Three approaches to estimate inorganic nitrogen loading under varying climatic conditions from a headwater catchment in Finland

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ABSTRACT

Inorganic nitrogen loading was simulated using two dynamic catchment scale models, Integrated Nutrients in Catchments–Nitrogen (INCA-N) and the Generalized Watershed Loading Functions (GWLF). The simulated N loading was compared to a standard method to calculate annual loading using measured discharge and discharge-weighted concentrations. The main aim of the study was to compare these three estimation approaches with regards to their performance in hydrologically variable years in a small headwater catchment in southern Finland. Inter-annual variability of INCA-N and GWLF was compared with measured inorganic N concentrations at the catchment outlet. In years where snow melt dominates the annual discharge pattern all methods gave concurrent annual loading estimates. However, the loading estimates differ between the studied methods in years where large rainfall events in late summer or autumn dominate the annual discharge pattern, or when the model was not able to reproduce the spring discharge maximum properly. The results suggest that both models can be useful tools in estimating dissolved inorganic nitrogen loading from a catchment under changing climate conditions, providing that the key influencing driver, hydrology, is well captured.

Key words | GWLF, INCA-N, inorganic nitrogen loads, modelling, seasonal runoff patterns

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INTRODUCTION

Long-term nutrient datasets indicate that leaching of nitrogen (N) from catchments is strongly related to seasonal and annual climatic and hydrological variation (e.g. George *et al.* 2004). Recent climate scenarios suggest marked changes in air temperature and precipitation in Fennoscandia (Jylhä *et al.* 2004; Rummukainen *et al.* 2004) which are likely to change the seasonal dynamic patterns in hydrology, and thus also the nutrient loading. Also soil N processes are estimated to react to an increase in air temperature in Scandinavia which might lead to enhanced N leaching (e.g. Eckersten *et al.* 2001). These projected changes increase the demand for reliable methods to evaluate nutrient loading.

There are several methods to model nutrient leaching on a catchment scale. Among the simplest approaches are mass balance models and statistical models. Mass balance models provide a static accounting of nutrient inputs (e.g. fertilizers, atmospheric deposition) and outputs (e.g. crop removal, nutrient leaching). Statistical models have their origins in correlations of stream nutrient concentrations/loads with catchment sources and landscape properties. These methods provide empirical estimates of the combined effect of nutrient input and loss through the use of stream monitoring data. Statistical models have their advantages in being easily applied even to large river basins (Lidén *et al.* 1999; Alexander *et al.* 2002; Vachaud & Chen 2002).

When using the so-called export coefficient method (Johnes 1996), annual nutrient load to a water body is calculated as the sum of individual loads exported from each nutrient source in the catchment (Meals & Budd 1998;

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Lepistö *et al.* 2001). The export coefficient method may have problems when extrapolating to other areas and larger scales because nutrient loads reflect area-specific variation in climatic conditions, nutrient sources, and terrestrial and aquatic retention processes (Beaulac & Reckhow 1982). There are recent examples of successful application of an export coefficient-based model to examine hydrological and inorganic N leaching patterns in the context of climate change (Moore *et al.* 2009; Schneiderman *et al.* 2009).

Dynamic deterministic models describe nutrient transport and loss processes in detail by using mechanistic functions. A compromise between conceptual and fully distributed models is the so-called semi-distributed models, which divide the catchments into smaller units based on, for example, land-use, topography or soil type (Krysanova *et al.* 1998; Whitehead *et al.* 1998; Karvonen *et al.* 1999; Wade *et al.* 2002). Spatially distributed models have their advantages in assessment where either detailed outputs or information about processes inside the catchment are needed, although the simpler models may provide an overall picture of catchment behaviour with less input information (Refsgaard & Knudsen 1996; Lidén *et al.* 1999; Alexander *et al.* 2002; Vachaud & Chen 2002).

The aim of this work was to compare three different methods to calculate annual dissolved inorganic N (DIN) load. The methods used were the semi-distributed model INCA-N (Integrated Nutrients in CAtchments–Nitrogen), the loading functions model GWLF (Generalized Watershed Loading Functions) and a statistical calculation method that is used as a standard in Finland. First the annual N loading using INCA-N and GWLF was calculated and then the result was compared to that estimated with the statistical method. In the next step the ability of the models to describe the seasonal dynamics in discharge and inorganic N concentrations was estimated. Finally the reasons behind the main differences of the model outputs and their possible consequences were discussed.

