MODELLING NITRATE LOSSES FROM AGRICULTURAL ACTIVITIES ON A NATIONAL SCALE

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ABSTRACT

The Nitrogen Risk Assessment Model for Scotland (NIRAMS) has been developed as a screening tool for prediction of streamwater N concentrations draining from agricultural land in Scotland. The objective of the model is to be able to predict N concentrations for ungauged catchments, to fill gaps in monitoring data and provide guidance in relation to policy development. The model uses national land use, soils and meteorology data sets and has been developed within an ArcView Geographic Information System (GIS) user interface. The model includes modules to calculate N inputs to the land, residual N remaining at the end of the growing season, weekly time-series of leached N and transport of N at the catchment scale. The N leaching and transport are controlled by hydrological modules, including a national water balance model and a catchment scale transport model. Preliminary testing of NIRAMS has been carried out on 8 Scottish catchments, diverse in terms of geographic location as well as land use. Comparisons of the simulation results with measured data demonstrate that the model is capable of predicting the correct mean level of stream N concentrations, as well as the basic characteristics of seasonal variation. As such the model can be of value for providing estimates of N concentrations in ungauged areas.

Keywords : Catchment; GIS; modelling; nitrate; policy development; ungauged; land use; soils

INTRODUCTION

Implementation of EU legislation such as the Nitrates and Water Framework Directives requires an extensive understanding of the hydrochemical quality of surface and groundwater resources. In general, monitoring of water bodies provides data pertaining to the larger river systems together with limited coverage of groundwaters. However, there is often a lack of data pertaining to water quality in ungauged basins, including sub-catchments and coastal 'gap' catchments. In response to the perceived need for this information, the Scottish Executive commissioned a project to develop a model to predict concentrations and fluxes of surface and groundwater nitrates draining from agricultural land across the whole of Scotland. This paper describes the development and preliminary testing of the resulting NIRAMS (Nitrogen Risk Assessment Model for Scotland) model.

Many models have been developed to predict nitrate leaching and transport at catchment scales eg. INCA (Whitehead *et al*., 1998), SWAT (Neitsch *et al*., 2002) and AGNPS (Young *et al*., 1989), but these models are quite complex and have detailed data requirements. As such, they do not provide useful screening tools for use in a planning context such as that required by the EU Nitrates Directive. At the other extreme very simple models, such as those based on export coefficients, (Johnes, 1996) do not give adequate information about either spatial or temporal variability in catchment scale N processes. In England and Wales the MAGPIE model (Lord and Anthony, 2000) was developed to provide a modelling framework for evaluating nitrates losses at the national scale and provides a good example of integration of nationally available datasets to predict nitrate leaching. The objective of the NIRAMS approach was to provide a similar tool to MAGPIE that could be applied to Scottish datasets, but that also included a more comprehensive methodology for hydrological transport and routing to predict streamwater N concentrations.

The need for a model to be applicable at the national scale and to predict water quality in ungauged catchments places a number of restrictions and requirements on its structure. These include the need for input data and parameters to be derived from nationally available data sets, limited calibration requirements and the need to model flows in catchments with very diverse characteristics. Model calibration can be simplified by limiting the number of model parameters but an increased level of process representation implies that the parameter values should be more identifiable. The representation of hydrological flowpaths provides one example of how adding complexity to the model can help to simplify the model application. By incorporating spatial data such as the Hydrology of Soil Types (HOST) (Boorman *et al*., 1995), the model can be designed to predict the proportions of flow originating from groundwater and sub-surface flowpaths. Hence, the model can take account of the effect on streamwater chemistry of the mixing of these different source waters. A similar logic can be applied to account for variability in other catchment characteristics, for example, inclusion of topographic and climatic influences. This philosophy has been adopted within the development of NIRAMS and is demonstrated in the model testing through application of the model to a very diverse range of catchments in Scotland.

