Hydrology and Earth System Sciences, 8(4), *695–705* (2004) © EGU

Adaptation of the Integrated Nitrogen Model for Catchments (INCA) to seasonally snow-covered catchments

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Abstract

Testing of the Integrated Nitrogen model for Catchments (INCA) in a wide range of ecosystem types across Europe has shown that the model underestimates N transformation processes to a large extent in northern catchments of Finland and Norway in winter and spring. It is found, and generally assumed, that microbial activity in soils proceeds at low rates at northern latitudes during winter, even at sub-zero temperatures. The INCA model was modified to improve the simulation of N transformation rates in northern catchments, characterised by cold climates and extensive snow accumulation and insulation in winter, by introducing an empirical function to simulate soil temperatures below the seasonal snow pack, and a degree-day model to calculate the depth of the snow pack. The proposed snow-correction factor improved the simulation of soil temperatures at Finnish and Norwegian field sites in winter, although soil temperature was still underestimated during periods with a thin snow cover. Finally, a comparison between the modified INCA version (v.1.7) and the former version (v.1.6) was made at the Simojoki river basin in northern Finland and at Dalelva Brook in northern Norway. The new modules did not imply any significant changes in simulated NO_3^- concentration levels in the streams but improved the timing of simulated higher concentrations. The inclusion of a modified temperature response function and an empirical snow-correction factor improved the flexibility and applicability of the model for climate effect studies.

Keywords: inorganic N leaching, degree-day snow model, snow pack, catchment scale model

Introduction

Variations in inorganic nitrogen (N) concentrations in surface waters are caused by complex interactions between external factors and numerous N transformation processes in catchments (e.g. Vitousek *et al.*, 1997). In N-limited northern terrestrial catchments, plant and microbial uptake usually reduce the concentrations of nitrate (NO_3) and ammonium (NH_4) in runoff to very low levels during the growing season. During the dormant season, NO_3 outputs are often higher due to low plant and microbial activity. The process-oriented Integrated Nitrogen model for Catchments (INCA) links hydrology and N inputs from atmospheric deposition, agriculture and populated areas with the microbial processes controlling N behaviour in soils and river reaches (Wade *et al.*, 2002a).

To provide a generic tool for management of water quality across Europe, the model has been tested and modified through investigations in a wide range of ecosystem types within eight European countries (Wade *et al.*, 2002b; Wade, 2004). During this work, it became evident that INCA underestimates N transformation processes in northern catchments of Finland and Norway to a large extent in winter and spring when the catchments are covered with snow. In the INCA model, mineralisation of N in soil is assumed to occur from an unlimited organic N pool at a constant rate and rate coefficients of N processes are temperature- and moisture-dependent. As the effect of seasonal snow cover is not included in the soil temperature function, simulated soil temperatures tend to drop too low to allow N mineralisation to occur.

Traditionally, N mineralisation is assumed to take place within a temperature range of 5–35 °C, and it is generally assumed that the rate of transformation roughly doubles when the temperature is increased by 10 degrees (Stanford *et al.*, 1973). However, there is evidence of microbial activity at lower and even at sub-zero temperatures; in a field incubation study in a sub-arctic region in northern Sweden, Schmidt *et al.* (1999) found both mineralisation and immobilisation of N and P in soil in winter. Also, Stottlemyer and Toczydlowski (1999b) found that 40% of net N mineralisation (an average of 15 kg N ha^{-1} yr^{-1}) in a boreal forest soil occurred in winter. Clein and Schimel (1995) found both C and N mineralisation to occur at sub-zero temperatures (–2 °C and –5 °C) in tundra and taiga soils. Kähkönen *et al.* (2001) found that microbial activities degrading organic matter ceased at –7.0 °C in boreal forest soils, though the actual soil temperature under snow cover never dropped below –3 °C at their study site in central Finland. Snow is an effective insulator of heat and, thus, in the case of snow-covered soil, the soil temperature is typically only some degrees below zero even though air temperature may be lower.

There are several methods to model snow cover, soil frost and soil temperature in winter. In energy balance models the accumulation and melt of a seasonal snow pack are driven by snow mass and energy transfer at the interfaces between air, snow and soil (for example, Anderson, 1976; Tuteja and Cunnane, 1997; Koivusalo and Heikinheimo, 1999; Koivusalo and Kokkonen, 2002). Futhermore, the energy balance approach is often used to calculate soil temperature (Karvonen, 1988; Koivusalo *et al.*, 2001) and soil frost (Isard and Schaetzl, 1995; Venäläinen *et al.*, 2001a). These approaches need inputs from records of standard meteorological data (air temperature, precipitation, radiation components, relative humidity, wind speed) and soil characteristics, such as thermal conductivity and soil heat capacity.

A simpler approach to simulate snow accumulation and melt is the degree-day model (Vehviläinen, 1992), in which snowmelt is assumed to depend only on air temperature and precipitation as well as a simple soil frost depth model, also requiring air temperature and precipitation as inputs (Vehviläinen, 1992). In this method, the heat flux from the snow surface to the soil is calculated by the heat conduction equation. Empirical relationships (Venäläinen *et al.*, 2001b) between soil frost depth and the sum of daily mean air temperatures calculated from the beginning of the freezing period are an even simpler approach, albeit limited to snow-free surfaces.

The degree-day model is included in the ICECREAM model (Rekolainen and Posch, 1993; Tattari *et al.* 2001), a modified version of the field scale erosion and phosphorus leaching model CREAMS (Knisel, 1980). Energy balance models of snow pack and soil frost are included in the COUP model (Jansson and Karlberg, 2001) for simulations of hydrology and nitrogen and carbon processes. Also, Blombäck (1998) used previous versions of that model (SOIL/SOILN) to calculate seasonal N leaching from catch crop systems in Sweden. Recently, Laurén *et al.* (2004) and Koivusalo *et al.* (2003) applied a mathematical model with an energy balance approach to assess hydrological impacts of forest harvesting and logging-induced N load in Finland.

This paper reports the modifications to the INCA model to improve the simulation of N transformation rates in northern catchments, characterised by cold climates and extensive snow accumulation during winter. To make the method suitable for distributed models, the input data used are generally available at the catchment scale. The model structure is kept as simple as possible to limit structural and parameter uncertainty, and the output from the unmodified and modified models is compared for sites in Norway and Finland. Specifically, the proposed modifications include alteration of the present temperature response function, introduction of a new method to simulate soil temperatures below the seasonal snow pack, and a simple degree-day model to simulate the depth of a snow pack.

