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STREAM WATER QUALITY AND NUTRIENT EXPORT IN THE SLAPTON CATCHMENTS

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ABSTRACT

A weekly programme of water quality monitoring has been conducted by Slapton Ley Field Centre since 1970. Samples have been collected for the four main streams draining into Slapton Ley, from the Ley itself and from other sites within the catchment. On occasions, more frequent sampling has been undertaken during short-term research projects, usually in relation to nutrient export from the catchment. These water quality data, unparalleled in length for a series of small drainage basins in the British Isles, provide a unique resource for analysis of spatial and temporal variations in stream water quality within an agricultural area. Not surprisingly, given the eutrophic status of the Ley, most attention has focused on the nutrients nitrate and phosphate. A number of approaches to modelling nutrient loss have been attempted, including time series analysis and the application of nutrient export and physically based models.

INTRODUCTION

There was concern in the 1960s that Slapton Ley was becoming increasingly eutrophic. In order to be able to quantify inputs of water, sediment and nutrients into the lake, a programme of continuous discharge measurement and weekly water quality monitoring was initiated in 1969 on the four streams which drain into the Ley. These water quality data, unparalleled in length for a series of small, rural drainage basins in the British Isles, provide a unique foundation for analysis of spatial and temporal variations in stream water quality within an agricultural area. The information has allowed researchers to monitor the changing patterns of nutrient input to the lake, providing some answers to the original questions posed and providing a basis for answering new questions, not anticipated when the study was begun. Long data sets allow slow, subtle changes in environmental systems to be investigated and ensure that rare events are not missed. By definition, monitoring programmes should give warning of untoward events (Burt, 1993); this has certainly been the case in relation to nutrient pollution and has led directly to research projects and management proposals to deal with this issue.

The importance of examining the different hydrological pathways of nutrient and sediment loss in the Slapton catchments has been recognised in several studies (e.g. Burt *et al.*, 1983; Heathwaite, 1995). At Slapton, a large proportion of runoff reaching streams arrives as subsurface flow (Burt & Arkell, 1987). Surface runoff is not an important source of nutrients except where catchment topography and land management practices coincide to create variable source areas of considerable nutrient export (see Burt & Heathwaite, 1996b); by contrast, surface runoff may be one of the main sources for suspended sediment in streamflow. In order to understand better the delivery of solutes and sediment to the stream system, a series of experimental studies have been conducted. These have sought to link runoff processes to the loss of sediment and nutrients from the catchment hillslopes. Most attention has been paid to nitrate, and to a lesser extent, phosphate (e.g. Heathwaite *et al.,* 1990a; 1990b). Soil erosion and sediment delivery have also received considerable attention in recent years (Heathwaite & Burt, 1992; Foster, Owens & Walling, 1996). Burt & Heathwaite (1993) emphasised the scale-dependent approach adopted in these studies, whereby small plot and hillslope studies have been nested within the small catchment research. Studies of nitrate transport exist at all these scales, but no work on phosphate has been carried out at the hillslope scale. Information concerning potassium is completely lacking at present; work is currently in hand to rectify this gap (Stott, in prep.). Heathwaite *et al.* (1990a, 1990b) used a rainfall simulator to examine nutrient export in runoff from small plots on different land uses. The magnitude of surface runoff from overgrazed permanent pasture was found to be double that from lightly grazed areas. Additionally, the removal of vegetation cover through severe poaching led to an increase in the rate of suspended sediment, total nitrogen and total phosphorus delivery in surface runoff by 30, 9 and 16 times respectively. Over 90% of the total nitrogen was in inorganic form as ammonium, whereas over 80% of the phosphorus loss was in organic form. The study of Heathwaite *et al.* (1990a, 1990b) and that of Johnes & Heathwaite (1996) both suggested the importance of riparian areas as major sources of sediment and solutes at Slapton, given their widespread and heavy use for grazing. There have been no lysimeter studies at Slapton but Coles & Trudgill (1985) used unbounded plots to study nitrate leaching. Even the weakly structured silty loam soils produce preferential flow down macropores. This could prove an important mechanism whereby surface-applied fertilisers and pesticides might bypass the soil profile and move rapidly into the stream system.

TEMPORAL AND SPATIAL PATTERNS OF SOLUTE TRANSPORT

There has been continued interest in temporal variations in stream solute load since Troake & Walling published their preliminary survey in 1973. Since then, studies have been conducted at a whole range of timescales: storm-period (Burt *et al.,* 1983; Burt & Arkell, 1987; Heathwaite *et al.*, 1989), seasonal (Burt, 1988), annual and long-term (Burt *et al.*, 1988; Johnes & Heathwaite, 1996). Most attention has been directed to the nitrate record. Unlike most solutes, nitrate concentrations are highest in the winter months when leaching processes are most active. Much nitrate is lost during those runoff events where two peaks in stream discharge occur. The delayed peak, a distinctive seasonal feature of catchments like Slapton (see Burt & Heathwaite, 1996b), involves significant contributions of 'old' soil water; both nitrate concentration and load are high at these times. Fig. 1 shows a typical hydrograph and chemographs for the river Gara. Suspended sediment concentrations increase by several orders of magnitude on the rising limb of the storm hydrograph; high concentrations of phosphate (PO_2-P) and ammonium (NH_4-N) also occur at this time, since both are associated with the sediment