METHODS

The NIRAMS model involves four linked components defining:
(1) Inputs of N to the land
(2) N cycling in the soil system to calculate residual N at the end of the growing season
(3) Leaching of residual N after the end of the growing season
(4) Transport of leached N to surface and groundwater systems

The structure of the model is illustrated in Figure 1 and the key features of each of the components are described below. A more detailed description of the model is given in Dunn *et al*. (2002).
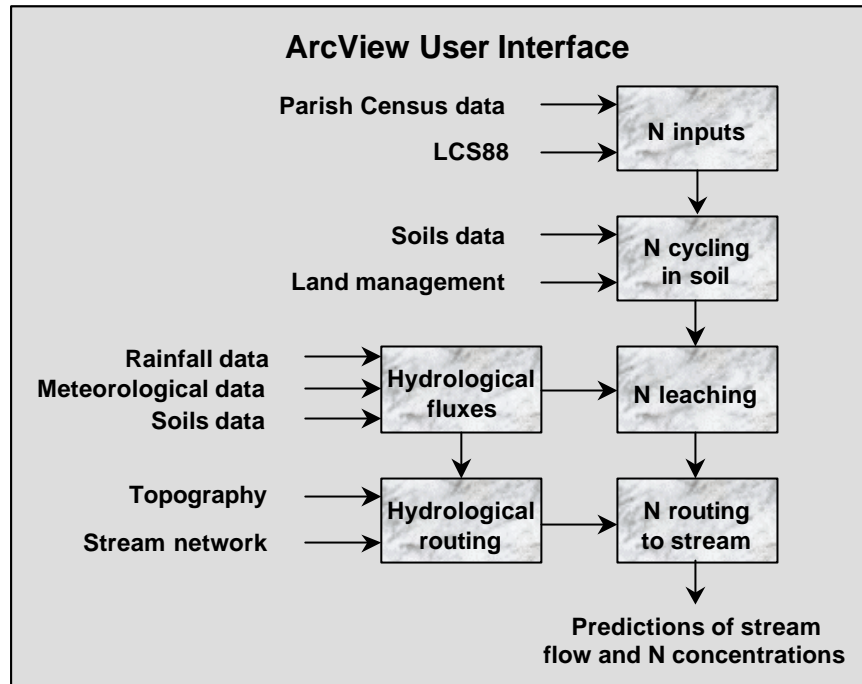
ArcView User Interface

Parish Census data → N inputs

LCS88 →

Soils data → N cycling in soil

Land management →

Rainfall data → Hydrological fluxes → N leaching

Meteorological data →

Soils data →

Topography → Hydrological routing → N routing to stream

Stream network →

↓

Predictions of stream flow and N concentrations

Figure 1. *Structure of the NIRAMS model*

LAND USE AND N INPUTS

Land use and crop management are the key controls on the amount of N input to the land and water in agricultural areas. They also determine the spatial distribution of inputs in a catchment, and the patterns of land use influence the manner in which organic wastes are spread on the land. Two core datasets are available in Scotland that can be used together in NIRAMS to represent agricultural land use in terms of N inputs. The Land Cover of Scotland (LCS88) dataset (MLURI, 1993) provides information on the spatial distribution of broad land cover types but does not specify which particular crops are grown on arable land. Crop rotations mean that the individual crops grown in a particular field vary from year to year, and there are regional differences in the proportion of crops within these rotations. The Agricultural and Horticultural Census data collected annually by the Scottish Executive for each 'Parish' administrative unit in Scotland provides a detailed summary of the areas of crops and numbers of livestock within each Parish. By combining these two datasets, information on the crop composition of the cultivated land as well as livestock densities and the age of grassland for mowing and grazing can be identified at the Parish scale.

