. Compared to human-induced alteration of N-retention, the selection of a 10-year period of climatological data had an overriding effect on the calculated average annual nitrogen transport. The overall change over time of riverine N-transport mainly reflected changes of the contribution from agricultural land, although also household emissions increased drastically over the period studied.

Key words nitrogen load; retention; climatic variability; historical changes; modelling; riverine; river basin; Sweden

INTRODUCTION

Studies of historical changes of nutrient loads can seldom be based solely on records of monitored concentrations in rivers or water bodies since few sets of water quality data extend over more than 20–30 years. Alternatively, assessments of historical changes can be based on historical data sets of relevant factors. In this study, historical changes of gross load and retention of nitrogen (N) are estimated with the HBV-N model, to assess the effects of: (a) human alteration of N-retention in the landscape, (b) climatological variability, (c) land-use changes, (d) changes of leaching concentrations, (e) changes of N-deposition on lakes, (f) changes in food consumption, and (g) introduction of water closets.

The study was performed in the Svartå River basin, situated between Lake Sommen and Lake Roxen in south central Sweden. The studied basin extends over 1400 km². The upper part is characterized by a hilly, forested moraine landscape with several lakes. The lower parts and a transitional zone along the Svartå River are characterized by farmland and a few lakes. Two small towns are situated in the basin, with present populations of approximately 5000 and 20 000 respectively. There are no industries that significantly contribute to the N-load.
MATERIAL AND METHODS

The process-based conceptual HBV-N model (Arheimer & Brandt, 1998) was applied to the river basin. A historical database was compiled so that modelling of N-transport could be made with consideration to changing environmental conditions during the study period (1885–1994). The model was driven by climatological data from a 10-year period (1985–1994) in order to avoid overriding influence from single years. The model was then applied with physiographic conditions and soil leaching estimates, representing different time intervals, but with the same set of climatological data. In addition, a 110-year time series from one meteorological station was used to simulate the impact from natural long-term climatological variability on N-transport.

A detailed description of the physiographic databases and databases on agricultural drainage, lowering of lakes and construction of dams is given in Andersson & Arheimer (2001).

Estimates of leaching from the unsaturated zone from agricultural areas were calculated with the SOIL-N model (Johnsson & Hoffmann, 1998; Hoffmann et al., 2000). Leaching from forest and other non-agricultural land categories was estimated from monitoring data, and assumed to be constant over time.

For 1994, we used the assumption that a person on average released 12.5 g N day⁻¹ in urine and faeces, and that 1 g N day⁻¹ was released from greywater (Sundberg, 1997). The amount of N released from a person depends on their N consumption with food. We used estimates by Schmid (2000) of Swedish per capita N consumption and release between 1876 and 1995.

Estimates of emissions from sewage plants were based on information from municipal authorities and from Löfgren & Karlsson (1987). For rural households, estimates of N-removal by the Swedish Environment Protection Agency (Sundberg, 1997) were used.

Atmospheric deposition in 1994 was calculated with the MATCH model (Langner et al., 1995), whereas calculations made by IVL (Swedish Environmental Institute Ltd) were used for relative change of deposition between 1900 and 1995 (Swedish EPA, 1997). For land areas, the atmospheric N-deposition was considered in the N soil-leaching estimates.

THE HBV-N MODEL

The HBV-N model (Arheimer & Brandt, 1998) is a conceptual, semi-distributed process-model (Fig. 1). The model is based on the hydrological model HBV-96 (Lindström et al., 1997), using a daily time step. In the N routine, leakage concentrations are assigned to the water percolated from the unsaturated zone to the groundwater from various land-use categories. The arable land is further divided into a variety of crops and management practices. N is also added from point sources. Atmospheric deposition is added to lake surfaces, while deposition on land is implicitly included in the soil leaching. The model simulates N residence, transformation and transport in groundwater, rivers and lakes. Equations used to account for the N-retention processes are based on empirical relationships between
physical parameters and concentration dynamics. Inorganic and organic N are treated separately. The model includes free parameters that are calibrated against observed time series.

RESULTS AND DISCUSSION

Climatic variability and changes of the wetness of the landscape

In Andersson & Arheimer (2001), the HBV-N model was used to evaluate changes in N transport and retention and transport in the lower Svartå basin caused by land drainage, lowering of lakes, building of dams and climatic variability. The rather modest change of the location of water bodies in the landscape, where in total 5.6 km$^2$ lake area was lost due to lowering of lakes and 4.2 km$^2$ of dams were constructed, had only a minor effect on the N-transport from the basin. Although the area lost from lowering of lakes was larger than the area gained by dams, the increase in N-load from lowering of lakes (1%) was outweighed by the decrease in load from construction of dams (4%). This was because lowered lakes were mainly situated in the upper, forest-dominated sub-basins, whereas dams also were located in the lower, agricultural dominated sub-basins. In addition, lowered lakes were often situated away from the main river course, whereas dams often were located close to the main river course (Andersson & Arheimer, 2001). Approximately 270 km$^2$ of agricultural land was tile
drained during the study period. The increase of tile-drained land was thus almost 200 times larger than the decrease of water bodies. According to the simulations, the drainage of agricultural land increased N load by 17%, due to reduced subsoil retention.

Although there was a considerable human impact on the N-retention capacity of the basin during the studied period, the choice of a 10-year period of climatological data had an overriding effect on the calculated N-transport. The average modelled annual transport was 91% higher when using climatological data from 1905–1914, compared to when using data from 1975–1984. Annual average N-retention varied between 22% when using the 1975–1984 record to 34% when using the 1925–1934 record, which demonstrates that using a 10-year period does not even out annual variability.

