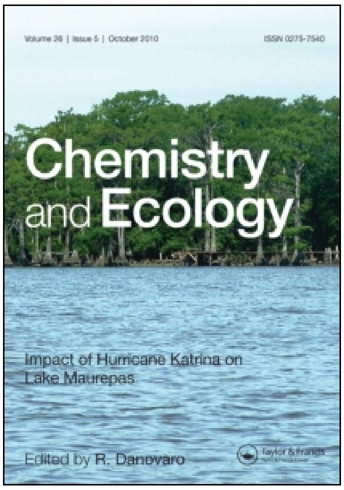

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NORTH EAST SCOTLAND RIVER CATCHMENT NITRATE LOADING IN RELATION TO AGRICULTURAL INTENSITY

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Modern agricultural practices have been strongly linked with increased NO_3-N loadings in surface waters. Nitrate leaching increases as land use progresses from forest and moorland through grassland, to arable agriculture. There are, within the UK, few studies on a regional scale capable of displaying a relationship between land cover (agricultural intensity) and water quality. This relationship can be investigated using computer manipulation of spatial geographic information together with conventional river and agricultural census data.

Simple regression analysis against primary land cover suggests that agriculture is reponsible for annual losses of nitrate in North East Scotland river catchments. Further multi-linear regression analysis, using the GIS data and agricultural census returns indicate that most of the outstanding variation can be accounted for if the agricultural variable is related to agricultural practice, such as spring, winter and grass cropping.

KEY WORDS: River Nitrate Loadings, Geographic Information Systems, Agriculture and North East Scotland.

INTRODUCTION

Amounts of nitrate (NO_3-N) in both ground (Foster *et al.*, 1986) and surface (ECETOC, 1988) waters have been increasing. Nitrate in surface waters has a variety of sources. Modern agricultural practice and in particular the marked increase in fertilizer-N usage, have been strongly linked with increased nitrate concentration in runoff. The world consumption of inorganic-N fertilizer has quadrupled during the last twenty years to over 80 million tonnes annually. Fertilizer N use in 'developed' countries has been reasonably constant during the last five years, while continuing to show a sharp rise in the 'developing' countries. Return of nitrogen to the land in animal manures and slurries is an additional major source of nitrogen.

While the harmful effects to man are not fully substantiated (Owen and Jurgens-Gschwind, 1986), excessive NO_3-N concentrations can either cause or aggravate problems connected with eutrophication of fresh waters (Stewart *et al.*, 1982) and can also represent an economic loss to the farmer. Recently, an EEC directive specified a 'maximum admissible concentration' of 11.3 mg nitrate-nitrogen per litre in drinking water and has also defined a target concentration of 5.65 mg NO_3-N per litre (EEC, 1980). In addition, guidelines are likely to be introduced regarding the loading (concentration x discharge) of nitrate entering the North Sea. Marine eutrophication is considered a major environmental issue for countries bordering the North Sea (UK-DoE, 1987).

Numerous investigations have shown that agriculture can influence nitrate levels in water (UK-DoE, 1979; UK-DoE, 1986 and ECETOC, 1988), but it has been difficult to attribute these effects to fertilizer use alone. Much of the early work on this subject indicated that land use or agriculture practice, rather than fertilizer use, were the major factors influencing nitrate loss to surface water (Haith, 1976; Haith and Dougherty, 1976). Various studies have examined the relationship between the land use and nitrate concentrations in isolated watersheds (Klepper, 1978; Edwards *et al.*, 1990). There are, however, within the UK, few studies on a regional scale (SSLRC/ITE, 1989) capable of elucidating the relationship between land cover (agricultural intensity) and water quality.

The purpose of this paper is to report an integrated study of conventional chemical river catchment analysis, and agricultural census returns, together with a computer technique for the manipulation of spatial geographic information (GIS) to investigate this problem. Computer manipulation of spatial map images allows the areal breakdown of land attributes within individual river catchments and sub-catchments.

NITROGEN AND AGRICULTURE

The relationship between leached nitrate and nitrogen applied is not straightforward. Soils contain substantial amounts of organically bound nitrogen. A number of factors affect the rate of release of nitrate from these organic sources and include soil type, temperature, moisture and management practices (Low, 1976; Jenkinson, 1982 and 1986). Additional inputs of nitrogen from atmospheric deposition and biological N fixation can also make significant contributions to the overall N budgets of natural ecosystems.

In general terms, the amount of nitrate leached from the soil is dependent on three main factors (UK-DoE, 1979). First, the water balance between rainfall received at a site, water lost in evapotranspiration from vegetation cover and the water holding capacity of the soil. Secondly, the quantity of nitrogen present in the soil either from natural sources or fertilizer input. Finally, the degree to which nitrogen is removed by the vegetation cover present at the site.

The importance of any single source of nitrogen will vary considerably over the study area. Aspects of the nitrogen cycle in the United Kingdom have recently been reviewed, atmospheric deposition (taken as 20 kg N/ha-yr) making a particularly important contribution to the overall nitrogen budget of upland areas (Batey, 1982). The importance of such variables as land cover and soil type on the potential for NO_3-N leaching is by no means clearly established (Ryden *et al.*, 1984; Gasser, 1982 and Kolenbrander, 1983). Nitrate leaching increases as land use changes from moorland through forest, and grassland to arable agriculture. It also varies with season, disturbance and site characteristics. In an individual heather or moorland plant community, there is a very little nitrate loss, of the order of 1 or 2 kg NO_3-N per ha-yr (Edwards *et al.*, 1985). Stevens and Hornung (1988) found that nitrate leaching could increase by six to ten times following clear felling of forestry.

On arable soils the greatest leaching losses occur during late autumn, winter and early spring following periods of reduced plant uptake, increased tillage and incomplete ground cover to intercept the nitrate released by mineralization or fertilizer application. During this time rainfall exceeds moisture losses by evaporation and transpiration. Arable land loses one third and grassland one tenth of the amount of nitrogen lost by fallow land into the drainage system (Low and

Armitage, 1970). An actively growing arable crop uses about 1 to 5 kg N/ha/year and thereby minimises nitrate being leached. Oakes *et al.*, (1981) reported a 200 kg N/ha loss from newly ploughed grassland, compared to 5 kg N/ha/day from a grass plot. Grassland management can have a considerable effect on leaching, with grazed swards showing greater losses than cut swards (Ryden *et al.*, 1984). Studies on non-recovery of fertilizer N have shown that 20 to 60 percent of that applied to various crop types is unaccounted for (Carey, 1985).