Proposed modifications of the INCA model

TEMPERATURE RESPONSE FUNCTION

The INCA model is described in detail in Whitehead *et al.* (1998) and Wade *et al.* (2002). In In the INCA model, the original temperature response function for the soil was:

$$f(T)_{soil} = 1.047^{(T_{soil}-20)} \tag{1}$$

Whilst this form of temperature response function continues to be used in the in-stream component of the model, it has now been replaced in the land phase component by a Q$_{10}$ relationship (Bunnel *et al.*, 1977):

$$f(T)_{soil} = t_{Q10}^{\,(T-t_{Q10bas})/10} \tag{2}$$

where t_{Q10} and t_{Q10bas} are parameters ([-] and [°C] respectively) and T is soil temperature [°C]. The parameter t_{Q10} is the factor change in rate with a 10 degree change in temperature and the parameter t_{Q10bas} is the base temperature for the N process at which the response is 1. The new temperature response parameters are determined by calibration within INCA.

EMPIRICAL SNOW DEPTH/SOIL TEMPERATURE RELATIONSHIP

The present version of INCA applies a sine function to simulate soil temperatures from ambient air temperatures (Whitehead *et al.*, 1998):

$$T_{SOIL} = T_{AIR} - C_{16}\sin\left(\frac{3}{2}\pi\frac{dayno.}{365}\right) \quad (3)$$

where T_{SOIL} is soil temperature [°C], T_{AIR} is air temperature [°C] and C_{16} is a parameter [°C], which denotes the maximum difference between summer and winter temperature. Soil temperature simulated by this function follows air temperature with a short lag, which is a reasonable assumption in summer. This may be the case in catchments without snow in winter as well but, in northern areas with heavy snow accumulations, this function results in an underestimation of winter soil temperatures (Fig. 1).

Soil temperature in winter depends strongly on snow cover thickness, and for the simulation of daily soil temperatures below the seasonal snowpack (T_{SOIL}*), a simple, empirical relationship is suggested:

$$T_{SOIL}{*} = T_{SOIL}.e^{(CF.SD)} \quad (4)$$

where T_{SOIL} is the soil temperature (°C) originally estimated by INCA, *CF* is a correction factor (cm^{-1}) that can be calibrated from within INCA, and *SD* is the snow depth in centimetres (Fig. 2). Based on Norwegian data sets containing time series of air temperature, soil temperature at 15 cm and snow depth, a correction factor (*CF*) of around –0.025 seems appropriate. In periods without snow, T_{SOIL}*

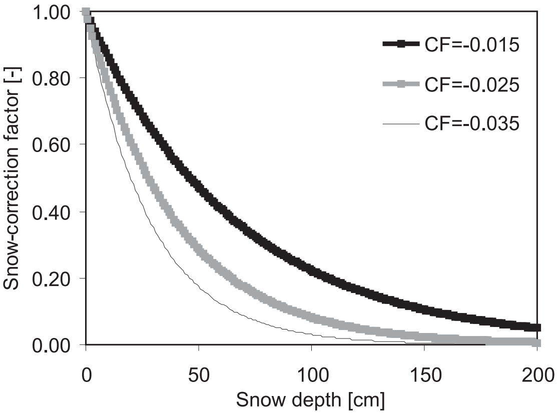


Fig. 2. *Empirical snow depth/soil temperature function*

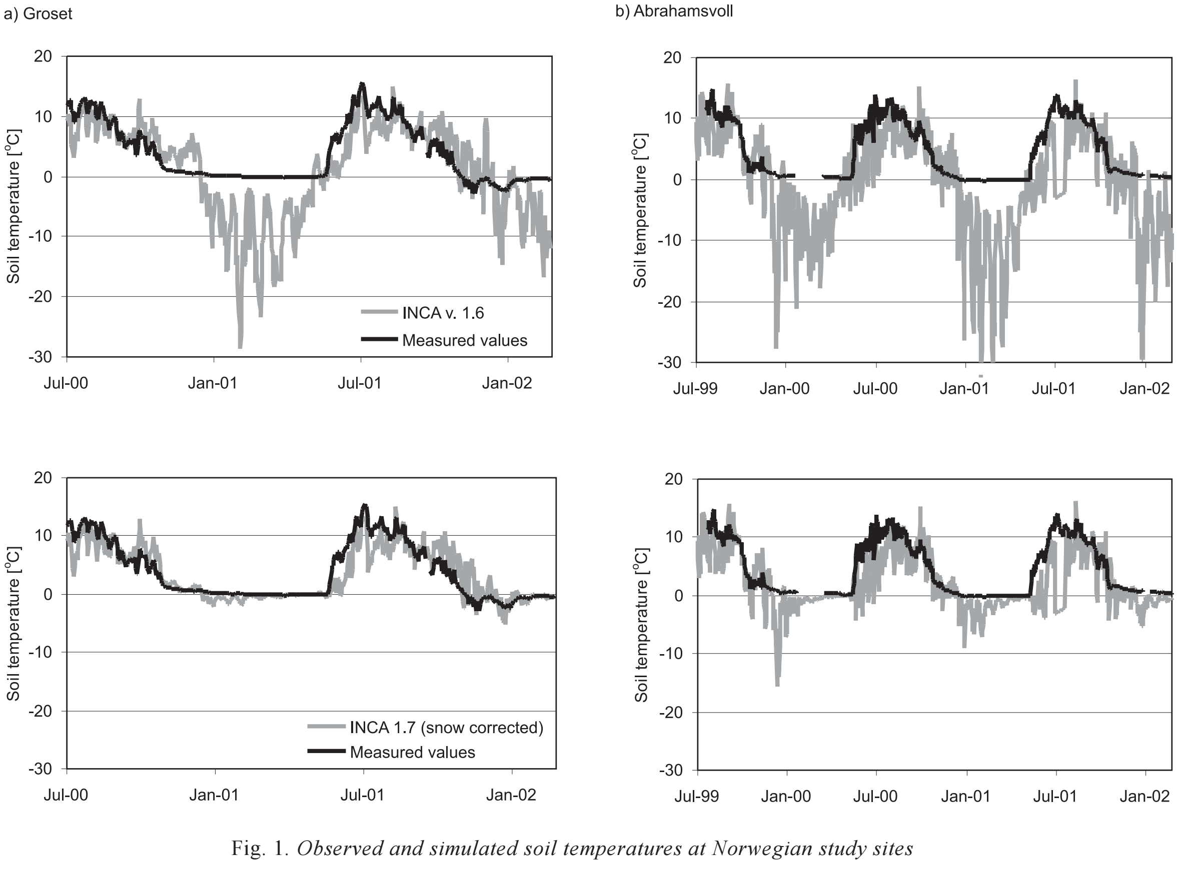


Fig. 1. *Observed and simulated soil temperatures at Norwegian study sites*

Table 1. Fixed values of snow model parameters in INCA

Parameter	*Unit*	*Value*
Correction factor for solid precipitation (C_S)	–	1.23
Temperature below which precipitation falls as snow (T_{LOW})	°C	-1.5
Temperature above which precipitation falls as rain (T_{UPPER})	°C	1.0
Temperature at which snow melts (T_M)	°C	0.5
Rate of evaporation from snow (E_S)	mm d^{-1}	0.09