MATERIAL AND METHODS

The Mustajoki catchment belongs to the drainage basin of Lake Pääjärvi (212 km^2; Arvola *et al.* 2002*a*). It is the largest sub-catchment and has an area of 76.8 km^2. The drainage area lies in the southern boreal vegetation zone. During winter, precipitation typically falls as snow and the soils are frozen. The forests are dominated by Norway spruce, Scots pine and birch with some European aspen. In the Mustajoki basin the land use is divided into forest (67% of total area), peatlands (20%) and agricultural land (13%). In the basin, 48% of the near-surface deposits are characterized by moraine, with some highly permeable sand and gravel deposits, and organic peat layers.

There are no point pollution sources of nutrients in the catchment and the area is sparsely populated. The main human influence comes through forestry and agriculture. Agriculture is mainly cereal cultivation but a low proportion of sugar beet is included. The use of N fertilizer per hectare is around 100 kg ha^{-1} according to the Finnish Agri-Environment Programme (Palva *et al.* 2001).

Samples for DIN concentration detection have been taken weekly at the Mustajoki river outlet (61°04′41″N; 25°12′47″E; 102 m a.s.l.) since the year 2000 by the Lammi Biological Station (LBS) of the University of Helsinki. Sampling started in 1993 but before 2000 the winter-time sampling took place on a monthly basis only–thus this period was partially used for model calibration but is not presented in this paper. The sum of nitrate-N and nitrite-N (NO_2-N + NO_3-N) as well as ammonium-N (NH_4-N) has been analyzed using standard methods (e.g. APHA 1985). Discharge has been measured on a daily basis since the early 1970s by the Finnish Environment Institute. The average annual discharge in the study period varied between 0.34 m^3 s^{-1} in 2003 and 0.78 m^3 s^{-1} in 2004. The hydrological pattern is dominated by spring floods and additionally by high runoff events in summer and autumn in the years 2000 and 2004 (Table 1).

Daily meteorological data for rainfall and air temperature to drive the models were available from the station of the Finnish Meteorological Institute located close to Lake Pääjärvi at the LBS (61°03′14″N; 25°02′13″E; 122 m a.s.l.). The Mustajoki catchment is low-lying, with little variation in topography (103–180 m a.s.l.), and therefore the meteorological station at LBS well represents the meteorological conditions of the small catchment studied. This climate data was used for the GWLF simulations, whereas for the INCA-N simulations regionally averaged meteorological data was used. This is because the hydrological input for INCA-N is

Table 1 | Monthly runoff ($l\,s^{-1}\,km^{-2}$) in the Mustajoki catchment for the years 2000–2004; in gray, high runoff events in autumn/winter 2000 and summer/autumn 2004

	Monthly runoff ($l\,s^{-1}\,km^{-2}$)											
	I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
2000	7.0	3.7	4.4	37.0	5.4	2.3	4.8	2.6	1.5	4.3	22.7	17.6
2001	3.6	4.9	5.8	26.6	9.6	12.8	4.7	1.7	3.2	3.7	8.2	1.6
2002	1.7	7.5	5.5	21.8	11.9	2.6	4.7	1.3	1.3	1.0	1.2	0.9
2003	0.1	0.1	1.0	10.4	14.1	4.0	1.7	0.6	0.9	8.0	5.8	7.3
2004	3.0	1.6	2.3	23.0	8.3	5.8	27.6	16.3	11.4	9.2	7.0	9.9

being calculated using an HBV (Hydrologiska Byråns Vattenbalansmodell) based approach, as described in more detail in the section introducing INCA-N. The monthly averages of daily air temperature measured at LBS correspond very well to the regionalized dataset (coefficient of determination $R^2 = 0.98$) but more variation can be detected in the precipitation data ($R^2 = 0.69$) (Table 2).

The differences in monthly precipitation values in Table 2 were accounted for in the calibration of the respective models. No systematic differences could be detected.