GEOGRAPHIC INFORMATION SYSTEM (GIS)

A Geographic Information System (GIS) is a method of storing and retrieving data which are held in a structured way, have locational identifiers, and can therefore be manipulated and mapped in a variety of ways (Aalders, 1980). When the processing of data is achieved by digital methods, a GIS is considered to be automated.

One of the main advantages of a GIS is that it enables machine overlaying of map information. Overlaying is a simple manual technique for extracting or comparing relevant information from a conventional paper map. Using the manual or conventional technique it is possible, for example, to extract all agricultural land below 300 metres (height OD), within a particular sub-catchment. The effort is proportional to the length and complexity of the lines followed. To repeat this procedure with one of these variables and a new parameter or both of them with two or more variables is clearly much more complex and time-consuming.

The digital computer technique represents maps as a numeric array and this allows the use of digital image classification techniques to compare two or more maps simultaneously. The approach is often termed 'masking', that is, comparing one map image within the constraints of another. This technique may be illustrated using regional (administrative) areas, sub-catchment and land cover data (Figure 1). In this way all pixel locations with identical regional digital numbers, within each sub-catchment with the same land cover type, can either be counted for area tabulation measurements or another 'map image' produced for further masking processes.

AREA OF STUDY

The study area, North East Scotland, lies mainly between the Moray Firth, Great Glen and the Tay estuary. The western and central catchments used in this study are dominated by the North East Grampian Highlands with its vast plateaux of the Cairngorm Mountains. To the north, north-east and south-east, the lowlands form the main arable belt in Scotland with major rivers flowing in a north-easterly or easterly direction

In general, the lowlands are fairly warm to warm and benefit from the shelter created by the mountain mass to the west. The growing season along the coastal lowlands decreases northwards as well as with altitude, but average 215 days from early April to early November. Annual average hours of bright sunshine in the lowlands are amongst the highest in Scotland, over 1300, and summer months have on average 170 hours. The bulk of the lowland area is subject to moderate winters without prolonged frost. Much of the rainfall is derived from the westerly airstream and is orographic, with the highest precipitation and number of rainy days occurring in the extreme south-west. Arable land in this part of the region often has over

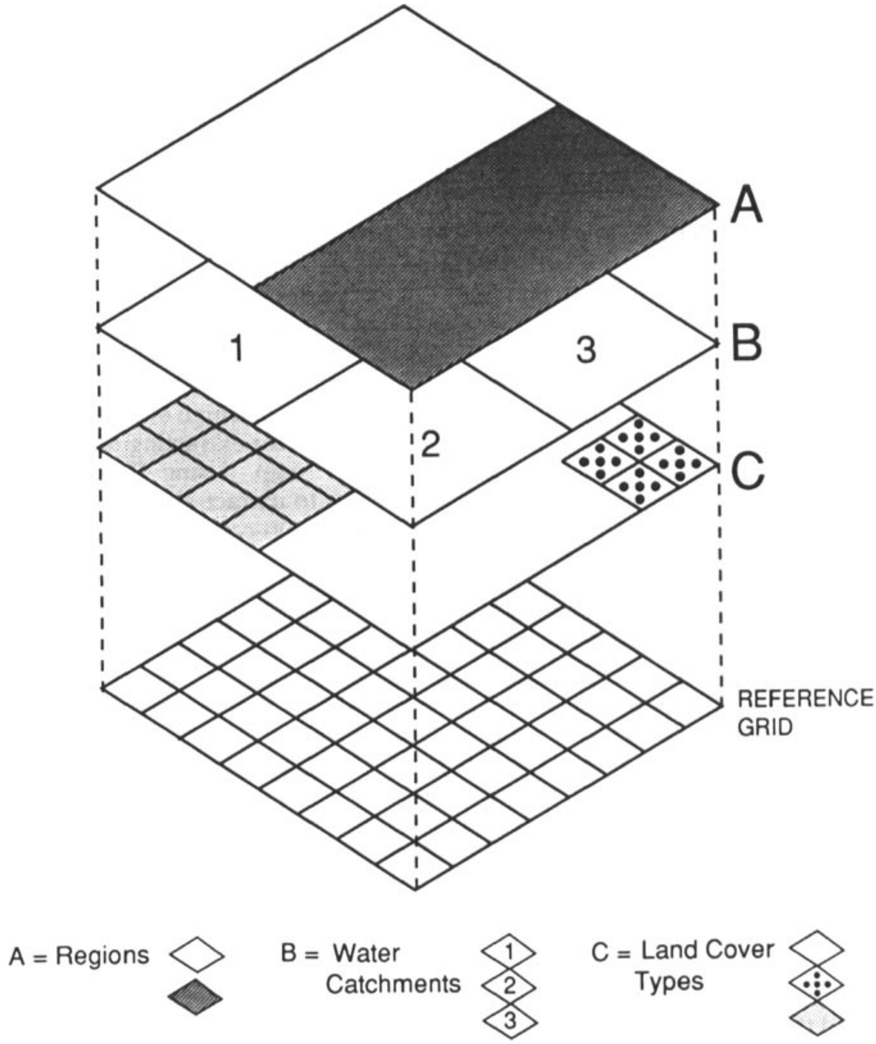


Figure 1 Simple multi-level "masking" or overlaying

460mm excess winter rainfall and field access may therefore be reduced to less than 140 days. The eastern areas are considerably drier and derive much of their precipitation from winds tracking across the North Sea. This combination of good climate, high agricultural productivity, ease of access and natural harbours has led to the historical development of many primary population centres in the coastal catchment.

The North East River Purification Board (NERPB) area is segmented into 9 coastal regions and 31 river catchments and sub-catchments. Flow data are obtained from 28 automatic and 16 daily read gauging stations. The Board also operate 400–450 water quality sampling points. Land cover information came from a spatial GIS developed for the Grampian Region, and NERPB areas outside the region were not included in the present study. Some Spey river sub-catchments within the test area have little or no agriculture, nor appropriate chemical and flow sample points at their outlets. Eleven main catchments and sub-catchments, 26 areas in all, together with their sampling stations, were finally used in the study (Figure 2).

DATA SOURCES

The analysis of the relationships between agricultural intensity and nitrate loss has involved the integration of satellite land cover classification, spatial map images, conventional point sampled chemical and flow data, together with parish agricultural census returns.

Chemical and Water Flow

Using annual flow data, 1980–1986, long-term average values were calculated (millions cubic metres per year). From corresponding monthly water quality sample data, an annual average, and then a long term average, concentration (mg/litre) for NO_3-N was obtained. The long-term flow, NO_3-N concentrations and "loads" (concentrations x volumes) for the 11 main river catchments are presented in Table 1.