Residual N

An input-output balance is used to estimate the excess N added to the soil over a growing season that will be available for leaching over the subsequent year. Actual leaching of this residual N is dependent on hydrological conditions. For arable crops, the residual N is estimated by:

$$N \text{ residual} = N \text{ fertiliser} + N \text{ organic waste} - N \text{ crop offtake} + N \text{ atmospheric} + N \text{ mineralisation} - N \text{ denitrification}$$

$$(1)$$

Figures for the various components of the balance were derived for different crops from a range of literature sources and experimental data and are described in detail in Dunn *et al*. (2002).

For grassland, typical actual N leaching was estimated using simulations with the SOILN model (Wu *et al*., 1998), for different drainage classes and under different grassland categories. The simulations were applied to a wet area in the south west of Scotland, where it is reasonable to assume that the actual N leaching approximates the residual N. Hence, the figures could be used as typical values of residual N applicable to other parts of Scotland.

Excess animal waste production, over and above the standard inputs to grassland, is also included in the N balance calculations. Estimates of the total N from wastes in each Parish are made using livestock numbers and N excretion rates. Excess waste is then allocated successively, up to specified levels, to different land use types until all the waste is accounted for at the Parish scale.

N Leaching

Actual leaching of residual N left towards the end of the growing season (leaching is assumed to begin by the end of August) is highly dependent on hydrological conditions. Within NIRAMS a simple exponential function, following Shaffer *et al*. (1994), has been used to describe N leaching. This function takes the form of:

$$NL_t = NAL_t \times (1 - \exp(-KNL \times (WAL_t / SATC))) \qquad (2)$$

where NL_t is the N leached at time t (kg ha^{-1}), NAL_t is the N available for leaching (kg ha^{-1}), KNL is the leaching coefficient (-), WAL_t is the water available for leaching (mm) and $SATC$ is the soil saturated capacity (mm).

NAL at the end of the growing season can be considered equivalent to the residual N. NAL is subsequently depleted with time as N is leached:

$$NAL_t = NAL_{t-1} - NL_{t-1} \qquad (3)$$

To determine the water available for leaching and also to enable calculations of transport at the catchment scale, a water balance model was integrated within NIRAMS. The water balance model is applied nationally at a resolution of 1km^2 and operates at a weekly time step. The model uses:

(1)   weekly precipitation spatially interpolated from daily raingauges covering the whole of Scotland (sourced from the NERC British Atmospheric Data Centre archive)

(2)   weekly evapotranspiration rates calculated from data from between 27 and 43 meteorological stations, depending on available data for different years

(3)   soil hydrological data defining values of water content at saturation and field capacity, derived by pedotransfer and applied to the 1:250,000 scale Scottish soil map

The water balance model also separates drainage fluxes into three components of runoff, corresponding to overland flow, sub-surface flow and groundwater flow. The relative proportions of each flow are dependent on the soil wetness. Overland flows are assumed to carry minimal N as the water has had little contact with the soil matrix.

N Transport

N that has been leached from the soil matrix by drainage water is transported in solution via different hydrological pathways to ground and surface waters. The principle objective of NIRAMS is to be able to predict stream N concentrations for any location in Scotland. In order to achieve this, the model is fully integrated within an ArcView User Interface. The user can select any point on the stream network to define their location of interest, and the NIRAMS transport model is then applied to the upstream catchment.

The N transport component of NIRAMS controls the routing of flows from any point on the land surface to the stream. The routing is carried out using a digital elevation model with a resolution of 50m. Overland flows are combined with sub-surface flows for routing purposes and the transport rate is assumed to be largely independent of the location within the catchment. The logic behind this is that the majority of the sub-surface water reaches the stream via some form of preferential pathway, such as agricultural drainage, soil macro-pores or rill flow. Its transport rate is therefore controlled mostly by the travel time to reach a preferential flow path (Dunn *et al*., 1998).

Groundwater flows are assumed to follow a Darcian type flow that is significantly controlled by the topography of the catchment. Slope analysis using the digital elevation model is used to control the transport rates for each 50m cell location within the catchment and route the flows to the stream network.