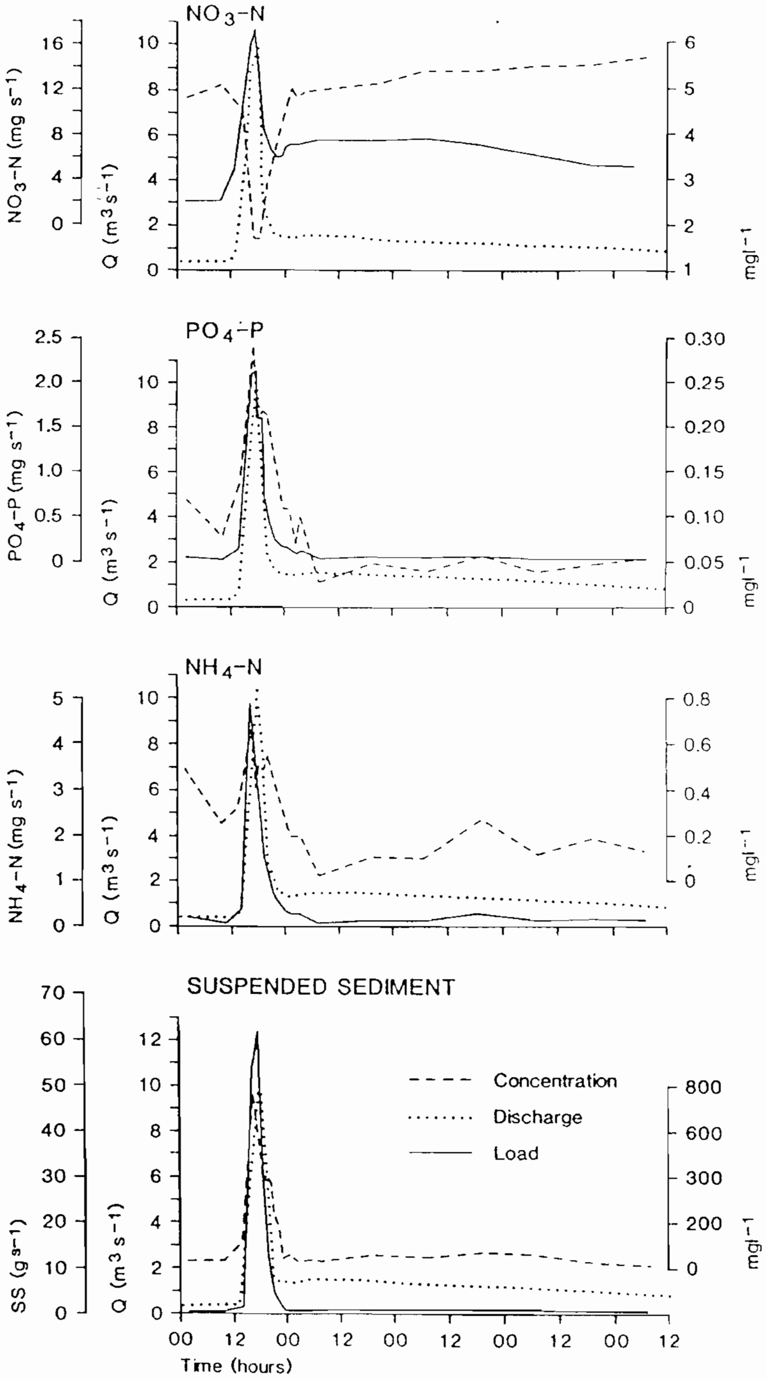


Fig. 1
Hydrographs and chemographs for the River Gara for the storm event of 23 March 1988.

TABLE 1. *Rainfall, runoff and nitrate concentration data for the period 1989–91. All nitrate concentrations are given as mg* l^{-1} NO_3-*N.*

Year	Month	Rainfall (mm)	Runoff Slapton Wood (mm)	Slapton Wood nitrate	Gara nitrate	Start nitrate
1989	1	55		6.3	3.8	5.8
	2	110		5.0	4.3	6.6
	3	151		8.0	5.4	8.4
	4	92		7.0	5.2	7.7
	5	2		7.8	3.9	7.3
	6	21		6.9	5.4	9.1
	7	18		5.8	5.5	9.0
	8	57		5.4	4.9	7.7
	9	160	11	5.5	4.1	7.2
	10	106	15	6.4	3.9	6.4
	11	67	50	7.3	4.3	6.1
	12	206	156	7.6	4.8	7.8
1990	1	156	107	14.3	10.5	14.8
	2	259	274	11.9	7.6	12.0
	3	11	58	10.9	8.2	11.0
	4	29	21	8.0	6.3	9.4
	5	19	14	6.0	4.5	7.8
	6	62	11	7.1	5.2	8.0
	7	33	10	6.3	4.8	7.2
	8	54	8	8.4	6.1	7.7
	9	53	7	7.1	4.0	6.2
	10	68	8	5.8	4.2	6.8
	11	58	9	7.0	7.6	8.0
	12	86	12	6.8	5.0	6.8
1991	1	151	90	9.4	7.1	12.7
	2	65	41	8.6	6.2	8.3
	3	111	130	9.9	7.1	10.1

Runoff data were collected by the Institute of Hydrology under contract to the University of Newcastle upon Tyne in a project funded by UK Nirex Ltd.

itself. (Heathwaite *et al.*, 1989). Nitrate concentrations fall during the quickflow period since the baseflow is diluted by inputs of 'new' water which has had little contact with the catchment soils. In this example, there is no delayed peak in stream discharge but, nevertheless, the rate of flow recession is very low for a few days after the quickflow event. Nitrate concentrations at this time rise above pre-storm levels since the runoff response is now completely dominated by subsurface runoff. The combination of sustained baseflow and high concentration means that there is actually a delayed peak in nitrate load about 36 hours after the quickflow peak. It should be noted that the absolute magnitude of stream nutrient loads during storm events is not known, as the total nitrogen and phosphorus load has not been fractionated for a sufficient number of storms. The focus in the water quality monitoring programme has been on inorganic determinands (but see Heathwaite & Johnes, 1996).