and T_{SOIL} will be equal, and if using a CF value of –0.025, snow depths of 10, 50 and 100 cm will result in T_{SOIL}^*/T_{SOIL} ratios of 0.78, 0.29 and 0.08, respectively.

This empirical function takes into account only the isolating effect of the snow pack. In reality when soil starts to freeze, a lot of energy is consumed in transformation processes (e.g. freezing of water in soil frost formation).

SIMPLE SNOW PACK MODEL

As only an estimate of snow pack depth is required to adjust the INCA soil temperature, a simplified version of the degree-day snow model (Vehviläinen, 1992; Karvonen, 2001) is used. This model is also known as the temperature index snow model.

The form of precipitation is determined on the basis of mean air temperature T_{AIR} (°C). If T_{AIR} is below a given critical temperature T_{LOW} (°C), precipitation is considered to be snow. If T_{AIR} is above an upper critical temperature T_{UPPER} (°C), precipitation is considered to be water. When T_{AIR} is between T_{LOW} and T_{UPPER} precipitation is considered to be partly water and partly snow:

$$\begin{aligned}
&P_S = 0.0 && ;T_{AIR} \geq T_{UPPER}\\
&P_S = \frac{P(T_{UPPER} - T_{AIR})}{(T_{UPPER} - T_{LOW})} && ;T_{LOW} \leq T_{AIR} \leq T_{UPPER}\\
&P_S = P && ;T_{AIR} \leq T_{LOW}\\
&P_{CORR} = P_S C_S
\end{aligned} \tag{5}$$

where P is measured precipitation rate (mm d^{-1}), P_S is the intermediate value for precipitation as snow (mm d^{-1}) before correction, C_S is a correction factor [-] which depends on precipitation gauge type (Mustonen, 1986) and P_{CORR} is the final corrected value for precipitation as snow (mm d^{-1}).

But if the mean air temperature T_A is above the temperature at which snow melts, T_M (°C), then both the snow pack and the incoming solid precipitation will undergo melting:

$$\begin{aligned}
&S_M = (T_A - T_M)\, F_M\\
&S_M = P_{CORR} && ;\, S_M > P_{CORR}
\end{aligned} \tag{6}$$

where S_M is the amount of melted water (mm) and F_M is the degree-day factor for snowmelt (mm °C^{-1} d^{-1}).

Losses due to evaporation must also be accounted for:

$$\begin{aligned}
&S_E = E_S && ;\, E_S \leq (P_{CORR} - S_M)\\
&S_E = (P_{CORR} - S_M) && ;\, (P_{CORR} - S_M) \leq E_S
\end{aligned} \tag{7}$$

where S_E is the amount of water lost due to evaporation (mm) and E_S is the rate of evaporation from snow (mm d^{-1}). Snow pack depth is then calculated by:

$$S_W = S_I + P_{CORR} - S_M - S_E \tag{8}$$

where S_W is the snow pack depth in mm as water equivalents and S_I is the initial snow pack depth. This is then converted to snow depth for use in the empirical snow depth/soil temperature relationship thus:

$$S_D = \frac{S_W}{10.F_W} \tag{9}$$

where F_W is the water equivalent factor (-) and S_D is the snow pack depth (cm), converted from millimetres to centimetres.

To simplify the snow pack model further, the majority of the model parameters have been fixed within INCA based on values (Table 1) from the literature (Kuusisto, 1984; Vehviläinen, 1992).

The initial snow pack depth (as water equivalent) S_I, degree day factor for snowmelt F_M and water equivalent factor F_W are left for calibration within INCA.

Sites and data

INTRODUCTION

The proposed snow-correction factor for the simulation of soil temperatures in snow-covered catchments was derived from two Norwegian sites (Groset and Abrahamsvoll) with measurements of air temperature, snow cover and soil temperature. Subsequently, the correction factor was tested using independent data from three Finnish sites (Jokioinen

Fig. 3. *Location of field sites and study catchments*

Observatory, Sodankylä Observatory and Sodankylä Vuotso). The degree-day model was tested using measured snow water equivalent in the small catchment Savijoki in southern Finland. Finally, the INCA model with these modifications was applied to the Simojoki river basin in Finland and the Dalelva catchment in Norway. (Fig. 3)

FIELD SITES USED FOR DEVELOPMENT AND TESTING OF THE SNOW-CORRECTION FACTOR

Norwegian field sites

The Norwegian field sites Groset (60°0'N; 8°30'E) and Abrahamsvoll (62°30'N; 12°0'E) are operated by the Norwegian Water Resources and Energy Directorate (Colleuille, 2001). Both are in mountainous areas at 950 and 750 m a.s.l., respectively, dominated by glacial tills and mountain birch vegetation. Mean air temperatures in 1961–1990 were 0.5 °C (Groset) and 0.6 °C (Abrahamsvoll), while the mean annual precipitation amounted to 810 and 692 mm, respectively (DNMI, 2002). Daily time series of air temperature, snow depth and soil temperature (several depths) are available at both sites (Colleuille, 2001; DNMI, 2002).

Finnish field sites

The three Finnish sites belong to the network of weather observation stations operated by the Finnish Meteorological Institute. Precipitation and air temperature are measured daily, whereas soil temperatures are measured six times per month at depths of 20, 50 and 100 cm.