The initial conditions of the groundwater component are extremely important both in terms of N concentrations and the size of the groundwater store. NIRAMS uses initial conditions for groundwater N concentrations that have been derived from a previous study of groundwater nitrate contamination (Lilly *et al*., 2001). The size of the groundwater store is estimated for each 50m cell in the catchment using a function that takes account of its topographic location, as well as the base flow index (BFI) for the soil. The BFI gives an indication of the fraction of runoff that is generated by groundwater flow. The function used is:

$$GWS_0 = KIC \times BFI \times \frac{HSLD + (SLU \times ARU)}{HSLD^2} \qquad (4)$$

where KIC is a calibration parameter (m), BFI is the baseflow index for the soil, $HSLD$ is the hill slope from the cell to the stream (-), SLU is the slope into a cell from above (-) and ARU is the number of cells contributing to flow into a cell from above (-)

Integration of flow contributions at the catchment scale is determined by simple summation. The resulting output from NIRAMS is predictions of weekly averaged stream flows and N concentrations.

RESULTS AND DISCUSSION

National Scale

The water balance and N leaching model has been applied to the whole of Scotland for a period of five years from August 1989 – August 1994. Example results from this application are illustrated in Figure 2 for 1990. Figure 2(a) shows the calculated residual N following the 1990 growing season. Values for residual N in the north and west of Scotland are very low as there are very few agricultural inputs to the system. The greatest residual N values occur in the east where crops with large fertiliser inputs, such as winter crops and brassicas, and those with low N efficiency, such as fodder crops, are grown. There are also intensive livestock units in some areas. In some places the model has calculated extreme values of residual N. This occurs because of large excess wastes that have been produced in a small Parish. In practice, these wastes will be exported from the Parish to a neighbouring area, and the N inputs will be smoothed spatially. At the catchment scale, the effect of averaging should mean that the calculations of streamwater N concentration are not significantly affected by this error. Figure 2(b) shows the predicted actual amounts of N leached. It can be seen that the greatest leaching occurs in the areas with greatest residual N. However, Figure 2(c) highlights that the proportion of the residual N that is leached in some of the areas with greatest residual N, in the east of the country, is relatively low. This reflects the

strong trend in decreasing availability of water resources from west to east across Scotland. The excess of the residual N in the drier areas will be immobilised within the soil, but has the potential to result in gradual increases in N leaching over the longer term.
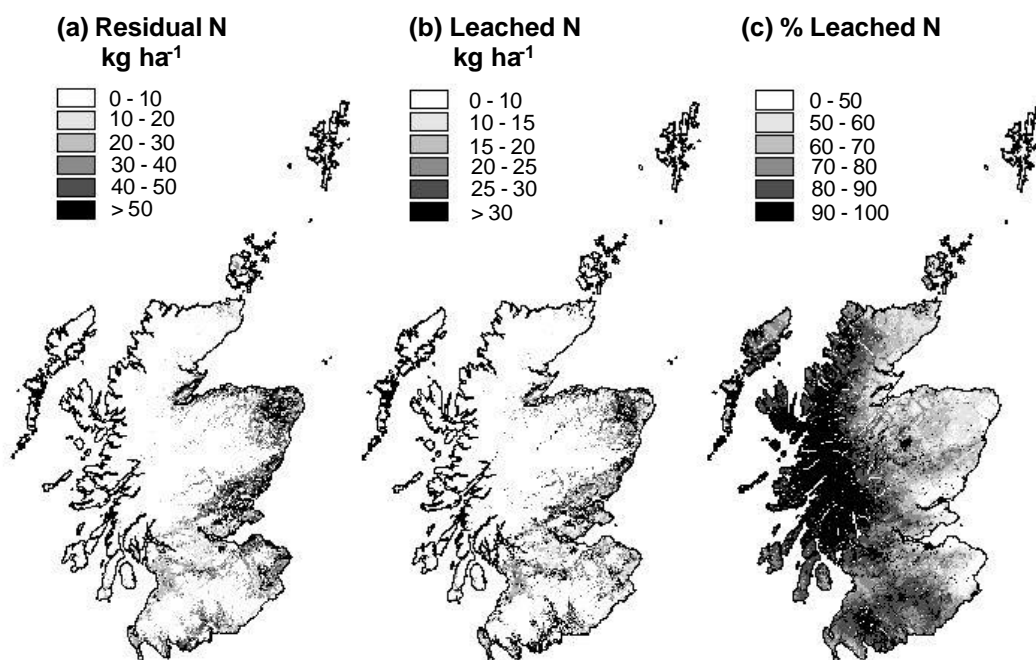