Table 1 shows monthly totals of rainfall, runoff, nitrate concentrations for 1989–91, a period which includes the hot, dry summer of 1989 followed by a very wet, mild winter. Nitrate concentrations are always lowest in the Gara, which includes the highest, wettest parts of the Slapton catchment and has the largest area of grassland; concentrations in the Slapton Wood and Start streams are higher, reflecting the lower relief and greater acreage of arable cropping in those basins. The combination of a droughty summer followed by a wet winter produces peak nitrate concentrations (see also next section); this is confirmed by comparison of nitrate figures for the 1989–90 and 1990–91 winters. Given high streamflow as well as high nitrate concentrations in the winter period, it is hardly surprising that this is the season of maximum nitrate export from the catchment area. However, owing to the rapid turnover of water stored in the Ley (see Burt & Heathwaite, 1996b and Johnes & Wilson, 1996), nitrate losses in winter may be less significant as a source for biological production in the Ley than those during the spring and summer. The annual regime of nitrate concentrations is clearly seen in the long-term records for the Slapton Wood and Gara streams; these records are discussed in more details in the next section.

Burt & Arkell (1987) investigated the spatial pattern of nitrate loss in the Slapton Wood catchment for the 1984 water year (see also below). All parts of the basin acted as sources of nitrate runoff but the most significant losses came from the most intensively farmed parts. Mean concentrations (mg l^{-1} NO_3-N) were as follows: headwaters (mainly arable)—10.0; Carness hollow (arable and grass)—7.4; valley-side slopes (arable and grass)—8.0; Eastergrounds hollow (grass)—6.6; Slapton Wood (woodland but with arable and grass above the wood)—4.6. The flow-weighted mean for the catchment as a whole was 7.9 mg l^{-1} NO_3-N. This equates with a loss of 3.6 tonnes of nitrogen in the form of nitrate (39 kg N ha^{-1}); this is equivalent to about one quarter of the annual application of fertiliser and is a very typical figure for nitrate export for areas of mixed farming in central and south west England (Johnes & Burt, 1993) .

There have been only occasional surveys of water quality across the whole of the Slapton Ley catchment (unpublished survey data collected by the NRA and as part of undergraduate project work). As expected, such maps show that land use and relief are the main determinants of nitrate concentrations: concentrations tend to increase towards the lower southern part of the catchment where arable farming is more extensive (Fig. 2).

STATISTICAL APPROACHES

The water quality record for various sites within the Slapton catchment is one of the longest available; an example is shown in Fig. 3. It is not surprising therefore that attempts have been made to study changes in the concentration of various determinands over time. In general, however, linear regression analysis with time as the independent variable is not a suitable statistical tool for modelling time series data since the observations making up the series are not usually independent of one another. However, for short series (less than 50 values) and where there is no significant autocorrelation in the dependent variable, then regression techniques may be used with caution. Accordingly, Burt *et al.* (1988) applied correlation and regression analysis to the annual mean nitrate