The Generalized Watershed Loading Functions model (GWLF)

The Generalized Watershed Loading Functions (GWLF) model is a non-point source loading model. GWLF was developed by Haith & Tubbs (1981) and further developed by Haith & Shoemaker (1987) to simulate monthly nutrient loads in stream flow. The GWLF version used in this study was created by the New York City Department of Environmental Protection (Schneiderman *et al.* 2002). The model is driven by daily temperature and precipitation data, and water balances are calculated with a daily time step. Stream flow consists of runoff and groundwater discharge components. Diffuse nutrient sources are modelled as a function of land use and runoff. Dissolved nutrient loads are derived by multiplying surface runoff and baseflow by land-use specific nutrient concentrations (Table 3). A detailed description of the GWLF model approach used is presented in Schneiderman *et al.* (2009) and Moore *et al.* (2009).

The GWLF hydrology model was calibrated using precipitation and air temperature data from the Lammi station for the time period 1982–2004. Land-use specific runoff concentrations (Table 3) were based on the long-term and intensively measured nutrient concentrations

Table 2 | Monthly cumulative precipitation (mm) at LBS used to drive the GWLF model and the monthly cumulative averaged regional precipitation (mm) from WSFS used in INCA-N modelling; in gray, high runoff events in autumn/winter 2000 and summer/autumn 2004

		Monthly cumulative precipitation (mm)											
		I	**II**	**III**	**IV**	**V**	**VI**	**VII**	**VIII**	**IX**	**X**	**XI**	**XII**
2000	LBS	45	41	49	31	26	39	159	77	21	58	63	30
	WSFS	43	23	36	32	16	31	117	67	39	74	91	54
2001	LBS	15	20	24	14	24	78	53	22	116	75	30	26
	WSFS	34	41	44	20	35	109	61	21	70	6	29	26
2002	LBS	64	58	38	3	46	83	88	38	24	17	69	8
	WSFS	31	27	17	1	96	111	91	44	72	37	59	13
2003	LBS	44	4	8	25	81	32	75	82	17	125	47	78
	WSFS	28	14	6	19	123	82	114	38	38	108	44	46
2004	LBS	46	37	27	2	59	125	203	84	63	40	42	69
	WSFS	49	40	39	2	63	125	210	86	84	50	37	71

Table 3 | Land-use specific nutrient concentrations ($g\,m^{-3}$) in direct runoff used in the GWLF model runs for the River Mustajoki catchment

Land-use	Land-use specific nutrient concentrations ($g\,m^{-3}$)
Coniferous forest, incl. mixed forest	0.168
Peatland	0.555
Complex cultivation patterns	2.82
Roads	0.02

from the streams of small sub-catchments of the Lake Pääjärvi catchment area with distinct land use (Arvola *et al.* 2002*b*; Hakala *et al.* 2002). The time period 1994–2004 was used for nutrient calibration: flow-weighted average nutrient concentrations were calculated and they were adjusted with the calibration factor of 1.01. This factor was obtained by minimizing the squared deviations between measured and simulated values in the time series of flow-weighted concentrations (Moore *et al.* 2009).

Integrated Nutrients in Catchments–Nitrogen (INCA-N)

The dynamic Integrated Nutrients in Catchments–Nitrogen (INCA-N) model integrates hydrology and N processes (Whitehead *et al.* 1998; Wade *et al.* 2002; Wade 2004). The model has previously been applied in Finland to the northern Simojoki river basin (Rankinen *et al.* 2006*a*). The model is semi-distributed in that the land surface is not described in detail, but rather by land-use classes in sub-basins. Sources of N include atmospheric deposition, leaching from the terrestrial environment and direct discharges. Terrestrial N fluxes are calculated in up to six user-defined land-use classes.

Hydrologically effective rainfall (HER) is used to drive the N through the catchment system and N can enter the river system by lateral flow through the surface soil layers or by vertical movement and transport through the groundwater zone. HER is defined as that part of total incident precipitation that reaches stream channels as runoff and it is given as a daily input time series. It is usually calculated by a hydrological model appropriate for the modelled scale (see later) and thus subject to the uncertainty linked to this methodology. Hydrology within the sub-catchments is modelled using a simple two-box approach, with reservoirs of water in a reactive soil zone and in a deeper groundwater zone.