Figure 2. National scale predictions by NIRAMS for the year from Aug 1990 – Aug 1991 showing (a) residual N, (b) actual leached N and (c) proportion of residual N leached

Catchment Scale

The full NIRAMS model has been tested by application of the model to eight diverse catchments that are geographically distributed around Scotland. The physical characteristics of the catchments are summarised in Table 1.

Table 1: Summary of characteristics of NIRAMS test catchments

Catchment	Area km^2	Av. annual Rainfall (mm)	Elevation range (mean) in m.	% area arable land	% area improved pasture
Ythan	526	826	4-380 (107)	88	5
North Esk	740	1074	15-929 (313)	26	8
Earn	738	1397	7-979 (284)	24	6
Eden	318	799	9-520 (110)	75	5
Tyne	313	713	15-527 (175)	65	13
Urr	200	1340	2-423 (156)	0	48
Irvine	480	1228	1-383 (144)	0.4	66
Carron	149	2620	4-1043 (365)	0	1

Simulations were carried out for one year using historic data from August 1997 – August 1998 for calibration of the transport model parameters, and the model was then applied to a five-year period from 1989–1994. Values for the parameters were kept constant between the catchments in order to test the robustness of the model with respect to prediction in ungauged catchments. The results of the simulations for 1989–1994 are summarised in Table 2.

Table 2: Summary of predicted flows and N concentrations compared with measured data

Catchment	Efficiency of flow predictions	Calculated mean annual runoff (mm)	Measured mean annual runoff (mm)	CALCULATED MEAN TON CONC. (MGL^{-1})	MEASURED MEAN TON CONC. (MGL^{-1})
Ythan	0.69	298	370	7.3	7.1
N Esk	0.53	616	669	2.1	2.1
Earn	0.78	1102	1327	1.5	1.3
Eden	0.82	372	392	6.7	7.5
Tyne	0.63	306	282	5.0	5.2
Urr	0.86	952	932	1.4	1.9
Irvine	0.84	901	721	1.8	1.0
Carron	0.66	1786	2504	.13	N/A