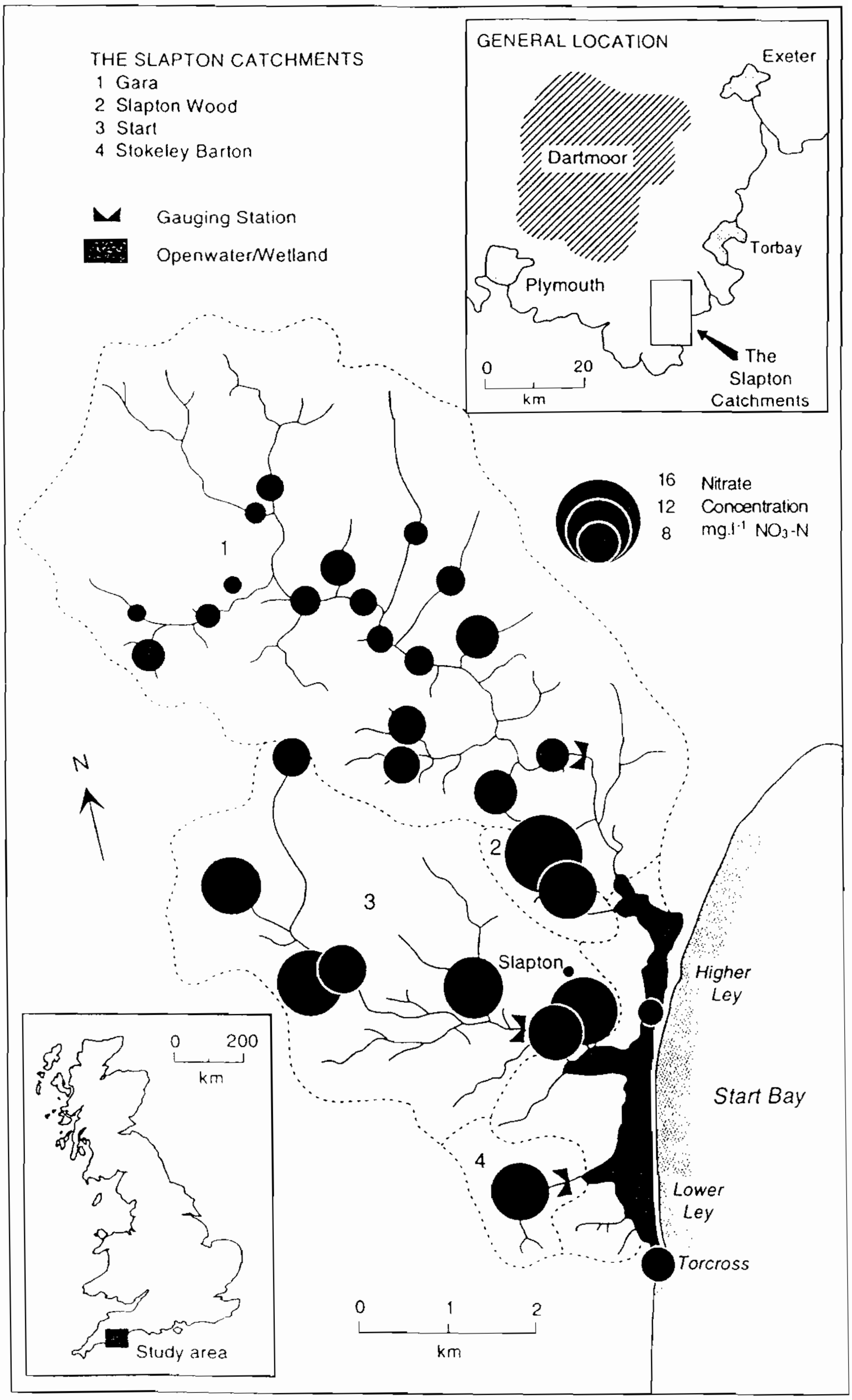


FIG. 2.
Nitrate concentrations in the Slapton catchment, 10 January 1994.
Data collection by Rachel Stott and Richard Field; map drawn by Emma Burt.

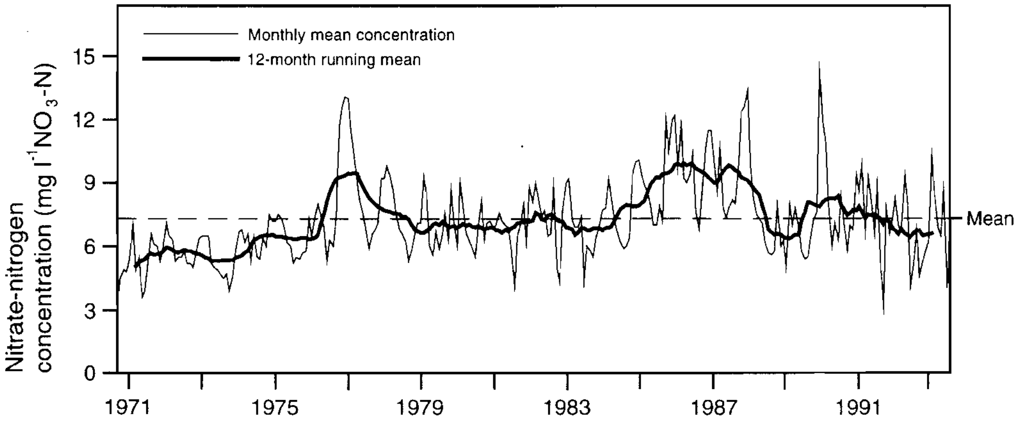


Fig. 3.
The long-term nitrate record of the Slapton Wood catchment.

series for the Slapton Wood catchment for the period 1970–85; this was extended to 20 years in Johnes & Burt (1993) with little change in the overall results. Bivariate correlations showed that nitrate was most strongly related to year ($r = 0.63$), although correlations with rainfall ($r = 0.48$) and runoff ($r = 0.59$) were also significant at the 0.05% level. Use of stepwise multiple regression showed that 48% of the total variance in nitrate was explained by year and rainfall together. Partial correlation (Johnston, 1980) shows that year alone accounts for 25.3% of the explained variance, rainfall alone accounts for 8.2% of the explained variance, and year and rainfall together account for 14.8% of the explained variance (in that later years have tended to be wetter).

Thus, notwithstanding the influence of climate, the upward trend in nitrate over this 20-year period is confirmed. Lane & Burt (in prep.) have used recursive state-space time series analysis of the monthly mean nitrate series for Slapton Wood (1971–1994). Use of techniques such as detrending, seasonal adjustment, auto- and cross-correlation have largely confirmed the results of the regression analysis, in particular the finding that a dry year will lead to high nitrate levels in subsequent years, and *vice versa*. This shows that antecedent conditions are important in regulating the supply of nitrate and that the soil system has a strong ‘memory’ with respect to nitrate production and leaching (Burt *et al.*, 1988).

APPLICATION OF THE NUTRIENT EXPORT MODEL

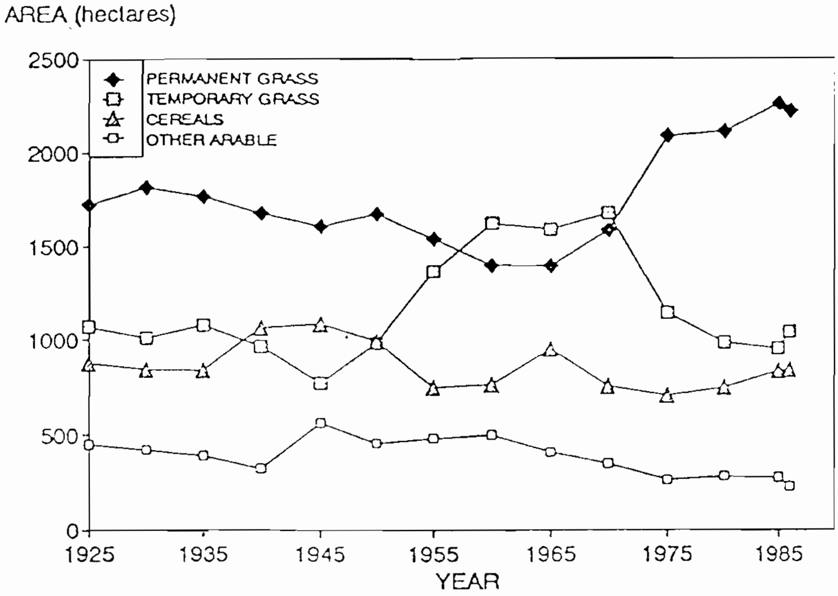
Nutrient export to the drainage network from different land uses in the catchment of Slapton Ley has been examined using a export coefficient modelling approach. The model was initially developed for the Slapton catchment by Johnes & O’Sullivan (1989) and refined and extended to include calibration and validation steps incorporating sensitivity analyses by Johnes (1996), Johnes & Heathwaite (1996) and Johnes *et al.*