The mass balance equations for NO_3-N and NH_4-N in the soil and groundwater zones are solved simultaneously with the flow equations. The key N processes that are solved in the soil water zone are nitrification, denitrification, mineralization, immobilization, N fixation and plant uptake of inorganic N in the six land-use classes modelled (spring barley, sugar beet, grass, fallow, forest and peatland). No biochemical reactions are assumed to occur in the groundwater zone. In the river the key N processes are nitrification and denitrification.

Hydrological input data (including HER) was calculated with the watershed model WSFS (Watershed Simulating and Forecasting System; Vehviläinen 1994) which is used for flood forecasts and water resources management nationally. The principles of the WSFS are based on the HBV model (Bergström 1976). WSFS simulates runoff using precipitation, potential evaporation and temperature as inputs. The system uses regionally averaged meteorological data (Taskinen *et al.* 2003). In operational use the system provides flood forecasts on large river basins but in this study a more detailed calibration against observed discharge in the River Mustajoki was used. Averaged precipitation used in the WSFS simulation is compared to observed precipitation at LBS in Table 2.

For this study INCA-N was calibrated with River Mustajoki data. The model parameters governing the rate of change in N fluxes in terrestrial (N mineralization, nitrification, denitrification and vegetation uptake) and aquatic (nitrification and denitrification) environments were adjusted to get simulated and observed discharge and inorganic N concentrations close to each other in the period 1995–2004. Simulated annual inorganic N fluxes in different land-use classes were compared to plot scale values reported in literature or small research catchment studies (Table 4). The model was calibrated with data from the period 1995–2002 and validated against data from the dry year 2003 and the rainy year 2004. The Nash–Sutcliffe efficiency for simulated discharge was 0.751 in the calibration period and 0.658 and 0.819 in the validation years. Values of the regression coefficient R^2 between the simulated and measured in-stream NO_3-N concentrations were 0.287, 0212 and 0.431, respectively.

Table 4 | Simulated and observed inorganic nitrogen fluxes from different vegetation types

Land use class	Simulated flux (kg ha^{-1} yr^{-1})	Observed/estimated flux (kg ha^{-1} yr^{-1})	Reference
Mineralization			
Barley	60	80–92	Paustian *et al.* (1990)
Grass	144	147–214	Paustian *et al.* (1990)
Forest + peat land	24	15–120	Persson & Wirén (1995) and Smolander *et al.* (1998)
Vegetation N uptake			
Barley	83	68–85	Statistics of yields
Grass	253	225	Statistics of yields
Forest + peat land	28	28–51*	Mälkönen (1974)
		26–42†	Finér (1989)
Inorganic N leaching			
Barley	30.3	21–31	Äijö & Tattari (2000)
		1–38	Jaakkola (1984)
Grass	20	17–18	Äijö & Tattari (2000)
Forest + peat land	3	1.4	Lepistö (1996)

*Forest on mineral soil.
†Forest on organic soil.

The calculation methods

The daily measured discharge and weekly sampled inorganic N concentration values were used to calculate the annual load by a variety of statistical standard methods used at the Finnish Environment Institute (Rekolainen *et al.* 1991). In the first method the concentration at the sampling time is multiplied by the discharge for the period after the sampling whereas in the second method the discharge period is chosen around the sampling time. In the third method the annual load is the product of annual discharge and the arithmetic mean of the sampled concentration values and, finally, in the fourth method the sampled concentration values are weighted with the flow at sampling times. Out of these methods, Kauppila & Koskiaho (2003) found N loads estimated by the periodic method, i.e. method 2, to be most reliable but in general the results were quite similar for the different estimation methods. Since a Mustajoki-type river was neither part of the Rekolainen *et al.* (1991) nor the Kauppila & Koskiaho (2003) studies, all four methods were included in this study. The average of all estimates and the difference between the minimum and maximum estimate was utilized (Figure 1). These statistical reference methods give annual loading estimates which are considered to be the basic level to which the GWLF and INCA-N simulation results are compared.