Satellite and Map

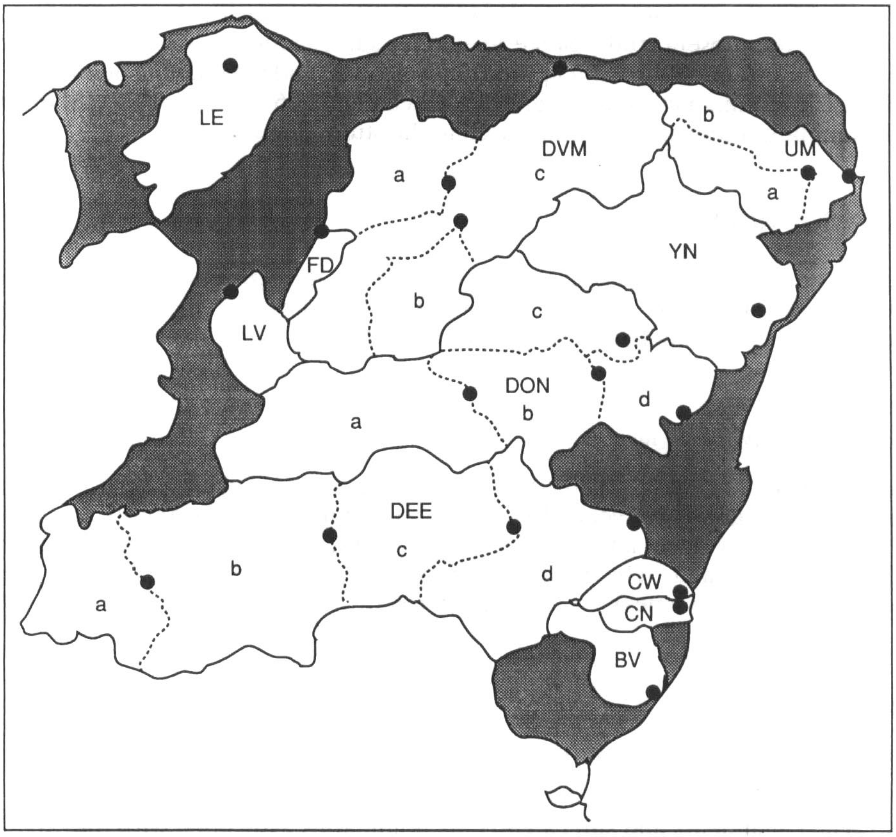
The following data sources were employed:

(i) *Catchments and sub-catchments*
The catchments and sub-catchments boundaries associated with the NERPB area were derived from 1:50,000 Ordnance Survey Landranger maps.

(ii) *Forestry*
Forest cover was obtained from a satellite classification using LANDSAT Thematic Mapper data to produce a spatial map image of forestry (distinguished as coniferous plantations, deciduous and mixed woodlands).

(iii) *Administration boundaries*
Parish boundaries were obtained from 1: 63,360 scale Ordance Survey maps. These are the administration units used by the Scottish Office Agriculture and Fisheries Department (SOAFD) to produce annual agricultural census statistics.

(iv) *Land cover*
No comprehensive land cover or agricultural intensity map is available. The Land Capability for Agriculture (LCA) maps (1:250,000) produced by the Soil Survey of Scotland (MISR, 1983a) provide an alternative. This series of maps separate land cover into two broad suitability categories together with built-up urban areas and inland water. The first of the categories, land suited to arable cropping, is separated into classes 1, 2, 3 and 4, depending on its potential to grow a variety of crops. The second category is land suited for improved grassland and rough grazing (classes 5, 6 and 7). From this map a measure of



● Gauging stations — catchments not included

CATCHMENTS (⬭ LE)

Lossie	(LE)	Deveron	(DVM)	Fiddich	(FD)	Livet	(LV)
Ugie	(UM)	Ythan	(YN)	Don	(DON)	Dee	(DEE)
Cowie	(CW)	Carron	(CN)	Bervie	(BV)		

SUB-CATCHMENTS (⬭ a)

Isla	(DVM a)	Bogie	(DVM b)	S Ugie	(UM a)	N Ugie	(UM b)
Don	(DON a)	Don	(DON b)	Don	(DON c)	Don	(DON d)
Don	(DON a + b)						
Dee	(DEE a)	Dee	(DEE b)	Dee	(DEE c)	Dee	(DEE d)
Dee	(DEE a + b)	Dee	(DEE a + b + c)				

Figure 2 NERPB catchments and sub-catchments in Grampian Region, together with sample points and flow stations

Table 1 Main river catchments, basic area, flow and NO_3-N concentration data.

Catchments and Subcatchments	*Area (ha)*	*Area Agric* (ha)*	*Area Non-agric† (ha)*	*Acidic Soils (ha)*	*Flow (MCum/y)*	*Conc NO_3-N (mg/l)*
Lossie (LE)	38300	21590	16710	10720	144.9	2.34
Deveron (DVM)	122970	85590	37380	11280	673.8	2.67
Fiddich (FD)	5690	1580	4110	3150	31.5	1.21
Livet (LV)	14360	3250	11110	3470	106.1	0.54
Ugie (UM)	34230	29420	4810	3590	153.9	4.13
Ythan (YN)	68390	65320	3070	890	377.4	5.31
Don (DON)	126710	81860	44850	4520	694.4	2.52
Dee (DEE)	182880	32690	150190	71380	1589.6	0.57
Cowie (CW)	7350	2090	5260	1270	37.5	1.47
Carron (CN)	4280	3420	860	4280	18.9	3.78
Bervie (BV)	13530	10770	2760	530	80.3	4.60
MEAN	56245	30690	25555	10460	355.3	2.65

* Area of spring crops, winter crops and grass

† Total area of catchment less agricultural area

agriculture, such as tillage crops and managed grassland, using category 1 (LCA classes 1 to 4), and hill (hill and upland) using category 2 (LCA classes 5 to 7) can be obtained.

(v) *Soil type — acidic soils*

From previous studies, the NO_3-N load differences between the Dee and Don catchments were thought to be associated with the area of acidic soils within the catchments (Edwards *et al.*, 1990). Using the 1:250,000 Soil map (MISR, 1983b) for Eastern Scotland, a map image was created separating soils into acidic and non-acidic groups.

(vi) *Rainfall*

For the test area, isohyets were digitised from the Meteorological Office (1941–1970) 1:625,000 Rainfall Map (Met. Off., 1975). Rainfall within the test area was subdivided into 16 bands across a range from less than 600mm to over 2,000mm.