The Sodankylä Observatory (67°22, 26°37) is in the northern boreal zone, and the soil type there is till. The observation station Sodankylä Vuotso (68°05, 27°11) is on sandy soils. The mean air temperature in 1961–1990 was –1 °C and mean annual precipitation was 499 mm (Finnish Meteorological Institute, 1991). In the period 1971–1990 the mean maximum snow depth in Sodankylä Vuotso in open areas was 69 cm, with a corresponding depth of 63 cm in forests. Maximum snow depths occurred in March. Frost depths were 102 cm and 126 cm respectively (Huttunen and Soveri, 1993).

The Jokioinen Observatory (60°49, 23°30) represents agriculturally dominated areas in the southern boreal climate zone in southern Finland. The soil type there is clay. Mean air temperature in 1961–1990 was 3.9 °C and mean annual precipitation 582 mm (The Finnish Meteorological Institute, 1991). In the period 1971–1990, the mean maximum snow depth in open areas was 32 cm, and 15 cm in forests. In each case maximum snow depths occurred in March. Frost depths were 41 cm and 49 cm respectively (Huttunen and Soveri, 1993).

SMALL CATCHMENT USED FOR TESTING OF THE DEGREE-DAY MODEL

The Savijoki catchment is in the south-western part of Finland (60°5, 22°5). It belongs to the Finnish network of small representative catchments (Mustonen, 1965; Vuorela, 1997), originally established for hydrological research in 1957. The area of the catchment is 15.4 km^2 and 39% of it is cultivated land. The annual mean values for temperature and precipitation for 1971–2000 were 5.2 °C and 698 mm, respectively. In winter (December–March) precipitation usually falls as snow. The water equivalent of snow is measured there once a month in winter and twice a month in spring. Snow is sampled at defined distances along a 4 km long line, which is laid down representing the different land use typical of the catchment.

CATCHMENTS USED FOR TESTING OF THE MODIFIED INCA VERSION

Simojoki river basin

The river Simojoki discharges into the Gulf of Bothnia in the Baltic Sea. The area of the river basin is 3160 km^2. Over the period 1961–1975, annual precipitation was 650–750 mm and annual runoff 350–450 mm. There are about 170–180 winter days and the mean annual temperature is 0.5–1.5 °C. The duration of the snow cover is from the middle of November to May. The river Simojoki freezes at the end of October or at the beginning of November and the ice cover usually breaks up in the middle of May. The river Simojoki is a salmon river in a near-natural state, and the dominant human impact is from forestry practices, specifically forest drainage and cutting. Peatlands and peatland forests are common in the region and an average of 0.5% of the total catchment area is felled annually. Urban areas cover only 0.06% and agricultural fields 2.7% of the catchment (Perkkiö *et al.*, 1995).

Dalelva Brook

The Norwegian study site, Dalelva, is in northern Norway (69°41, 30°23). Dalelva is a small (3.2 km^2) and undisturbed mountain to fjord catchment dominated by heathland. The bedrock geology in the Dalelva catchment is mica schist and micaceous gneiss covered by glacial sediments of similar lithology (Wright and Traaen, 1992). Soils are podsolic, thin and patchy in the upper parts of the catchment. Vegetation is birch forest up to about 150 m elevation, with heathlands and moorlands above. About 15% of the Dalelva catchment is lakes.

Results and discussion

TESTING OF THE DEGREE-DAY MODEL

The parameterisation of the degree-day model was tested against observed snow water equivalent data measured in the Savijoki catchment (Fig. 4), where a 10 year time-series was available. Calibration of the INCA model to the Savijoki catchment is described in detail by Granlund *et al*. (2004). The degree-day model with fixed parameterisation was able to simulate the duration of the snow covered period, the date when snow cover started to accumulate and the date when snow cover was melted. The model simulated the pattern of snow cover accumulation in successive winters reasonably well. During the mild winters of 1991–1992 and 1992–1993, simulated and observed snow water equivalents agreed well but in some years, water equivalent of snow was overestimated.

DEVELOPMENT AND TESTING OF THE NEW SOIL TEMPERATURE SIMULATION ROUTINE

The soil temperature modification was tested using 20 cm depth soil temperature data from two observation stations run by the Finnish Meteorological Institute, the Jokioinen Observatory and the Sodankylä Observatory. Precipitation and air temperatures at these observation stations in winter 1985–1986 are shown in Fig. 5. Precipitation is measured as daily values (mm) and temperature as daily mean values