RESULTS AND DISCUSSION

The estimated annual DIN loadings varied from 120–570 kg km^{-2} yr^{-1} (10–45 t DIN yr^{-1}) between the methods during the study period (Figure 1). With the INCA-N model the difference from the reference method was highest in the

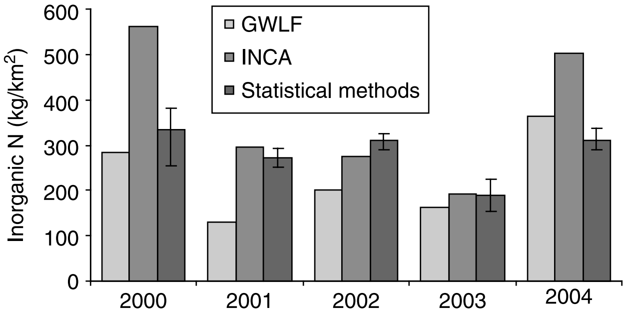

Figure 1 | Annual dissolved inorganic nitrogen loads (kg DIN km^{-2}) of the River Mustajoki for the years 2000–2004 as simulated by the models GWLF and INCA-N, and the calculation methods (average + range minimum–maximum).

wet years 2000 and 2004 when summer and late autumn discharge was high. The GWLF model estimation for the DIN load was close to the level given by the reference method, except in the years 2001 and 2002, when the model was not able to reproduce the spring discharge maximum properly.

The seasonal pattern of runoff as presented by the box–whisker plots (Figure 2) shows that INCA-N repeats the seasonal pattern of runoff but overestimates the snow melting peak in April. The hydrological input derived from the WSFS system, which uses regionalized meteorological input data, seems to overestimate precipitation in the rainy year 2004 (Table 2) while the model was calibrated for the years 1995–2002 when the WSFS system slightly underestimated precipitation during several months successively. The overestimated snow melt peak occurred in the year 2000, when WSFS produced +1°C higher than observed air temperatures, leading to rapid snow melting. These overestimations of discharge lead to higher leaching losses of DIN (Figure 1). The first requirement for a credible N simulation, as pointed out, for example, by Krysanova *et al.* (1998), is that the hydrological module should be tested and validated in advance. In those years when the hydrological output of the INCA-N model was at a correct level compared to observations, the simulated DIN load was also of the same magnitude as the measured/calculated load.

GWLF depicts the measured runoff level both in the spring peak and in the low flow periods well. The increase in spring runoff in March, which is not observed in measured data, is probably related to the too early snow melt simulated in the catchment.

The seasonal pattern of DIN concentration is presented as box–whisker plots of daily modelled concentrations and weekly observed concentrations (Figure 3). INCA-N repeats the seasonal pattern of DIN concentrations, but seems to give broader confidence limits compared to the observations. On the other hand, it is possible that weekly water quality sampling is not frequent enough to catch the concentration peaks. In the detailed analysis of hydrology, nutrient concentrations and nutrient loads made by Tikkanen *et al.* (1985) in two other small sub-catchments of the Lake Pääjärvi drainage basin (Koirasuolenoja (K), 6.75 km^2 and Löyttynoja (L) 8.02 km^2) the N concentrations showed marked increase at the time of spring high water followed by low values during summer. Sharp fluctuations were detected in early autumn predominantly in the agriculturally dominated sub-catchment (K) where the maximum value of total N was 29.9 $\mathrm{mg\,l^{-1}}$ (16 September 1982) whereas the monthly mean in 1982 was approximately 3 $\mathrm{mg\,l^{-1}}$N. Tikkanen *et al.* (1985) concluded that accurate assessment of the changes in material transport associated with these fluctuations would require the taking of water samples several times per day during the flood season. On the other hand, INCA-N seems to overestimate the lowest concentrations during the growing seasons. One reason for this may be a missing retention process in the model, probably in the riparian zone (Rankinen *et al.* 2006*b*).