Parish Agricultural Census

Using Scottish Office Agriculture and Fisheries Department (SOAFD) annual census returns, the areas of arable crops (spring and winter) and managed grass for all parishes within the NERPB test catchments were obtained. These area figures were then calibrated against the total area of agricultural land within the parish (obtained from the land capability map) and new catchment percentages obtained for all crops, spring crops, winter crops and grass.

MAP IMAGE PRODUCTION

The river sub-catchments, rainfall, soil acidity, administrative parish and land capability for agriculture (surrogate land cover) map overlays were manually digitized (vector format) using high resolution Summagraphics and Ferranti

Freescan flatbed digitizing tablets. The cursor positions were converted to map coordinates using the map corners as reference points and stored along with identifying feature codes in a digital map file (Benny, 1980).

All vector format map files were then converted to produce a representation of the maps as a spatial image (raster format) by an algorithm that calculated the cells that a stored vector would pass through. The corresponding pixels in the image were set to a specific value S ($0<S>255$). A 50×50 metre picture element (pixel) or cell size was adopted for all raster format map files, giving a pixel area of 0.25ha.

To function as a spatial (raster format) GIS, it was necessary that all pixels within a polygon boundary have the same identifying value as the original map line feature code. This was produced by 'seeding' the raster line file polygons with the feature code value for each sub-catchment, administrative area and land cover type and then machine polygon filling.

GIS INTEGRATION OF DATA

In the first instance the areas of catchments and sub-catchments were obtained from the spatial geographic data (GIS). Using these areas together with concentrations and flow data, the total NO_3-N load (tonnes) and NO_3-N losses (kg/ha) were calculated for each catchment and sub-catchment (Table 2, main rivers only). Primary cover data for each sub-catchment was obtained from a combined overlay analysis (as example, Figure 1) of NERPB catchment, rainfall, land capability for agriculture (LCA), soil acidity group and a LANDSAT Thematic Mapper satellite

Table 2 Main river catchment NO_3-N load and loss analysis.

Catchments and Subcatchments	*Non-agric† NO_3-N Load (Tonnes/year)*	*Agric* NO_3-N Load (Tonnes/year)*	*Total NO_3-N Load (Tonnes/year)*	*Overall Loss (kg/ha)*	*Agric° Loss (kg/ha)*
Lossie (LE)	27.6	311.4	339.0	8.85	14.42
Deveron (DVM)	61.7	1737.3	1799.0	14.63	20.30
Fiddich (FD)	6.8	31.3	38.1	6.70	19.86
Livet (LV)	18.3	39.0	57.3	3.99	11.98
Ugie (UM)	7.9	627.7	635.6	18.57	21.34
Ythan (YN)	5.1	1998.7	2003.8	29.30	30.60
Don (DON)	74.0	1675.9	1749.9	13.81	20.47
Dee (DEE)	247.8	658.3	906.1	4.95	20.14
Cowie (CW)	8.7	46.4	55.1	7.50	22.26
Carron (CN)	1.4	69.9	71.3	16.65	20.41
Bervie (BV)	4.6	364.6	369.2	27.29	33.86
MEAN	42.2	687.3	729.5	13.84	22.40

* Total load less non-agricultural load

† Non-agricultural area, times 1.66 kg/ha loss (estimated hill loss)

° Agricultural load divided by agricultural area

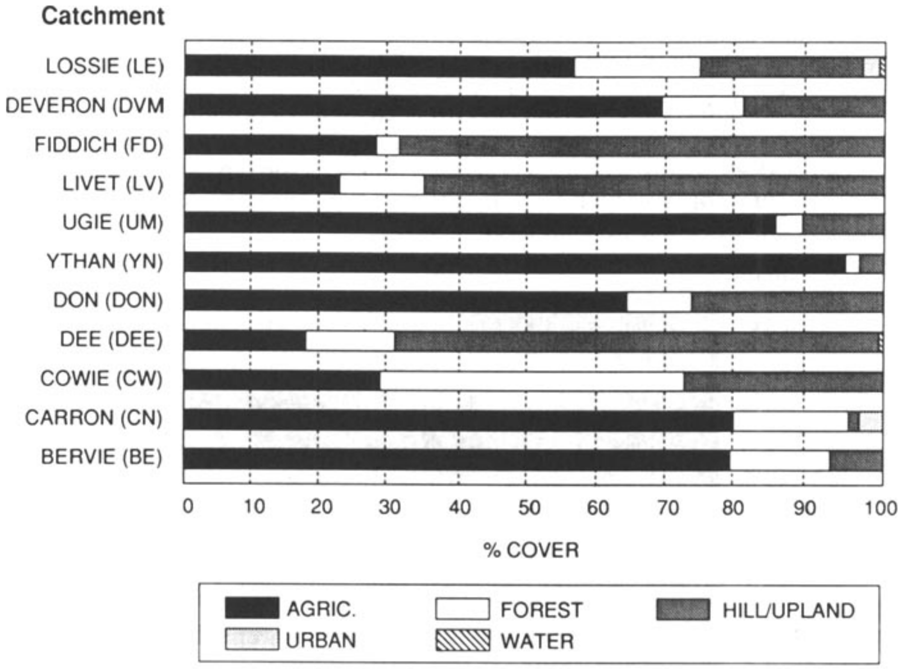


Figure 3 Distribution of land cover in main catchments

classification of forestry. This analysis provided the primary land cover (Figure 3, main rivers only) areas for:

(i) Agriculture = (LCA 2, 3 and 4) – (area under forestry)
(ii) Hill (and upland) = (LCA 5, 6 and 7) – (area under forestry)
(iii) Forestry (areas greater than 2ha)
(iv) Urban zones
(v) Inland water
(vi) Rainfall, cubic metres/ha-yr (also the volume of water per catchment, million cubic metres/sq km-year)
(vii) Acidic soils (area and percentage within each catchment).

By overlaying LCA, rainfall and soil acidity digital map images, agricultural land (arable and managed grassland), hill/upland, total rainfall, inland water bodies and acid soil area values were obtained for each catchment and sub-catchment. Using the agricultural census data, the percentages of all tillage, spring and winter crops, together with managed grass, was calculated from the returns for each parish. The agriculture image resulting from the above combinations was further segmented with a parish map image, so that the area of agriculture within each parish, catchment and sub-catchment could be obtained. From this GIS, conventional river analysis and flow data, agricultural and non-agricultural NO_3-N loads, overall and agricultural NO_3-N losses were calculated (Table 2).