The simulations of stream flow were generally very successful, both in terms of the shape of the hydrograph and the water budgets. Figure 3 shows example predictions and measurements of flow for the Tyne and Earn catchments. The separation into groundwater and sub-surface flow components appeared to be successful, with good prediction of baseflows as well as hydrograph peaks. The poorest water balance, for the Carron catchment, is due to simplifications within the rainfall interpolation procedures, which did not account for any precipitation–elevation weightings.
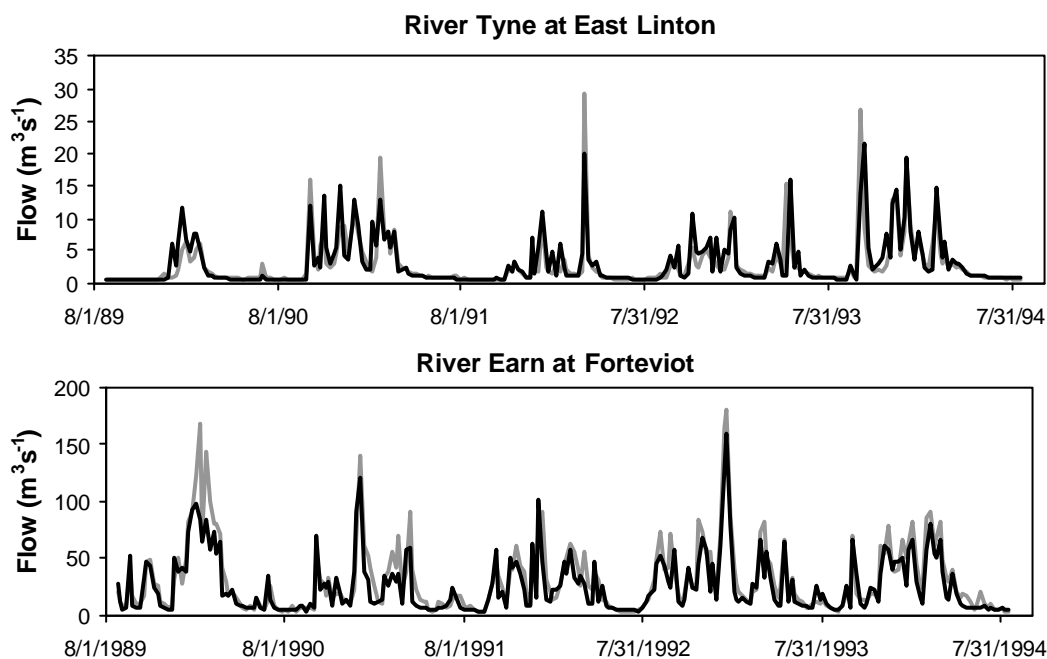

Figure 3. *Predictions of weekly streamflows (black lines) compared with measured flows (grey lines) for the Tyne and Earn catchments for 1989-1994*

The predictions of stream N concentrations also match the observed data very well in terms of their mean values. The time-series plots in Figure 4 demonstrate that the simulations are capable of reproducing the broad seasonal trends in variation of stream N concentrations, but there are some consistent differences between the predictions and observations. The weekly variability in N concentrations is modelled less effectively due to the simplifications of the NIRAMS model in terms of process representation and temporal resolution. However, the predicted range of N concentrations is reasonable and the model reproduces the general seasonal variability.