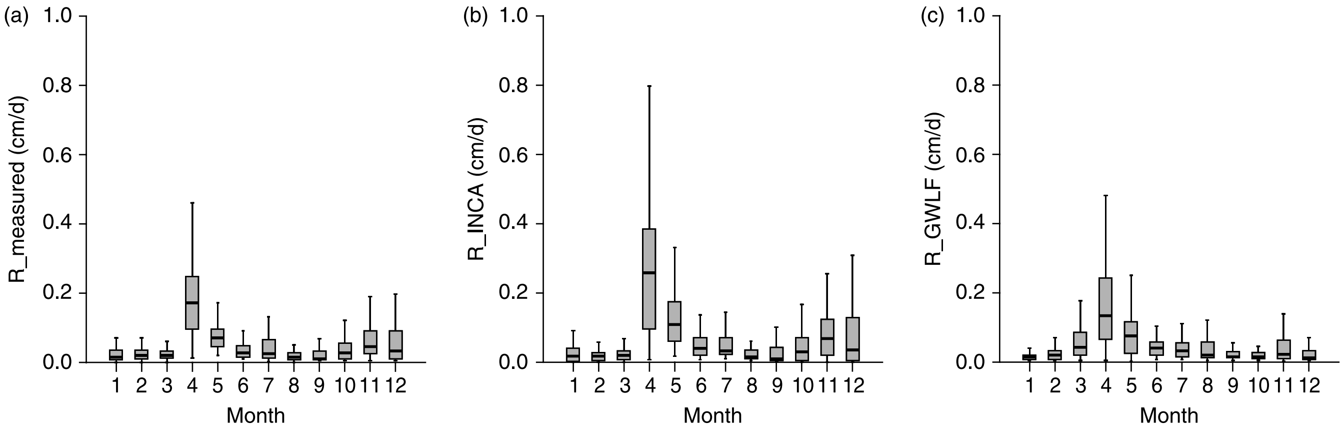

Figure 2 | Mean measured and modelled monthly runoff ($\mathrm{cm\,d^{-1}}$) in the River Mustajoki in 2000–2004. The box–whisker plots show the mean, 95% confidence limits and 25% quartiles for the monthly mean (a) measured runoff, (b) INCA-N simulation and (c) GWLF simulation.

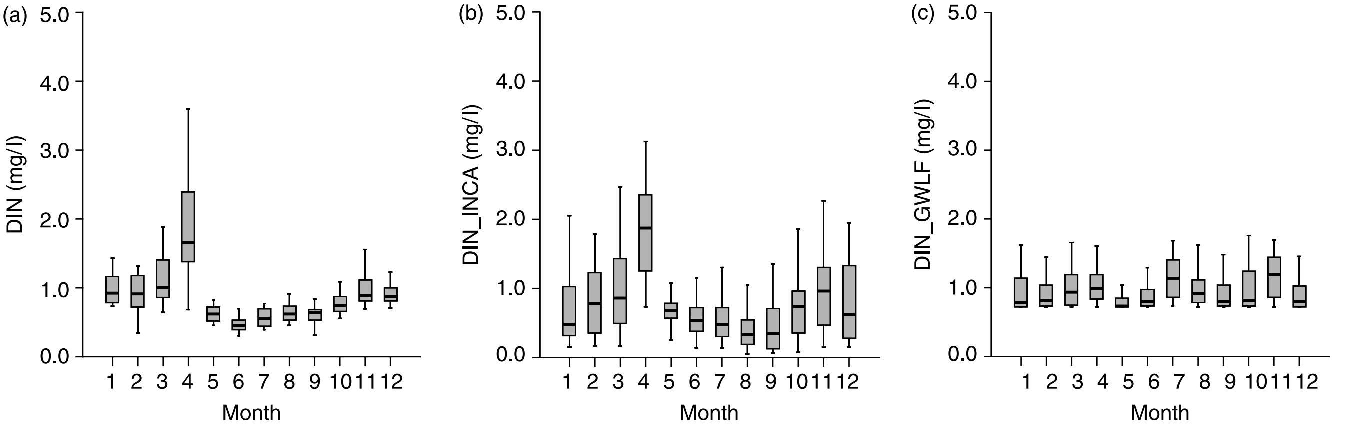

Figure 3 | Mean measured and modelled monthly DIN concentrations (mg DIN l^{-1}) in the River Mustajoki in 2000–2004. The box–whisker plots show the mean, 95% confidence limits and 25% quartiles for monthly mean (a) measured runoff, (b) INCA-N simulation and (c) GWLF simulation.

GWLF produces correctly the general DIN concentration level but does not reproduce the seasonal concentration variation pattern. This results from the loading function structure of the model. The GWLF model has been shown to perform well in simulating monthly streamflow and dissolved nutrient loads but it may be unsuited for simulating short-term extreme events (Schneiderman *et al.* 2002).