The percentages of all arable (tillage) spring and winter crops, together with managed grass, were derived from agricultural census data. To obtain the total area of these crop types within each parish, these figures were normalised against the area of agricultural land in each parish. Within each catchment and sub-catchment, the parish fractions of these crop areas were combined to give an estimate of the percentage spring crops, winter crops and managed grass (Figure 4, main rivers only). In the present context, fertilizer N for each area is a primary interest. Typical application rates for spring crops, winter crops and grass are 95, 205 and 125 kg N/ha, respectively (SFPS, 1986). The total N applied for each crop type has been calculated using these values together with the relevant crop type area data for each catchment and sub-catchment (Table 3, main rivers only).

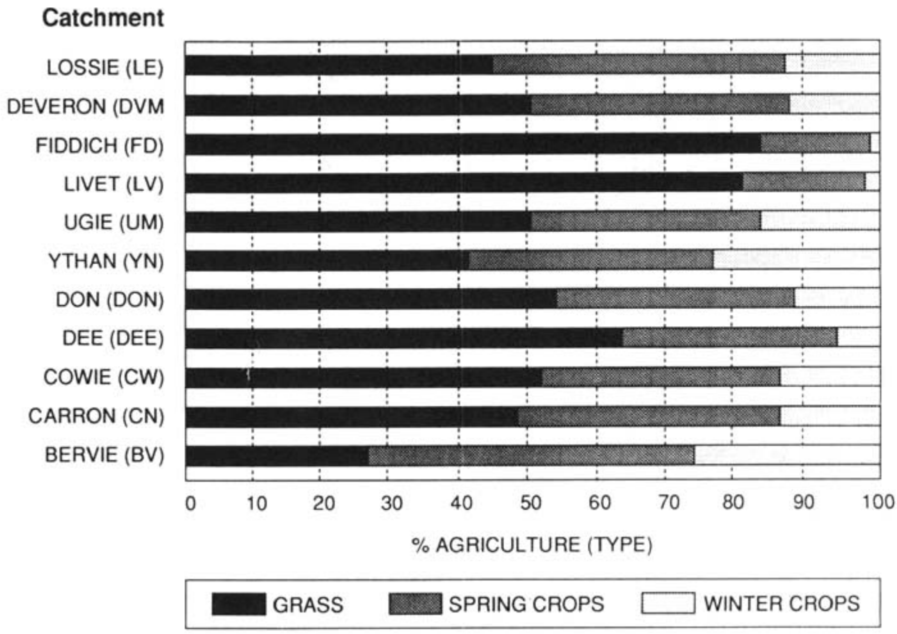


Figure 4 Distribution of agriculture in main catchments

Table 3 Main river catchment fertilizer N applications according to crop type.

Catchments and Subcatchments	*Total Fertilizer N applied (Tonnes/year)*				
	Spring Crops (I)	*Winter Crops (II)*	*Grass (III)*	*Arable (I+II)*	*All N (I+II+III)*
Lossie (LE)	864.9	612.6	1187.2	1477.5	2664.7
Deveron (DVM)	3028.9	2237.1	5349.4	5266.0	10615.4
Fiddich (FD)	25.5	3.3	161.7	28.8	190.5
Livet (LV)	55.6	12.3	326.1	67.9	394.0
Ugie (UM)	922.6	1025.3	1838.4	1947.9	3786.3
Ythan (YN)	2194.2	3165.5	3347.6	5359.7	8707.3
Don (DON)	2714.0	2030.5	5423.1	4744.5	10167.6
Dee (DEE)	962.6	402.0	2574.0	1364.6	3938.6
Cowie (CW)	69.3	59.9	133.0	129.2	262.2
Carron (CN)	123.6	98.2	205.4	221.8	427.2
Bervie (BV)	481.0	595.9	350.1	1076.9	1427.0
MEAN	1040.2	931.1	1899.6	1971.3	3870.9

REGRESSION ANALYSIS

Statistical analysis was performed using MINITAB 6.1.1 software package operating on a VAX computer (Ryan *et al.*, 1985). Statistical advice suggested that preliminary regression analysis should be performed against NO_3-N catchment loads, thus reducing bias due to irregularities in catchment area, rainfall or flow characteristics. Land cover data used in the regression models were areas (hectares) and not percentages, further reducing catchment bias.

Many single predictor and stepwise multi-predictor models were examined, using both total NO_3-N load (TN) and agricultural NO_3-N load (AGN), expressed as tonnes per year. The term catchment has been used to describe both main and sub-catchments. A measure of the accuracy of each equation is given as a coefficient of variation (CV); this is the standard deviation of a predicted value as a percentage of the mean value of all samples used in the dataset. For the catchments under examination, no significant role was found for "Urban" or "Inland" water bodies. The most significant single regressions for these categories were: NO_3-N load in tonnes/year; "Cover types", in hectares; "N applied", in tonnes/year.

Land Use and Nitrate Loss Relationships

A stepwise regression on all primary land cover data (no separation of agricultural type) indicated that the area under agriculture was indeed the most significant land cover parameter responsible for total NO_3-N load (TN) within mixed land cover catchments.

(1) TN = 0.0228 (Agriculture)
($r^2 = 0.9220$, $df = 25$, $p < 0.001$, $CV \pm 29.3\%$)

(2) TN = 0.0254 (Agriculture) - 0.0286 (Forest) + 0.00452 (Hill)
($r^2 = 0.9420$, $df = 25$, $p < 0.001$, $CV \pm 27.2\%$)

The non-agricultural NO_3-N loss was taken as 1.66 kg/ha-year, a value taken from an upland dominated (99.4%) subcatchment of the river Dee. When multiplied by the area of non-agricultural land (forest and hill) within a catchment and subtracted from the TN value, AGN could be estimated and regressions established:

(3) AGN = 0.0216 (Agriculture)
($r^2 = 0.9158$, $df = 25$, $p < 0.001$, $CV \pm 31.6\%$)

The relationships were examined further using all separations of agricultural land cover:

(4) TN = 0.0564 (Arable) + 0.00293 (Hill) - 0.0127 (Grass)
($r^2 = 0.9710$, $df = 25$, $p < 0.001$, $CV \pm 19.2\%$)

(5) TN = 0.0212 (Spring crops) + 0.00270 (Hill + Forest)
($r^2 = 0.9820$, $df = 25$, $p < 0.001$, $CV \pm 15.4\%$)

(6) AGN = 0.0518 (Arable) + 0.00748 (Grass)
($r^2 = 0.9676$, $df = 25$, $p < 0.001$, $CV \pm 19.8\%$)

(7) AGN = 0.0285 (Spring crops) + 0.829 (Winter crops)
($r^2 = 0.9770$, $df = 25$, $p < 0.001$, $CV \pm 16.7\%$)