TABLE 2. *Nutrient inputs to and exports from the Slapton catchment, 1986 (Johnes & Heathwaite, 1996)*

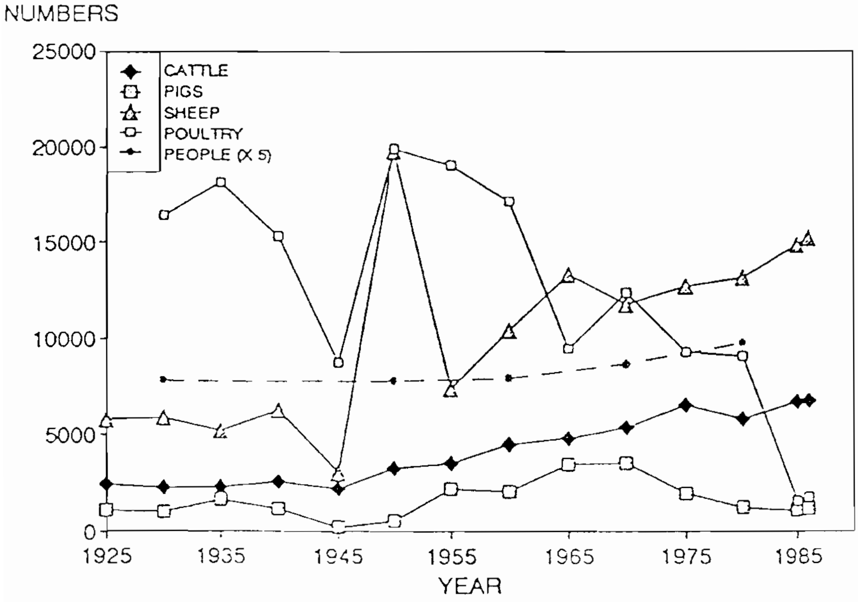
	INPUTS (kg)		EXPORTS (kg)	
NUTRIENT SOURCE	Nitrogen	Phosphorus	Nitrogen	Phosphorus
Permanent grass	330,000	39,300	27,700	723
Temporary grass	341,000	31,900	26,100	604
Cereals	102,000	19,700	12,300	458
Root crops	28,400	10,400	7,180	127
Field vegetables	16,400	2,620	4,090	48.9
Oilseed rape	0	0	0	0
Rough grazing	1,240	3.08	1,560	2.48
Woodland	3,830	3.82	2,490	3.83
Cattle	484,000	52,700	80,900	1560
Pigs	17,100	5,160	2,810	149
Sheep	92,200	15,500	16,300	484
Poultry	530	354	78.9	9.82
Horses	4,450	661	744	19.5
Humans	8,060	2,370	4,380	777
Rainfall	91,100	683	51,000	383
Total load	1,520,000	181,000	238,000	5,350
Mean annual nutrient concentrations	mean annual runoff = 23,900,000 m^3		9.96 mg TN l^{-1}	224 mg TP l^{-1}

Nutrient exports were calculated using the export coefficients presented in Table 3.
All data are reported to 3 significant figures.

(submitted). The approach is relatively simple and essentially involves a nutrient budget calculation taking into account all inputs to land in the catchment (e.g. fertiliser, directly voided animal waste, atmospheric inputs) together with all losses from the catchment in terms of the nutrient load recorded in streams and rivers draining the catchment. An example of a nutrient budget for Slapton is given in Table 2 shows the nutrient balance for the 1986 water year (after Johnes & Heathwaite, 1996). Without considerable expenditure on detailed field research it is not possible to quantify nutrient export for all land uses and for all locations in a particular catchment. Hence the export coefficient model makes use of published sources of nutrient loss. Examples of the export coefficients used by Johnes & Heathwaite (1996) for the Slapton catchment are given in Table 3. These export coefficients reflect the intensive dairy and beef cattle farming regime of the Slapton area and also incorporate the results of plot scale experiments conducted on different land uses in the catchment (Heathwaite *et al.*, 1990; Heathwaite & Johnes, 1996). The use of export coefficients is combined with sensitivity analysis to isolate the key controls on nutrient export in the catchment together with validation of the model, which in the case of Slapton, was possible using the long-term water quality records discussed above.



(a) LAND USE



(b) LIVESTOCK and PEOPLE

FIG. 4
Land use, livestock and people in the Slapton catchment, 1925–1986
(Johnes and Heathwaite, 1996)

Once the export coefficient model is set up, it is possible to evaluate, using an annual time-step, the impact of changes in past land use and management on the nutrient loadings delivered to receiving waters. Fig. 4 illustrates the changes in catchment land use, livestock and human population between 1921 and 1986 for the Slapton catchment (Johnes & Heathwaite, 1996). These data were derived from OPCS and Annual Agricultural Census Return parish summaries for the catchment, together with a detailed catchment land use survey conducted in 1986. Johnes & Heathwaite (1996) discuss the implications of such changes in terms of water quality in the Slapton catchment over the past 70 years, using the model to hindcast the pattern of water quality change through time. This is illustrated in Fig. 5. Independent water quality records are available from 1970 (see above) and these are included in Fig. 5. A full explanation of the approach is given in Johnes (1996) and Johnes & Heathwaite (1996).

The model may also be used to *forecast* the likely impact on nutrient loadings of land management strategies such as the construction of buffer zones in riparian land, the implementation of the Nitrate Sensitive Areas (NSA) scheme or the impact of committing land to set-aside (Johnes, 1996). Johnes & Heathwaite (1996) found that it was possible to predict the impact on water quality of management options such as relocating high risk land associated with high nutrient export to less vulnerable areas of the catchment. For example, grazing of grassland in riparian zones may contribute relatively high loads of nitrogen and phosphorus to streams, particularly where stocking densities are high (Heathwaite *et al.*, 1990). The model suggests that such land uses should be confined to areas where the risk of nutrients exported from the land reaching the stream is much lower. On this basis it is possible to define the Best Practicable Environmental Options (BPEO) for a catchment in the context of minimising the impact of agriculture on water quality.