The load given by INCA-N is almost twice as high as the load given by the reference method in years 2000 and 2004, when discharge is high also in late summer (2004) and late autumn (2000). This might result from the higher DIN concentration variation at that time, as INCA-N calculates N processes dynamically, which in combination with larger variation in discharge in these months leads to higher annual inorganic N loads.

Concerning the role of N deposition, it has been estimated to be around 420 kg $km^{-2}yr^{-1}$ (L. Arvola, unpublished, LBS 1999). This equals 4 kg $ha^{-1}yr^{-1}$ which is clearly less than the estimated fluxes of N mineralization, vegetation uptake or leaching (Table 4). N deposition is considered in the INCA-N model but in the GWLF model the contributions of NO_x from atmospheric deposition are implicit in the land-use inputs and are not considered as a separate term (Moore *et al.* 2009).

There are clear implications that an export coefficient-based model like GWLF can be used to detect annual N loading from a catchment like Mustajoki which is, according to Johnes (1996), its purpose. Further, studies by, for example, Ierodiaconou *et al.* (2005) and Antikainen *et al.* (2005) demonstrate that export coefficient approaches can be utilized to assess basin or national scale nutrient loading and to assess effects of land-use change (e.g. Stroud 2001; Worrall & Burt 2001). Observations from years with exceptionally mild winters indicate an increase in N losses in Finland. Simulations with the process-oriented soil profile model SOIL/SOIL-N suggest that the main reasons for this increase are the acceleration of organic matter mineralization in agricultural soils and the increased water flow through the soil column (Kallio *et al.* 1997). In an export coefficient-based model like GWLF only the change in the hydrological regime can be taken into account which, as demonstrated in Figure 3, is not reflected in the simulation of the inter-annual N concentration dynamics. The nutrient loading will only change if the land-use specific runoff concentrations are changed.

The three methods applied to estimate annual DIN loading show different sources of uncertainty. In a study of 15 Nordic rivers it was concluded that in small agricultural rivers 12–26 samples taken in proportion to flow seemed to produce load estimates for total phosphorus with $\leq 10\%$ scatter and bias. A lower number of samples would be sufficient for the estimation of total N (Ekholm *et al.* 1995). With weekly sampling (approx. 50 annual samples) included in this study, the measurement-based estimate can be considered fairly certain. Both models can be calibrated against measured discharge and observed DIN concentrations but for GWLF the most uncertain component remains the land-use specific runoff coefficient that has to be defined by the model user, whereas the INCA-N application shows the greatest challenges in years where hydrological conditions are beyond the range of calibration.

CONCLUSIONS

Under the current situation dominated by snow-melt, all the methods seemed to give annual loading estimates in agreement with each other. However, the loading estimates differ between the studied methods in years when snowmelt was not the dominating hydrological pattern (INCA-N in 2000 and 2004) or when the model was not able to reproduce the spring discharge maximum properly (GWLF in 2001 and 2002). It seems that, in order to capture the DIN loading, which is based on weekly measurements, the model performance concerning hydrology is more important than the reproduction of the temporal DIN concentration dynamics. These results suggest that attention needs to be paid not only to the calibration process but also to the correct validation process when a model is used to simulate or forecast future changes in nutrient loads, e.g. under changing land-use or changing climate.

The results of this research indicate that both the export coefficient-based GWLF model with a dynamic hydrology feature and the dynamic INCA-N model can be useful to estimate the effects of future changes in precipitation and air temperature. Recent nutrient flux projections with the GWLF model show that the model can be used with some confidence in climate change research (e.g. Moore *et al.* 2009). The structural analysis showed that, for climate change modelling, it may be beneficial to use a tool which includes N processes that are affected by changing precipitation and temperature conditions. The INCA-N result indicates the need for more frequent data sampling (daily or sub-daily) to capture the range of variability in observed and simulated N concentrations, or in measured and simulated N process rates, in a more reliable manner. The next challenge for model validation would be to develop a validation scheme for nutrient leaching modelling in a climate change context because, as also pointed out by Refsgaard *et al.* (2005), little progress has taken place in this field since Klemeš (1986).

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