Then nitrogen applied as fertilizer is included for all agricultural, arable, grass, spring crops and winter crops within the catchments:

(8) TN = 0.698 ([Spring crops + Grass crop] N applied) + 0.503 ([Winter crops] N applied) + 0.00240 (Forest and Hill area)
(r^2 = 0.9835, df = 25, p < 0.001, CV ± 14.7%)

(9) AGN = 0.0868 ([Spring crops + Grass crop] N applied) + 0.464 (Winter crops N applied)
(r^2 = 0.9806, df = 25, p < 0.001, CV ± 15.2%)

The assumption that a 1.66 kg/ha-year NO_3-N loss for an upland catchment may be justified. According to recent work on critical loads for nitrogen, 1 to 2 kg leaching losses per ha may also be expected from production forests (Nilsson and Grennfelt, 1988). However, in a large catchment with a high proportion of hill and forest cover, this component may provide a more significant contribution to the total load. A general purpose regression equation was therefore required using total NO_3-N load (equation 8). Within the context of this regional study, the regression, justified the combining of hill and forest cover in earlier equations. The NO_3-N loads predicted from the above regression, and their 95 percent confidence limits, were compared with actual NO_3-N loads (Figure 5).

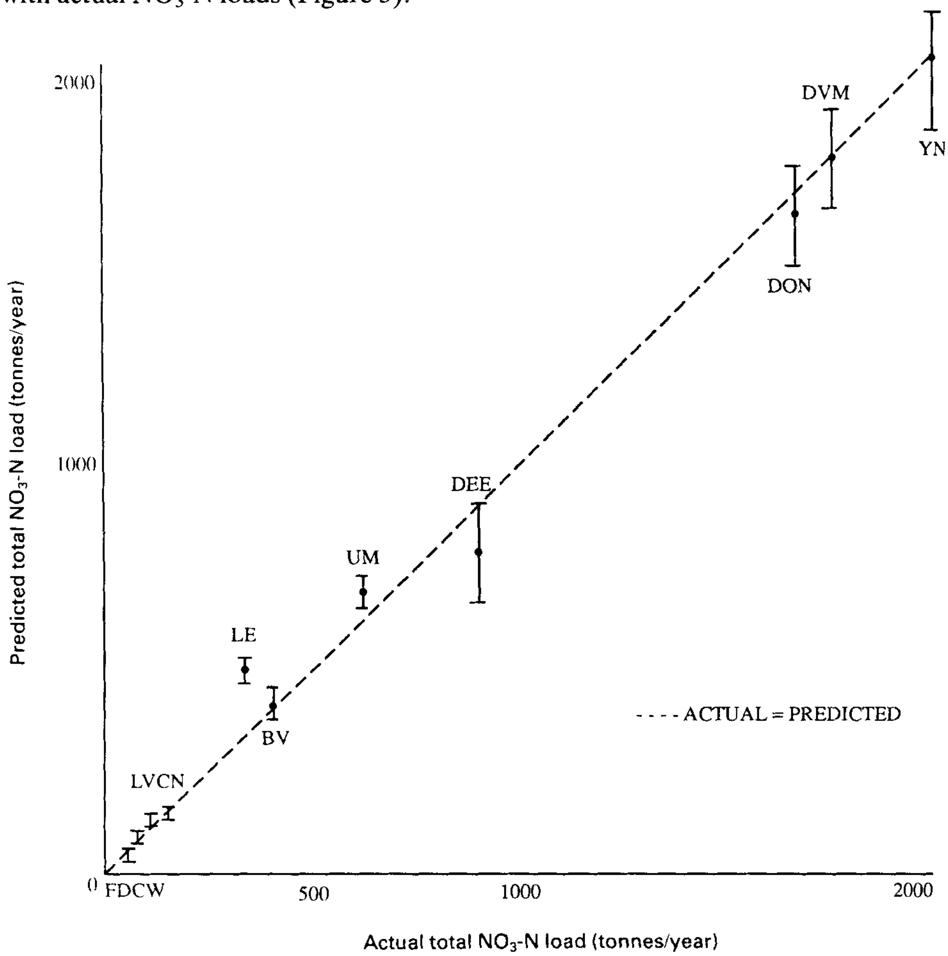


Figure 5 Comparison of actual NO_3-N loadings and predicted values for main river catchments

River Water NO_3-N Concentrations

The above equations provide a means of estimating the total NO_3-N load or potential NO_3-N load entering these primary or secondary river systems. Stepwise multi-linear regressions for NO_3-N concentration (mg/1) were performed to find a satisfactory regression that estimated the potential concentration in river water. From the GIS data, the mean rainfall volume (cubic metres/ha-year) for each catchment was available, as well as total volume of water entering the catchment (million m^3/km^2-yr). The following regression produced the best fit, with the smallest CV on predicted values:

(10) NO_3-N (mg/1) = 10.7 + 0.00253 (TN load [tonnes/year]) + 0.00594 (Area acidic soils [km^2]) – 0.0775 (Rainfall [million m^3/km^2-year]) – 0.00426 (Catchment area [km^2])
($r^2 = 0.863$, $df = 22$, $p < 0.001$, $CV \pm 30.3\%$)

From the total NO_3-N loads predicted by equation (8), the expected mean NO_3-N concentrations (mg/1) in the river systems were estimated using equation (10). A comparison of the expected and actual values for the main catchments is presented in Figure 6, together with the correlation and 95 percent confidence limits on the predictions.

DISCUSSION

Catchment Distribution of Land Cover

Examination of the category of land use within the study area of approximately 6395 km^2 showed that slightly more than half, 54%, is classified as agricultural. Some 34% is hill/upland and the remaining 12% afforested, with less than 1 percent urban and water. A similar division on the catchment or sub-catchment scale shows a range for agricultural use of <1 to over 95%, hill/upland area <2 to over 99% and forestry falling between 2 and 44% (Figure 3). These substantial differences in land use over a relatively small area confirm the suitability of the region for the present investigation.

A considerable variety of land management practice (fertilizer rates and timing of tillage operations) likely to influence NO_3-N leaching is possible within the rather broad land use categories already discussed. The amounts and timing of fertilizer N additions for winter sown crops are double (205 kg N/ha) the amounts applied to spring crops (95 kg N/ha) and managed grass (125 kg N/ha). A further division using agricultural census data was therefore necessary. The areas of managed grass and tillage crops (dominated by spring sowing) on agricultural land are very similar (Figure 4). The choice of sowing arable crops in NE Scotland has considerable dependence on climatic factors with the importance of winter crops being greater in coastal areas. The variety of cropping practice in the individual catchment and sub-catchment areas is again substantial. As would be expected, grassland dominates the upland areas (in particular, the Fiddich, Livet and upper Dee catchments).