PHYSICALLY-BASED MODELLING OF NITRATE LOSS

An alternative approach to modelling nutrient concentrations in rivers is to use a distributed, physically based model. A distributed model has the capability of predicting the spatial pattern of process operation within the catchment as well as outflow. Physically-based models are firmly based upon understanding of the mechanisms which control runoff (physics) and nutrient transport (chemistry and biology). Physically-based models are necessarily distributed because their fundamental equations generally involve one or more spatial co-ordinates (Beven, 1985). Whelan (1993; see also Whelan *et al.*, 1995) has developed a process-oriented model of nitrate leaching: MONITOR (**M**odel **o**f **Ni**trogen **T**urn**o**ver and **R**unoff). The model encompasses both the processes which control the availability of nitrate in the soil, and those which affect nitrate transport i.e. soil and hillslope hydrological processes. The model was calibrated using data collected from the Slapton Wood weir and then validated using independent data from the same site. The model was able to reproduce the pronounced annual cycle discussed earlier, although it failed to forecast the significant peak in nitrate concentration following the 1975–76 drought. The model was also able to distinguish between the drier 1970s and the wetter 1980s, though estimates for individual years were not always close. This may be because the model fails to accommodate the leaching of nitrate below the root zone in the winter following a dry summer; such losses are only

TABLE 3. *Export coefficients selected for the Slapton catchment (Johnes & Heathwaite, 1996)*

	ExOport coefficients for nitrogen		Export coefficients for phosphorus	
	Distance from stream		Distance from stream	
Nutrient source	<50m	>50m	<50m	>50m
Permanent grass	15%	7.5%	0.5 kg ha^{-1}.a	0.4 kg ha^{-1}.a
Temporary grass	15%	12%	0.5 kg ha^{-1}.a	0.4 kg ha^{-1}.a
Cereals	24%	25%	0.8 kg ha^{-1}.a	0.6 kg ha^{-1}.a
Root crops	50%	25%	0.9 kg ha^{-1}.a	0.7 kg ha^{-1}.a
Field vegetables	50%	25%	0.8 kg ha^{-1}.a	0.6 kg ha^{-1}.a
Oilseed rape	50%	25%	0.8 kg ha^{-1}.a	0.6 kg ha^{-1}.a
Rough grazing	13 kg ha^{-1}.a	13 kg ha^{-1}.a	0.02 kg ha^{-1}.a	0.02 kg ha^{-1}.a
Woodland	13 kg ha^{-1}.a	13 kg ha^{-1}.a	0.02 kg ha^{-1}.a	0.02 kg ha^{-1}.a
Cattle*	32.3%	16.2%	5.7%	2.85%
Pigs*	28.9%	14.5	5.1%	2.55%
Sheep*	34%	17%	6%	3%
Poultry*	30.6%	15.3%	5.4%	2.7%
Horses*	32.3%	16.2%	5.7%	2.85%
Humans**	2.14 kg ca^{-1}.a	2.14 kg ca^{-1}.a	0.38 kg ca^{-1}.a	0.38 kg ca^{-1}.a
Rainfall***	56%	56%	56%	56%

Sources: Vollenweider (1968); Royal Commission (1972); Alexander & Stevens (1976); Cooke (1976); Jorgensen (1980); Reckhow & Simpson (1980); Gostick (1982); Heal et al., (1982); Royal Society (1983).

* The export coefficients for livestock derive from standard figures of 17% nitrogen loss, and 3% phosphorus loss (34% for nitrogen and 6% for phosphorus in the riparian zone), taking into account the % of manure voided that is applied to the land after storage losses. These are 95% for cattle; 85% for pigs; 100% for sheep; 90% for poultry; 95% for horses (Vollenweider, 1968; Gostick, 1982; Johnes & O'Sullivan, 1989). The coefficients are expressed to 3 significant figures.

** The export coefficients selected for human sources assume that all sewage receives primary and secondary treatment.

*** The export coefficient for rainfall is the 20-year mean % rainfall lost to runoff.

incorporated into the throughflow the winter after. An underestimation one year is therefore followed by overestimation the next. Such 'memory' effects are very difficult to accurately model.

Physically based models like MONITOR require large amounts of data for calibration; this may make them less attractive and more costly to apply than much simpler models such as the export coefficient model. The attraction of the former is that, in theory at least, they should be capable of application under conditions which differ significantly from the calibration period: rare events, after major changes in land use, and at new sites. At present, however, such models are still at a developmental stage and are rarely be applied to basins greater than 10 km^2 in area (although the use of Geographical Information Systems (GIS) may help to ease the problem of scale). Despite its simplicity, the export coefficient model remains preferable given its accuracy and ease of application to large basins.