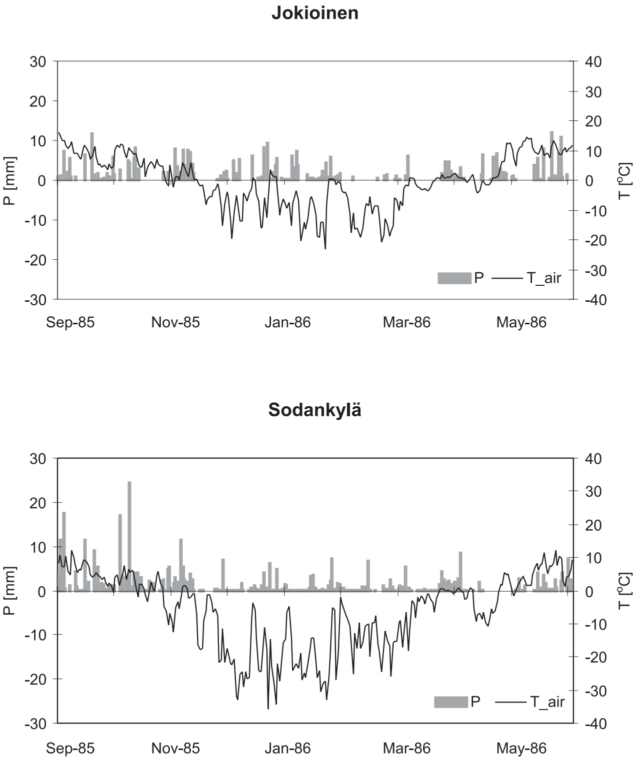


Fig. 5. *Precipitation and air temperature at Sodankylä and Jokioinen*

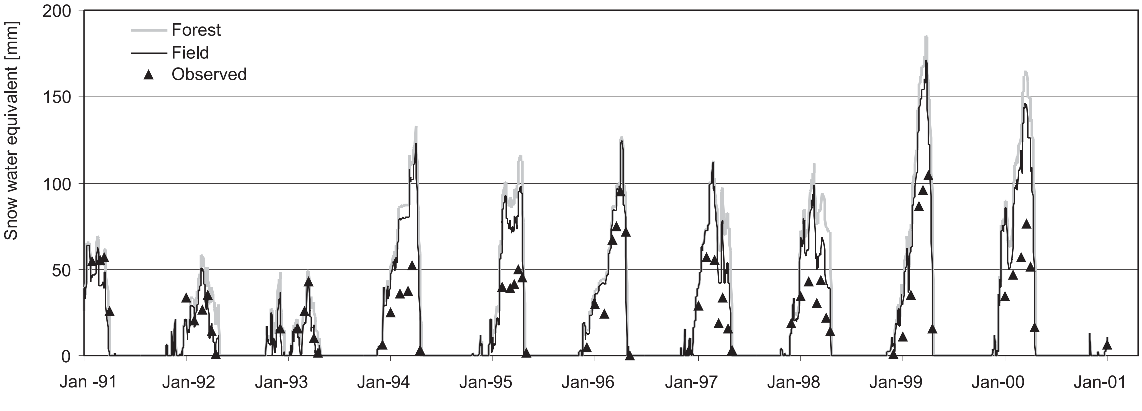


Fig. 4. *Simulated and observed soil water equivalent at the Savijoki catchment*

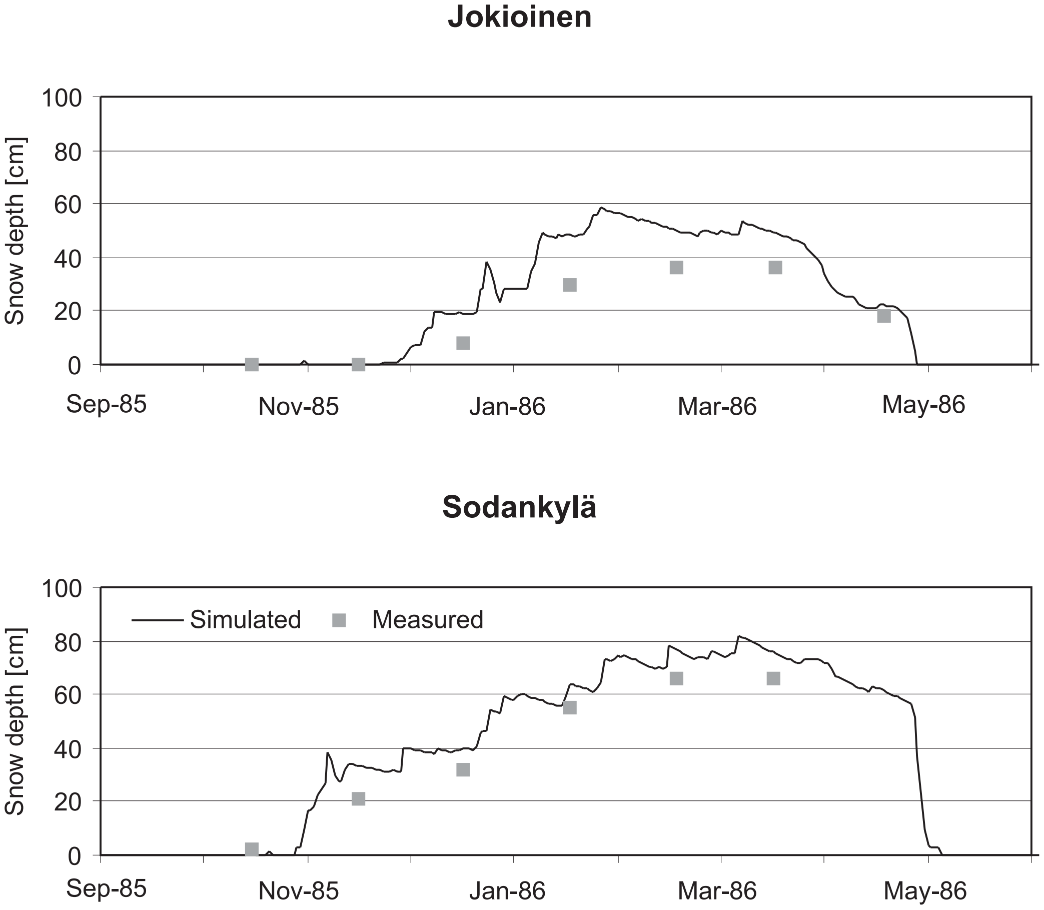


Fig. 6. *Simulated and observed snow depths at Sodankylä and Jokioinen*

(°C) at the height of 2 m. In Sodankylä, snow cover was permanent from 27th October until it melted from open areas on 20th May and from forest on 30th May. In Jokioinen, permanent snow cover started from 23rd November until snow melted from open areas on 16th April and from forests on 29th April. Simulated and observed snow depths are compared in Fig. 6. The snow model overestimated the depth of snow cover in Jokioinen, but in Sodankylä the simulated snow depth agreed well with observations.

Figure 7 compares simulated soil temperature with soil temperature measured at 20 cm depth The parameter values used to calibrate the equation for different stations are given in Table 1. The simulated soil temperatures agreed fairly well with observations at the different stations. In early winter, when snow cover is shallow, simulated soil temperatures are too low because they follow the variation in air temperature; the empirical snow depth/soil temperature relationship does not take into account the energy consumed in freezing water in the soil. When the depth of snow cover increases, simulated and measured soil temperatures agree. Both measured and simulated soil temperatures increase rapidly when the snow melts. The duration of snow cover seems to be more important for controlling soil temperature than the depth of snow cover.

MODEL PERFORMANCE ON A CATCHMENT SCALE

The modified version of the INCA model (v.1.7) has already been calibrated to the Simojoki river basin (Rankinen *et al*., 2004) and the Dalelva Brook (Kaste, 2004). The calibration routines followed the procedures recommended by Wade *et al*. (2002a). Accordingly, INCA was set up to simulate the actual hydrology, both in terms of dynamics and absolute flow, before any parameters controlling N storage, transformations or transport were adjusted. Secondly, the parameters controlling land phase and in-stream N transformation rates were adjusted such that annual process loads were within the ranges reported in the literature and a reasonable match between simulated and observed streamwater inorganic N concentrations was obtained. The parameter values used for the temperature response application and the snow models are included in Table 2.