Changes of household wastewater emissions

Wastewater nitrogen emissions increased from about 13 t year\(^{-1}\) in 1927 to 190 t year\(^{-1}\) in 1994. Changes of the emissions could be attributed to: urbanization and migration to the lower parts of the basin; increased N-content in the diet; increased use of water closets; and introduction and improvement of wastewater treatment. The annual per capita household wastewater production of N was estimated to have increased from 2.0 kg in 1885 to 4.7 kg in 1994 due to increased consumption of meat and dairy products (Schmid, 2000). Although piped wastewater was not treated in 1927 and 1957, N-emission per capita through municipal pipes was higher in 1994, compared to in 1927. This was due to the modest removal of 20% in the wastewater treatment plants, which did not manage to compensate for the 50% increase of per capita N-emission.

Land-use changes

The total area used for agricultural activities has remained fairly constant over time, but with considerable changes of the proportions of land used for crops, ley and bare fallow. The percentage of bare fallow decreased continuously over time, whereas the

![Fig. 2 Proportions of the total area of the lower Svartå basin covered by crops, ley and bare fallow 1885–1995.](image)
fraction used for crops reached its maximum in the 1970s. The proportion used for ley was highest in the 1920s, after which it decreased to its minimum in the 1970s (Fig. 2).

Leaching from agricultural land

There was no straightforward relationship between increased agricultural productivity and increased N leaching. In the late nineteenth century, N concentrations in soil leaching from agriculture was, according to Hoffmann et al. (2000), similar to concentrations in the late twentieth century (Fig. 3). The fact that the area used for crop cultivation was 26% larger in 1994, compared to 1885, was, with regard to its effect on soil leaching of N, fully compensated by the concurrent decrease of the area under bare fallow, since bare fallow causes substantial loss of N from the root zone.

![Fig. 3 Soil-N simulations of temporal changes of leaching of N from the soil profile to groundwater or tile drains from loamy sand, loam and clay soils in the studied region (based on Johnsson & Hoffmann, 1998; and Hoffmann et al., 2000).](image)

Changes in retention and net load of N in the lower Svartå basin 1885–1994

The highest net load was estimated for the 1976 scenario (46% higher than in 1994). The lowest gross load was estimated for the 1927 scenario (33% lower than in 1994), whereas the lowest net load was estimated for 1885 (32% lower than in 1994). The fact that the net load was lower for the 1885 scenario compared with 1927, in spite of a higher gross load, was mainly due to the higher retention in groundwater and surface water from soil leaching originating from agricultural land, caused by the limited tile drainage in 1885. For all time periods, agriculture was the overriding source for the total-N export, and changes over time of the total-N load were mainly reflections of changes of the contribution from agricultural land. The contribution from household wastewater was insignificant until the 1927 scenario (Fig. 4).

Sensitivity analysis

The effect on N-load from substituting one single environmental factor at the time or from substituting the 1985–1994 climatic record with the ten other available 10-year climatological records (Fig. 5) was assessed. Substituting the 1985–1994 climatic
conditions with the 1905–1914 record, representing the driest 10-year period, reduced the N-load by 19%, whereas parameterizing land that had been artificially drained after 1885 as poorly drained reduced the load by 17%. The highest reduction (23%) was

![Diagram showing changes in N-loads](image)

**Fig. 5** Increase or decrease of N-loads from temporal changes of single factors, compared to N-loads estimated with environmental conditions in 1994, and the climatic record from 1985 to 1994. Black bars indicate factors related to climate or human alteration of the retention in the landscape, whereas grey bars indicate factors related to land use or point source emissions.
obtained if the soil-leaching concentration estimates for agricultural land in 1994 were substituted by estimates for 1927. Assuming that water closets, which transport urine and faecal matter through water-borne sewerage systems, were substituted by ecological sanitation, decreased the N-load by 16% whereas substituting the 1994 food consumption with that prevailing in 1885, reduced the N-load from the basin by 8%. All factors that contributed to higher historical N-load, compared to that in 1994, prevailed during the 1976 scenario. Substituting the 1985–1994 climatic record with that from 1974–1985 increased the N-load by 44%, whereas substituting soil leaching from agriculture with estimates representing the conditions in 1976 increased the N-load by 30%, and substituting land use with that in 1976 increased the N-load by 12%.

CONCLUSIONS

Factors contributing to landscape fluxes of N changed significantly during the study period. This was to a large degree a result of changes in agriculture and lifestyle. However, climatic variability between different 10-year periods was as important. Due to its large areal extent, drainage of agricultural land had an overriding impact on N-load, compared to the effect of lowering of lakes and building of dams. Changes of household food consumption and use of water closets were shown to have increased the N-load significantly.

Acknowledgements Marcus Hoffmann is acknowledged for providing historical estimates of N-leaching from agricultural soils, calculated with the SOIL-N model. Tina Schmid is acknowledged for assistance in collecting information about wastewater treatment plants, dams and lowered lakes. In addition, her work on the impact of food consumption on the N-flux has been valuable for this paper. The study was financed by CKS (Centrum för Kommunstrategiska Studier) and the Swedish Water Management Research Programme (VASTRA), financed by the Swedish Foundation for Strategic Environmental Research (MISTRA).

REFERENCES

Adv. 27, 471–480.
historical perspective. Agric. Ecosyst. Environ. 80, 277–290.
Langner, J., Persson, C. & Robertson, J. (1995) Concentrations and deposition of acidifying air pollutants over Sweden: 
HIIV-96 hydrological model. J. Hydrol. 20, 272–289.
Households Use their Resources? (Proc. Workshop, April 2000). Department of Technology and Social Change, 
Linköping University.