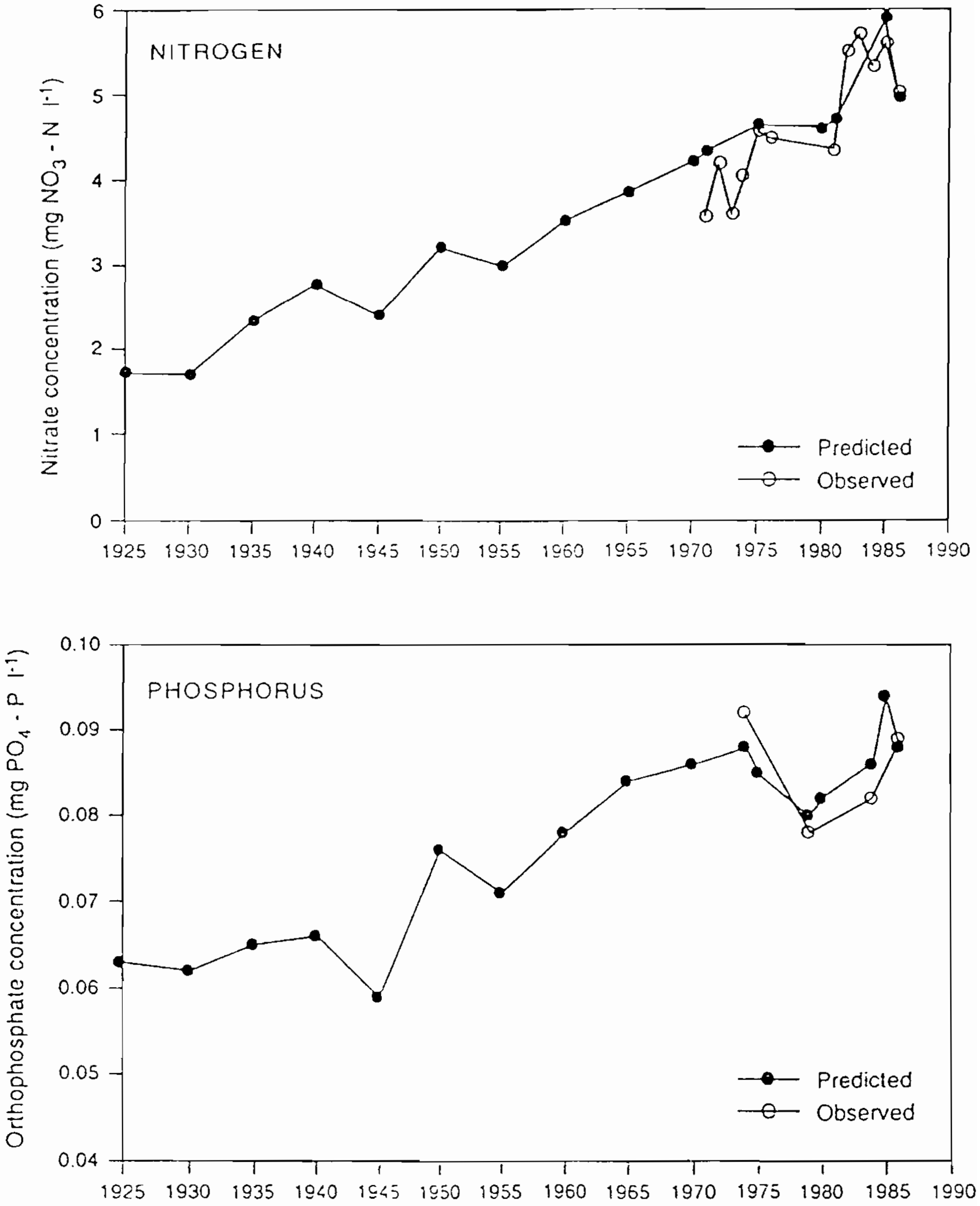


FIG. 5
Observed and predicted total nitrogen and total phosphorus concentrations in the Slapton catchment, 1925–1986 (Johnes and Heathwaite, 1996)

THE FUTURE

The water quality archive held by Slapton Ley Field Centre has, as yet, barely been touched; doubtless there remains much of interest to be discovered in those records. Their value lies most of all in their continuity. Subtle changes in the environment may take a long time to become apparent, so that long continuous records of high quality are vital. In addition, as new environmental problems emerge, the data from such monitoring programmes may be needed to address these new questions (Burt, 1994). For example, the archive has been used recently to investigate temporal changes of potassium concentration in the river Gara (Stott, in prep.). Preliminary results suggest that, unlike nitrate, there has been no long-term upward trend. A peak in concentrations in October may be caused by surface and near-surface runoff being relatively rich in potassium. Later in the winter, these runoff sources may be diluted by deeper throughflow of lower potassium concentration. Even so, potassium loads are highest in January and February, presumably because discharge dominates concentration in the load calculation.

Future modelling initiatives seem likely to involve a number of approaches. The export coefficient model may be further developed to include a greater degree of spatial distribution; this would allow, for example, the role of buffer zones to be investigated in more detail than was possible in Johnes & Heathwaite (1996). The large body of information available for the Slapton catchment makes it an ideal site for the calibration and testing of new models. Research funded by the Ministry of Agriculture, Fisheries and Food (MAFF) aims to link the export coefficient model to a GIS (Bennett, Heathwaite and Wise at Sheffield University; Johnes at Reading University). This will enable more detailed evaluation of the role of land use distribution in determining the pattern of nutrient export from the Slapton catchment than has so far been possible. At the same time, work is in hand to develop a GIS-based nitrate model incorporating Whelan's MONITOR model (McDonnell and colleagues at Oxford University).

Finally, some mention should be made of attempts to limit nutrient runoff in the Slapton catchment. The NRA has installed a phosphate stripper at the Slapton Sewage Treatment Works. The area is the site of the MAFF Water Fringe Habitats pilot scheme to establish buffer zones along the major valley bottoms and around the Ley shore. There are also preliminary discussions taking place about the setting up of an integrated catchment management scheme involving relevant agencies, local government, landowners and the local population. It is tempting to hope that the future success of such initiatives might be anticipated using the various simulation models discussed here!

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REFERENCES

ALEXANDER, G. C. and STEVENS, R. J., (1976). Per capita phosphorus loading from domestic sewage. *Water Research,* **10**, 757–764, 1976.

BEVEN, K. J., (1985). Distributed models, in Anderson, M. G. and Burt, T. P., *Hydrological forecasting,* John Wiley and Sons: Chichester, 405–35.

BURT, T. P., (1988). Seasonality of subsurface flow and nitrate leaching. *Catena*, Supplement 12, 59–65.