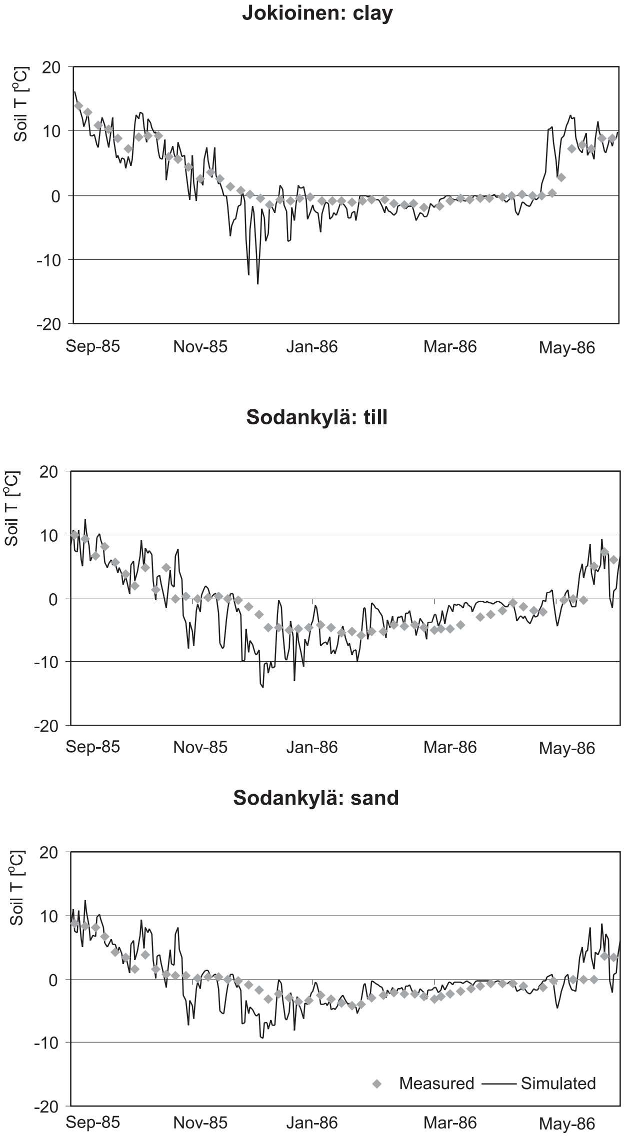


Fig. 7. *Simulated and observed soil temperatures at Sodankylä and Jokioinen*

Figure 8 compares the modified INCA version (v.1.7) and the former version (v.1.6) applied to the Simojoki river basin and Dalelva Brook. In these two catchments, characterised by low NO$_3$-N in surface water, the inclusion of the new modules in version 1.7 did not result in a significant improvement in simulated inorganic N concentration level.

The introduction of the empirical snow-correction factor (*CF*) has led to a more realistic simulation of soil temperatures in winter (cf. Figs. 2 and 7). In turn, this gives an increase in model-simulated nitrogen mineralisation in winter, which can be identified as a slight increase in streamwater NO$_3$-N concentrations (Fig. 8) at Dalelva Brook. Improved timing of simulated concentration peaks is clear in the Simojoki river basin (Fig. 8), where simulated (INCA 1.6) inorganic N concentrations peak later in spring than those observed . Furthermore, simulated concentrations tend to be higher than observed in early autumn. Values of R^2 (Nash and Sutcliffe, 1970) for simulations of NO$_3$-N were equally good with both model versions (INCA1.6 and INCA1.7) at Dalelva brook but improved from inadequate (INCA1.6) to 0.5 (INCA1.7) at Simojoki river basin.

The reason for this modest change in the output concentrations of NO$_3$-N at Dalelva brook is that the responses of each N process included in the model are positively correlated with temperature, i.e. the increased N supply from mineralisation will largely be balanced by N retaining processes, such as immoblisation during winter. In contrast to this, both laboratory and large-scale experiments indicate that decomposition and N mineralisation respond faster to a temperature increase in lower temperature ranges than the corresponding N retention processes (cf. references in Kaste *et al.*, 2004).

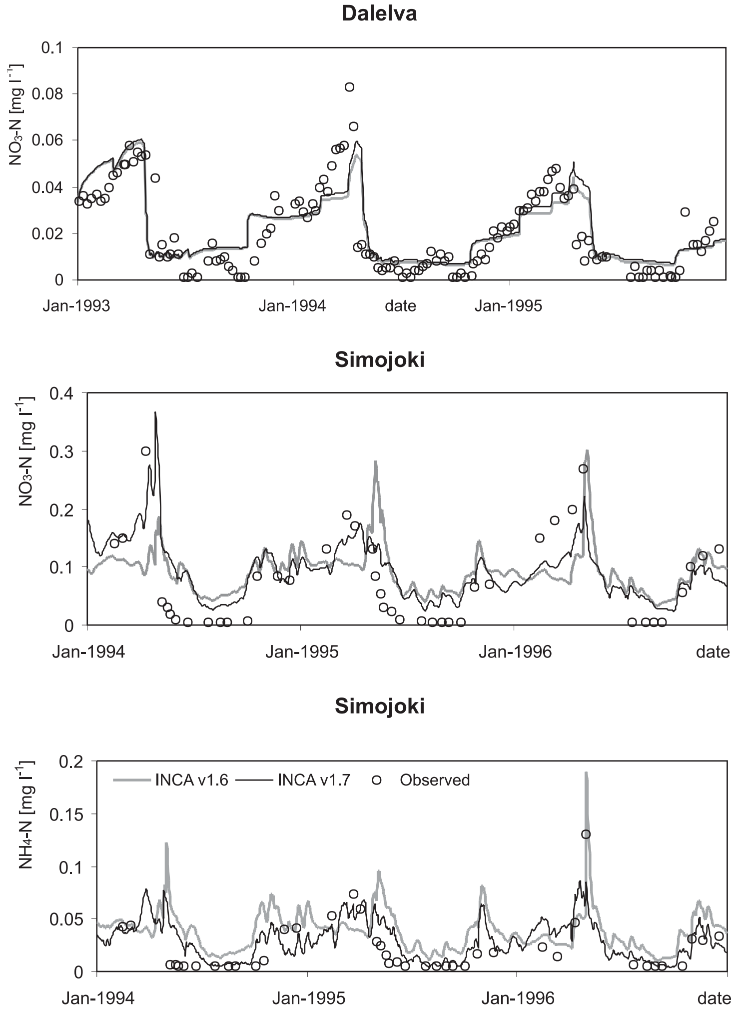
With the recently adapted version of the INCA model (1.7) it is now possible to apply individual temperature response functions (Q$_{10}$ values) to different land cover classes. Altogether, the recent changes to INCA are important steps

Table 2. Parameter values used to calibrate soil temperature model to Finnish observation sites. C_{16} is the maximum temperature difference (°C) between summer and winter conditions (Whitehead *et al.*, 1998)

Observation station	*Soil type*	C_{16}	*Snow depth factor*
Sodankylä Observatory	Till	3	0.02
Sodankylä Vuosto	Sand	3.5	0.03
Jokioinen Observatory	Clay	2	0.025

Table 3. Parameter values used for the temperature response application and the snow models in the Simojoki river basin and the Dalelva Brook.