River NO_3-N Loading and Catchment Losses

There is a wide range in NO_3-N loads, whether expressed as a total annual figure for each river (38–2003 tonnes/year) or on loss per unit area basis for each catchment

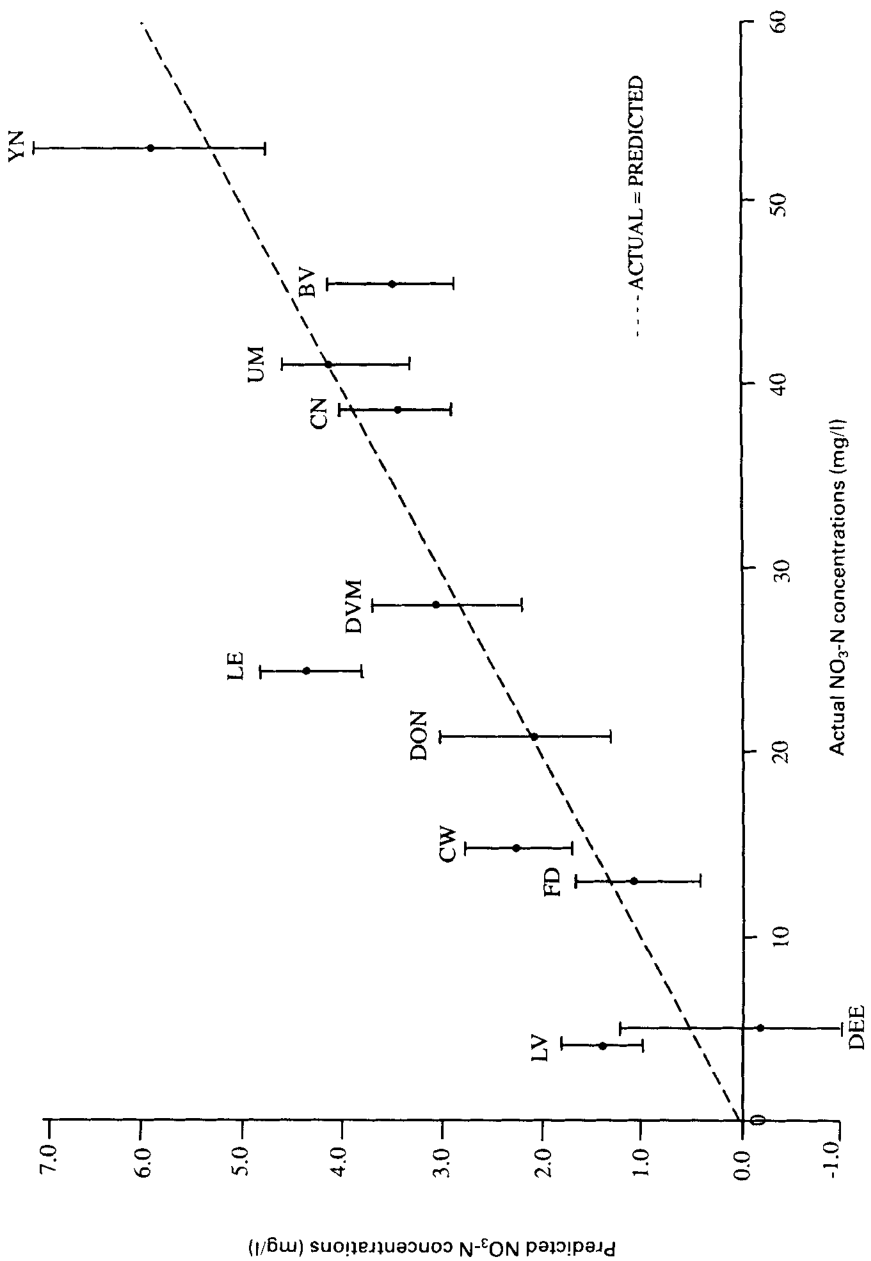


Figure 6 Comparison of actual river NO_3-N concentration and predicted values for main river catchments.

(1.66–29.3 kg NO_3-N/ha) (Table 2). With a substantial variety of land use between sub-catchments, the calculation of losses solely from agricultural land is possible. A figure of 1.66 kg NO_3-N/ha for Dee sub-catchment (a) represents 98.2% hill and 1.2% forestry. When this value is subtracted from the total NO_3-N load for each individual catchment, the amount remaining (0.6–1999 tonnes/year) represents the contribution from agricultural land (Table 2), with a range from 0.30 to 33.86 kg/ha. This range must, in part, reflect the differences in the proportions of crop, in particular spring crop, winter crop and grassland within the catchment.

Nitrate contributions from forest and hill areas may be higher (equation 8, 2.40 kg/ha-year) than the original estimate of 1.66 kg/ha-year taken from Dee sub-catchment (a). The soil types here are dominated by N-deficient organic coarse textured soils which may not be true for other north-east upland catchments. However, none of the regressions for NO_3-N loading showed a significant component for acidic soils. Acidic soil areas used in the regressions were whole catchment values and not segmented into agricultural and non-agricultural components. The total NO_3-N load regression (equation 8) was therefore regarded as a more reliable measure of catchment NO_3-N losses.

River Water NO_3-N Concentrations

The prediction of river water NO_3-N concentrations was less accurate, with the best fit regression having a large coefficient of variation. The most significant components in equation 10 were the rainfall and catchment area, i.e., the volume of water entering the catchment. Total NO_3-N load was the next most significant component, with the acidic soil values only significant with the constant in the equation. The importance of the water volume terms may reflect a contribution from soil texture or more likely, infiltration or runoff, rather than acidic soil.

The amount of NO_3-N available for leaching is dependent upon the complex interaction of the numerous biological, hydrological and climatic processes. For example, the predicted NO_3-N concentration for the Lossie catchment was considerably more than the actual value (Figure 6). This catchment has for many years had a weed infestation problem in the lower reaches of the river, resulting in reduction of NO_3-N in the water. Other variation could be explained by local differences in levels of fertilizer applied because of crop or soil types. This is particularly true of the Bervie, which has an actual value greater than predicted. Arable cropping dominates this catchment and winter oilseed rape in particular, a crop often receiving more than 270 kg N/ha. The combined result is a marked variation in monthly river NO_3-N concentrations, resulting in a high coefficient of variation for long term averages. For the South Ugie, average NO_3-N concentration is 1.21 mg/l ± 13%, but variation in the Don figures is much greater, 0.57 mg/1 ± 60%.