BURT, T. P., (1994). Long-term study of the natural environment—perceptive science or mindless monitoring? *Progress in Physical Geography,* **18**, 475–96.

BURT, T. P. and ARKELL, B. P., (1987). Temporal and spatial patterns of nitrate losses from an agricultural catchment. *Soil Use and Management,* **3**, 138–43.

BURT, T. P. and HEATHWAITE, A. L., (1993). A scale-dependent approach to the study of nutrient export from basins. *Institute of Hydrology Report,* **120**, 82–92.

BURT, T. P., BUTCHER, D. P., COLES, N. and THOMAS, A. D., (1983). Hydrological processes in the Slapton Wood catchment. *Field Studies*, **5**, 731–752.

BURT, T. P., ARKELL, B. P., TRUDGILL, S. T. and WALLING, D. E., (1988). Stream nitrate levels in a small catchment in south west England over a period of 15 years (1970–1985). *Hydrological Processes*, **2**, 267–284.

COLES, N. and TRUDGILL, S. T., (1985). The movement of nitrate fertiliser from the soil surface to drainage waters in by preferential flow in weakly structured soils, Slapton, South Devon. *Agriculture, Ecosystems and Environment*, **13**, 241–59.

COOKE, G. W., (1976). A review of the effects of agriculture on the chemical composition and quality of surface and underground waters, in *Agriculture and Water Quality,* MAFF Tech. Bull. 32, 5–58, HMSO, London.

GOSTICK, K. G., (1982). Agricultural Development and Advisory Service recommendations to farmers on manure disposal and recycling, *Philosophical Transactions of the Royal Society of London, Series B,* **296**, 309–332.

HEAL, O. W., SWIFT, M. J. and ANDERSON, J. M., (1982). Nitrogen cycling in United Kingdom forests: relevance of basic ecological research, *Philosophical Transactions of the Royal Society of London, Series B,* **296**, 427–444.

HEATHWAITE, A. L., (1995). Sources of eutrophication: hydrological pathways of catchment nutrient export. *International Association of Hydrological Science Publication,* **230**, 161–76.

HEATHWAITE, A. L. and BURT, T. P., (1992). The evidence for past and present erosion in the Slapton catchment. In Bell, M. and Boardman, J. (eds), *Soil Erosion, Past and Present: Archaeological and Geographical Perspectives*, Oxbow Monograph **22**, 89–100.

HEATHWAITE, A. L., BURT, T. P. and TRUDGILL, S. T., (1990a). Land-use controls on sediment production in a lowland catchment, south west England. In Boardman, J., Foster, I. D. L. and Dearing, J. A. (eds), *Soil Erosion on Agricultural Land,* John Wiley and Sons: Chichester, 69–86.

HEATHWAITE, A. L., BURT, T. P. and TRUDGILL, S. T., (1990b). The effect of agricultural land use on nitrogen, phosphorus and suspended sediment delivery in a small catchment in south west England, in Thornes, J. B. (ed.), *Vegetation and erosion,* John Wiley and Sons: Chichester, 161–79.

HEATHWAITE, A. L. and JOHNES, P. J., (1996). Contribution of nitrogen species and phosphorus fractions to stream water quality in agricultural catchments. *Hydrological Processes,* **10**, in press.

JOHNES, P. J., (1996) Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. *Journal of Hydrology,* in press.

JOHNES, P. J. and BURT, T. P., (1993). Nitrate in surface water, in Burt, T. P., Heathwaite, A. L. and Trudgill, S. T., (eds.), *Nitrate: Processes, Patterns and Management,* John Wiley and Sons: Chichester, 269–317.

JOHNES, P. J. and HEATHWAITE, A. L., (1996). Modelling the impact of land use change on water quality in agricultural catchments. *Hydrological Processes,* in press.

JOHNES, P. J., MOSS, B. and PHILLIPS, G. L. (in prep). The determination of water quality by land use, stock headage and population data—testing of a model for use in conservation and water quality management. Submitted to *Freshwater Biology.*

JOHNES, P. J. and O'SULLIVAN, P. E., (1989) Nitrogen and phosphorus losses from the catchment of Slapton Ley, Devon—an export coefficient approach. *Field Studies,* 7, 285–309.

JOHNSTON, R. J., (1980). *Multivariate statistical analysis in geography.* Longman, Harlow.

JORGENSEN, S. E., (1980). *Lake Management.* Pergamon, Oxford.

LANE, K. and BURT, T. P., (in prep.). Steam nitrate levels in the Slapton Ley catchment over a period of 24 years (1970–1994).

RECKHOW, K. H. and SIMPSON, J. J. (1980). A procedure using modelling and error analysis for prediction of lake phosphorus concentration from land use information, *Canadian Journal of Fisheries and Aquatic Science,* **37**, 1439–1448.

ROYAL COMMISSION ON ENVIRONMENTAL POLLUTION. (1972). *Pollution in some British Estuaries and Coastal Waters,* 3rd report, HMSO, London.

ROYAL SOCIETY (1983). *The Nitrogen Cycle of the United Kingdom,* Royal Society, London.

STOTT, R. E., (in prep.). The behaviour of potassium in surface soils and waters. PhD thesis, University of Reading, UK.

VOLLENWEIDER, R. A., (1968). Scientific fundamentals of stream and lake eutrophication, with particular reference to nitrogen and phosphorus, *OECD Technical Report DAF/DST/88.*

WHELAN, M. J., (1993). *Numerical modelling of small catchment nitrogen dynamics with particular reference to the Slapton Wood catchment, South Devon.* Unpublished PhD thesis, University of Leeds, UK.

WHELAN, M. J., KIRKBY, M. J. and BURT, T. P., (1995). Predicting nitrate concentrations in small catchment streams, in Trudgill, S. T., (ed.), *Solute Modelling in Catchment Systems,* John Wiley and Sons: Chichester, 165–192.