	SIMOJOKI		DALELVA
	Forest	*Arable*	
t_{Q10} values	2	2	2
t_{Qbas} values (°C)	20	22	20
Snow-correction factor (*CF*)	–0.025	–0.03	–0.02
Snowmelt factor (F_M) (mm °C^{-1} day^{-1})	2.24	3	3
Snow water equivalent (F_W)	0.3	0.3	0.3



Dalelva

Simojoki

Simojoki

Fig. 8. *Simulated and observed inorganic N concentrations in the river Simojoki and the Dalelva brook*

in making the model more flexible and applicable to climate effect studies, especially in cold regions characterised by extensive snow accumulations during winter.

Conclusions

The purpose of this study was to suggest modifications to the INCA model to make it more suitable for predicting inorganic N concentrations in river water in winter and spring in seasonally snow-covered catchments. These modifications are based on the assumption that N processes such as mineralisation continue in soils in winter at northern latitudes (e.g. Stottlemyer and Toczydlowski, 1999a; Schmidt *et al.*, 1999). The model structure was no more complex than necessary nor was the requirement for input data increased. The modifications require precipitation and air temperature as input, data for which are already input to INCA. The number of new parameters added to the model is six.

Here, to simulate soil temperature in winter under snow, an empirical function was derived from observed snow cover depth and soil temperature at two Norwegian field sites; it was able to simulate soil temperature in Finland in different climatic zones and soil types, although soil temperatures were still somewhat underestimated during periods with a thin snow cover. This happens because the empirical snow depth/soil temperature relationship does not take into account the energy used to freeze water in soil. However, the variation in simulated soil temperature abates when depth of snow cover increases. Snow pack depth is simulated by a simple degree-day model with a fixed parameter set. Finally, the model was tested by applying it to two study catchments, different in size and vegetation. The model simulated the annual dynamics of inorganic N concentrations both in the river Simojoki in Finland and the Dalelva brook in Norway. To validate these modifications to the INCA model, as a test, simulated N transformation rates should be compared with observed rates during the growing and dormant seasons.

Acknowledgements

This study was supported by the Commission of the European Union, the INCA project (EVK1-CT-1999-00011).

References

Anderson, E.A., 1976. *A point energy and mass balance model of a snow cover.* NOAA Technical Report NWS 19, USA. 150pp.

Blombäck, K., 1998. *Carbon and Nitrogen in Catch Crop Systems. Modelling of seasonal and long-term dynamics in plant and soil.* Doctoral Thesis. Department of Soil Sciences, Swedish University of Agricultural Sciences, Uppsala, Sweden.

Bunnel, F.L., Tait, D.E.N., Flanagan, P.W. and Van Cleve, K., 1977. Microbial respiration and substrate weight loss. I. A general model of the influences of abiotic variables. *Soil Biol. Biochem.,* **9**, 33–40.

Clein, J.S. and Schimel, J.P., 1995. Microbial activity of tundra and taiga soils at sub-zero temperatures *Soil Biol. Biochem.,* **27**, 1231–1234.

Colleuille, H., 2001. *National observation network for soil water. Status report 1989-2000.* Report no. 12-2001, The Norwegian Water Resources and Energy Directorate (NVE), Oslo, Norway, 175 pp.

DNMI, 2001. *Daily precipitation volumes and snow depths at the monitoring stations Møsstrand and Vauldalen.* The Norwegian Meteorologial Institute (DNMI), Oslo, Norway.

Finnish Meteorological Institute, 1991. *Climatological Statistics in Finland 1961–1990.*

Granlund, K., Rankinen, K. and Lepistö, A., 2004. Application of the INCA model in a small agricultural catchment in southern Finland. *Hydrol. Earth. Syst. Sci.* **8,** 717–728.

Huttunen, L. and Soveri, J., 1993. *Luonnontilaisen roudan ajallinen ja alueellinen vaihtelu Suomessa. The Regional and Temporal Variation of Frost in Natural Conditions in Finland* [in Finnish]. Publication of National Board of Waters and the Environment - series A 139, Finland.74pp.

Isard, S.A. and Schaetzl, R.J., 1995. Estimating soil temperatures and frost in the lake effect snowbelt region, Michigan, USA. *Cold Reg. Sci. Technol.,* **23**, 317–332.

Jansson, P. E. and Karlberg, L., 2001. *Coupled heat and mass transfer model for soil-plant-atmosphere systems.* Division of Land and Water Resources, Department of Civil and Environmental Engineering, Royal Institute of Technology. TRITA-AMI REPORT 30, 87pp.

Kähkönen, M.A., Wittmann, C., Kurola, J., Ilvesniemi, H. and Salkinoja-Salonen, M.S., 2001. Microbial activity of boreal forest soil in a cold climate. *Boreal Environ. Res.,* **6**, 19–28.

Karvonen, T., 1988. *A model for predicting the effect of drainage on soil moisture, soil temperature and crop yield.* Publications of the Laboratory of Hydrology and Water Resources Engineering 1/1988, Helsinki University of Technology, Finland, 215pp.

Karvonen, T., 2001. *http://www.water.hut.fi/wr/kurssit/Yhd-12.135/kirja/snow_www.htm [WWW, refered 31.1.2003].*

Kaste, Ø., 2004. Simulation of nitrogen dynamics and fluxes in contrasting catchments in Norway by applying the Integrated Nitrogen model for Catchments (INCA). *Water Air Soil Pollut.: Focus,* **4,** 85–96.

Kaste, Ø., Rankinen, K. and Lepistö, A., 2004. Modelling impacts of climate and deposition changes on nitrogen fluxes in northern catchments of Norway and Finland. *Hydrol. Earth Syst. Sci.* **8,** 778–792.

Knisel, W. G., 1980. *CREAMS, a field scale model for chemicals, runoff and erosion from agricultural management systems.* USDA, Conservation Research Report No. 26, 643pp.