The test simulations have shown that acceptable results can be achieved on a range of very different catchments, without the need for re-calibration of parameters. Whilst fine-tuning of parameters could be used to improve individual simulations, the model can be applied to ungauged catchments or coastal gap areas with the confidence that an acceptable simulation will be achieved. Such applications are of value for general screening purposes, to identify where large streamwater N concentrations may occur, and hence focus more detailed monitoring or modelling studies in appropriate areas. This has been possible with NIRAMS because many of the controlling factors are implicit within the model. These factors include, for example, estimates of initial conditions for groundwater N concentrations and the use of the Base Flow Index and Standard Percentage Runoff statistics to calibrate parameters determining the relative flow proportions at different times.
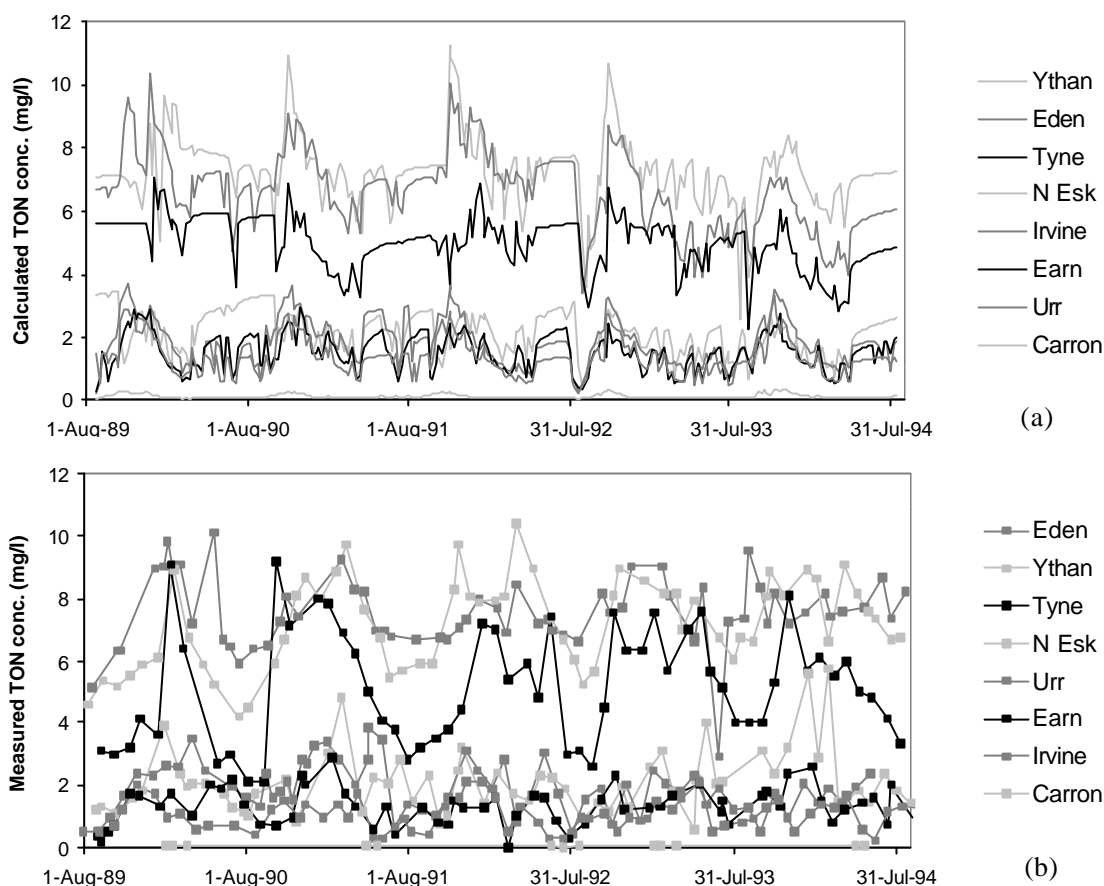
Figure 4. *Predicted (a) and measured (b) time-series of TON concentrations for 8 catchments for 1989-1994*

The modelling success also demonstrates that large scale N modelling can be carried out, with great simplification of N cycle processes, providing that the key transport processes are adequately represented within the model. However, at present, NIRAMS has limitations for long-term modelling in that it assumes a steady-state situation with respect to soil N content. The residual N available for leaching during the year is calculated on the basis of agricultural activities in the preceding season. In the drier parts of Scotland the leaching results showed that a substantial proportion of the residual N is retained within the soil and will contribute to a gradual increase in soil N stores. To adapt the model to study long-term changes in N it would be necessary to build in some aspects of the N cycle, notably mineralisation and immobilisation, to carry over unleached excess residual N from one years simulation to the next. Such modifications, should also help to improve prediction of the weekly variability in N concentrations.

CONCLUSIONS

A national scale model has been developed within a GIS system to predict streamwater N concentrations draining from agricultural land for any catchment area in Scotland. Predictions of weekly N leaching have been made for a five-year period from 1989 to 1994 and show that the greatest levels of leaching are associated with the areas of most intensive agriculture, but that the leaching in many of these areas is limited by hydrological conditions. Application of the full NIRAMS model to eight test catchments has confirmed that the model is capable of predicting average streamwater N concentrations in a range of very different catchments. Use of the same values for the calibration parameters in each catchment was found to give successful results, demonstrating the suitability of the model for application to ungauged areas.

ACKNOWLEDGEMENTS

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