Using long term averages (1980–1986) in the NO_3-N loading regressions gives a more accurate prediction, as it overcomes the possible effect of crop rotations within a catchment, which vary on an annual basis. The long term averages dominate the regression producing large numbers (e.g. rainfall; million m^3), while the concentrations we are trying to predict are small (mg/l) with a wide daily variation. To improve this prediction, the monthly rainfall variation must be separated, as well as estimation of the soil type infiltration or runoff variation within a catchment.

CONCLUSIONS

The data presented were taken from a variety of conventional surveys as well as maps of varying scales and had not been specifically collected with the present study in mind. For this reason the data are not as comprehensive as the authors might have wished and are limited to defining the empirical relationships between NO_3-N status and land cover attributes. It does, however, bring together a unique blend and wide ranging type of information, illustrating the future potential of developing a more complex model with GIS data.

A predictive relationship between agricultural intensity and long term average nitrate losses within North-East Scotland river catchments has been established. This relationship will enable preliminary predictions of nitrate sensitive areas to be made, but some variation remains to be explained. The results, so far, indicate that this variation is related to soil type or factors such as texture and permeability, as well as to agricultural practice (spring, winter and grass farming) and seasonal rainfall effects.

River NO_3-N concentrations downstream appear to be directly related to an overall increase in agricultural productivity and intensity. Simple regression analysis against primary land cover suggested that agriculture accounted for the majority (91%, CV$\pm$31.6%) of annual nitrate losses in North-East Scotland river catchments. Rainfall variation across this regions is small and discharge tends to be closely related to catchment area. There is therefore, a direct relationship between agriculture and catchment annual mean $N0_3$–N concentration in river waters (Figure 7).

There are, however, significant differences in NO_3-N losses between catchments of similar agricultural intensity. Most of the outstanding variation could be accounted for if the GIS agriculture variable was segmented into arable and grass crops (97%, CV$\pm$19.8%) or fertilizer N applied to spring, grass and winter crops (98%, CV$\pm$15.2%). The Bervie has some 80% of its catchment under agriculture, with nitrate loss of 34 kg N/ha-year, whereas the Ugie has 86% of its catchment under agriculture but only 21 kg N/ha-year nitrate loss. Agricultural land within the Ugie catchment is dominated by grassland (50%) and has only a small area (17%) in winter crops with high inputs of fertilizer N. The Bervie on the other hand has less grassland (26%) with almost half (47%) of the catchment given over to winter crops.

There is a considerable range in mean river NO_3-N concentrations (0.12–5.31 mg/l) over the whole study area, even in N-deficient upland catchments. Multi-linear regression analysis indicated long term river water NO_3-N concentrations could be explained by catchment area, acidic soil type, rainfall and total NO_3-N load (86%, CV$\pm$30%). It is believed that the accuracy of these predictions could be improved if monthly rainfall and soil infiltration or runoff variation were included in the regression model.

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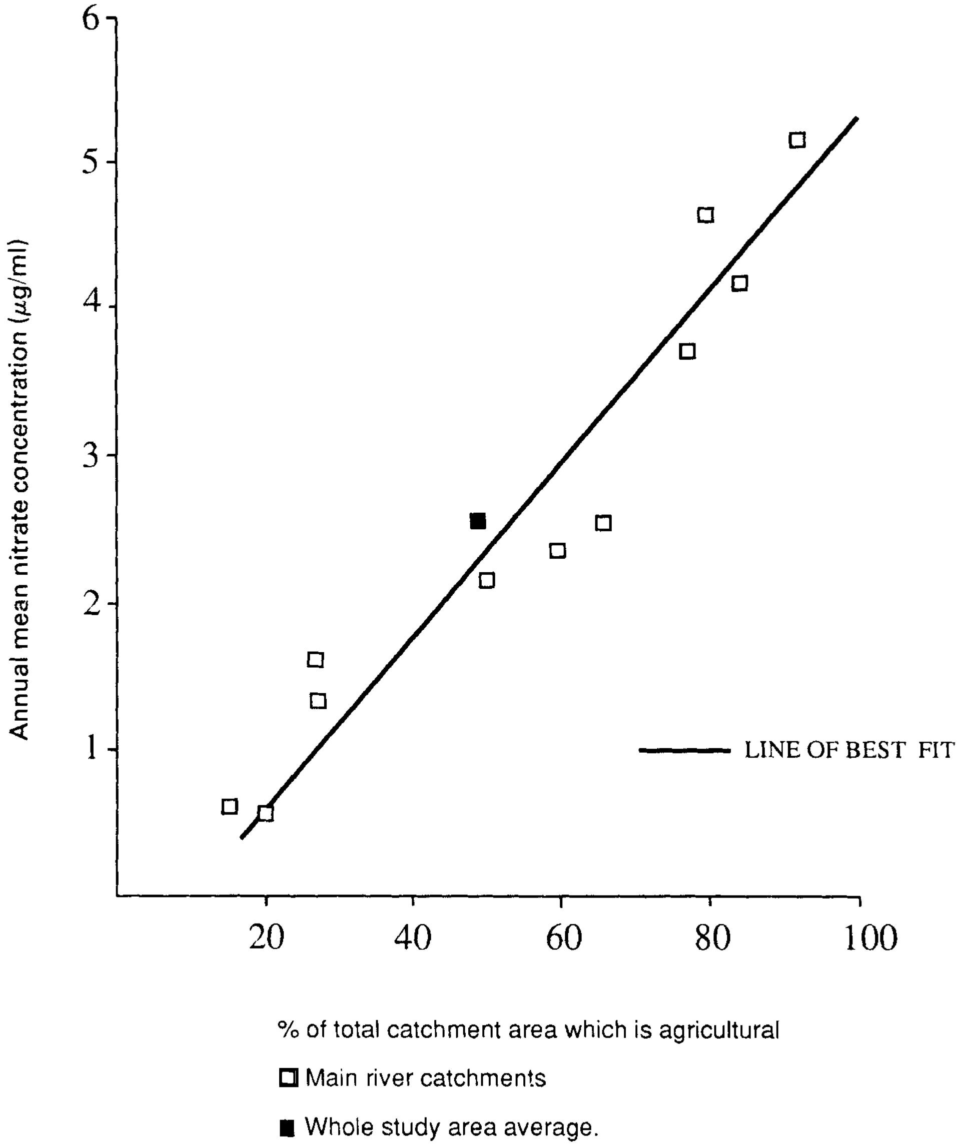

Figure 7 Catchment agricultural area and mean annual river nitrate concentrations

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