Koivusalo, H. and Heikinheimo, M., 1999. Surface energy exchange over a boreal snowpack: comparison of two energy balance models. *Hydrol. Process.,* **13**, 2395–2408.

Koivusalo, H. and Kokkonen, T., 2002. Snow processes in a forest clearing and in a coniferous forest. *J. Hydrol.,* **262**, 145–164.

Koivusalo, H., Heikinheimo, M. and Karvonen, T., 2001. Test of a simple two-layer parameterisation to simulate the energy balance and temperature of a snow pack. *Theor. Appl.Climatol.,* **70**, 65–79.

Kuusisto, E., 1984. *Snow accumulation and snowmelt in Finland.* National Board of Waters, Helsinki, Finland. 49pp.

Laurén, A., Finér, L., Koivusalo, H., Kokkonen, T., Mannerkoski, H., Palviainen, M. and Piirainen, S., 2004. Application of a mathematical model (FEMMA) in assessing logging-induced nitrogen load through a peatland buffer zone. In: *Wise Use of Peatlands*. 12th International Peat Congress 6-11 June 2004 Tampere, Finland.

Mustonen, S., 1965. *Maataloushallituksen hydrologiset tutkimukset vuosina 1957...1964. Hydrologic investigations by the Board of Agriculture during the years 1957 to 1964.* Maa- ja vesiteknillisiä tutkimuksia. Soil and Hydrotechnical Investigations. 11., Helsinki, Finland. 144pp.

Mustonen, S. (Ed.), 1986. *Sovellettu Hydrologia*. Vesiyhdistys r.y., Mäntän Kirjapaino Oy. 503pp.

Nash, J. E. and Sutcliffe, J. V., 1970. River flow forecasting through conceptional models. 1. A discussion of principles. *J. Hydrol.,* **10**, 282–290.

Perkkiö, S., Huttula, E. and Nenonen, M., 1995. *Simojoen vesistön vesiensuojelusuunnitelma.* Vesi- ja ympäristöhallinnon julkaisuja-sarja A 200, 102pp.

Rankinen, K., Lepistö, A. and Granlund, K., 2002. Hydrological application of the INCA (Integrated Nitrogen in CAtchments) model with varying spatial resolution and nitrogen dynamics in a northern river basin. *Hydrol. Earth Sys. Sci.,* **6**, 339–350.

Rankinen, K., Lepistö, A. and Granlund, K., 2003. Integrated nitrogen and flow modelling (INCA) in a boreal river basin dominated by forestry: scenarios of environmental change. *Water Air Soil Pollut.: Focus,* **4**, 161–174.

Rekolainen, S. and Posch, M., 1993. Adapting the CREAMS model for Finnish conditions. *Nord. Hydrol.,* **24**, 309–322.

Schmidt, I.K., Jonasson, S. and Michelsen, A., 1999. Mineralization and microbial immobilization of N and P in arctic soils in relation to season, temperature and nutrient amendment. *Appl. Soil Ecol.,* **11**, 147–160.

Stanford, G., Frere, M.H. and Schwaninger, D.H., 1973. Temperature Coefficient of Soil Nitrogen Mineralization. *Soil Sci.,* **115**, 321–323.

Stottlemyer, R. and Toczydlowski, D., 1999a. Nitrogen mineralization in a mature boreal forest, Isle Royale, Michigan. *J. Environ. Qual.,* **28**, 709–720.

Stottlemyer, R. and Toczydlowski, D., 1999b. Seasonal Relationships Between Precipitation, Forest Floor, and Streamwater Nitrogen, Isle Royale, Michigan. *Soil Sci. Soc. Amer. J.,* **63**, 389–398.

Tattari, S., Bärlund, I., Rekolainen, S., Posch, M., Siimes, K., Tuhkanen, H-R. and Yli-Halla, M., 2001. Modeling Sediment Yield and Phosphorus Transport in Finnish Clayey Soils. *Trans. ASAE,* **44**, 297–307.

Tuteja, N.K. and Cunnane, C., 1997. Modelling coupled transport of mass and energy into the snowpack- model development, validation and sensitivity analysis. *J. Hydrol.,* **195**, 232–255.

Vehviläinen, B., 1992. *Snow cover models in operational watershed forecasting.* Doctoral Thesis, National Board of Waters and the Environment, Finland. Publications of Water and Environment Research Institute, Finland. 112pp.

Venäläinen, A., Tuomenvirta, H., Heikinheimo, M., Kellomäki, S., Peltola, H., Strandman, H. and Väisänen, H., 2001a. Impact of climate change on soil frost under snow cover in a forested landscape. *Climate Res.,* **17**, 63–72.

Venäläinen, A., Tuomenvirta, H., Lahtinen, R. and Heikinheimo, M., 2001b. The influence of climate warming on soil frost on snow-free surfaces in Finland. *Climatic Change,* **50**, 111–128.

Vitousek, P.M., Aber, J.D., Howarth, R.W., Likens, G.E., Matson, P.A., Schindler, D.W., Schlesinger, W.H. and Tilman, D.G., 1997. Human alteration of the global nitrogen cycle: sources and consequences. *Ecol. Appl.,* **7**, 737–750.

Vuorela, A., 1997. *Satellite image based land cover and forest classification of Finland.* Reports of the Finnish Geodetic Institute 97, Finland. 42–52.

Wade, A., Durand, P., Beaujoan, V., Wessels, W., Raat, K., Whitehead, P.G., Butterfield, D., Rankinen, K. and Lepistö, A., 2002a. Towards a generic nitrogen model of European ecosystems: New model structure and equations. *Hydrol. Earth Syst. Sci.,* **6**, 559–582. (See also Errata. *Hydrol. Earth Syst. Sci.*, **8**, 858–859.)

Wade, A.J., Whitehead, P.G. and O'Shea, L.C.M., 2002b. The prediction and management of aquatic nitrogen pollution across Europe: an introduction to the Integrated Nitrogen in European Catchments project (INCA). *Hydrol. Earth Syst. Sci.,* **6,** 299–313.

Whitehead, P.G., Wilson, E.J. and Butterfield, D., 1998. A semi-distributed Integrated Nitrogen model for multiple source assessment in Catchments (INCA): Part I-model structure and process equations. *Sci. Total Envir.,* **210/211**, 547–558.

Wright, R.F. and Traaen, T.S., 1992. *Dalelva, Finnmark, northernmost Norway: prediction of future acidification using the MAGIC model.* Report 2728, Norwegian Institute for Water Research, Oslo, Norway. 17pp.