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PREDICTING THE EFFECT OF LAND USE ON STREAM WATER QUALITY IN THE UK

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ABSTRACT The effect of land use change at both long (90 year) and short (single water year) time scales are discussed. Current annual sediment and solute export from this area of arable and grassland farming in SW Devon is of the order: 6 t for NH_4-N, 282 t for NO_3-N, 2 t for P and 1440 t for suspended sediment. Sediment cores from the lake receiving these catchment inputs provides long-term evidence for an increase in erosion and nutrient export since the 1950s. A significant increase in stream NO_3^- load is also recorded over the past 30 years. As a result of catchment inputs, the lake is now hypertrophic. Models currently used to predict the effect of land use change on stream water quality are limited because they fail to account for the effect of hillslope hydrological pathways and the physical and biochemical modification of the potential nutrient and sediment load.

INTRODUCTION

It is well known that land use affects stream water quality. The problem is one of applying the large number of studies, whether predictive models often based on nutrient export coefficients (Cooper & Thomsen, 1988; Johnes & Burt, 1990; Owens *et al.*, 1989; Todd *et al.*, 1989) or plot studies (Lee *et al.*, 1989), to the catchment scale which is the level at which water quality control decisions must be made. Plot studies contain detailed nutrient input-output information, for which processes of nutrient transformation and transport usually are implied by difference. Models which have no physical basis may not accurately simulate observed water quality.

Within this framework, there is the further problem of linking hillslope processes to stream processes. Hydrological pathways are critical in determining how much, and in what form, land use-derived nutrients will reach the stream (Burt, 1989; Lee *et al.*, 1989). The process is complex: for example, phosphorus (P) transfer down the hillslope to the stream will involve a number of hydrological and biochemical interactions. The P moving down the soil profile with infiltrating water or downslope with surface runoff is part of a hydrological pathway with direct links from the hillslope to the stream. Starting with the assumption that P is present mainly in insoluble form, the transfer process begins with erosion (detachment and/or dissolution). Erosion is governed by soil and hydrological factors, such as soil nutrient and organic matter content, soil structure and texture, rainfall intensity and runoff velocity. P once eroded is further acted on by physical and biochemical mechanisms in its progress down the hillslope towards the stream. These include deposition of sediment, adsorption of dissolved forms on to suspended sediment (SS), and assimilation by microorganisms. All these mechanisms may prevent eroded P from reaching the stream. Given these controls, it is unlikely that the same P eroded at the top of the hillslope will arrive at the stream during a storm event. Unless hydrological pathways easily override physical and biochemical controls, a piston mechanism of nutrient transport similar to the hydrological model described by Burt & Butcher (1985) is more likely to apply.

Bearing in mind the complexities of hillslope processes, this paper, whilst including some of the links between hillslope and stream, will examine several facets of a long-term catchment study that bring us closer to predicting the effects of land use on stream water quality. In this catchment, the impact of land use change is readily observed in the accelerated eutrophication of a lake receiving the catchment sediment and solute load.

The effect of land use on stream water quality will be examined at two time scales. First, a detailed study of catchment land use change over the period 1985-1990 will be presented, together with the results of an intensive program of water quality sampling in a catchment. The intensive study was conducted in the 1988 water year (beginning 1 October 1987). Second, long-term changes in land use and water quality will be examined over the period 1905-1990. Land use changes will be used to predicted nutrient export, and, where appropriate, compared to observed water quality changes. The sediment and nutrient record of catchment changes stored in the sediments of Slapton Ley, also will be examined.

SITE DESCRIPTION

Slapton Ley is a coastal lake, 10 km southwest of Dartmouth, Devon (UK National Grid Reference: SX 825479). It is divided into the Higher Ley, a 39 ha reedbed system, and the 77 ha Lower Ley, 84% of which is open water. The lake is a sink for solute and sediment inputs from the surrounding arable and grassland catchment. The 46 km^2 catchment of Slapton Ley is divided into four subcatchments (Table 1). Topography consists of wide plateaux of low gradient dissected by narrow deep valleys (maximum slopes of 25°). The area is underlain by impermeable Lower Devonian slates and shales, with freely draining acidic and nutrient-poor silty clay loam soils. The soils are shallow on steep slopes and less than or equal to 3 m deep in valley bottoms. Land use in the largest (Gara) subcatchment is dominated by permanent pasture and temporary grass. The lower altitudes of the Start catchment further south results in a higher proportion of arable land use (Table 1). Mean annual rainfall for the catchment (1961-88) is 1039 mm; mean annual runoff is 650 mm. The area has a mean annual temperature of 10.5°C.

LAND USE, HYDROLOGICAL PATHWAYS, AND STREAM WATER QUALITY

Table 1 shows the annual catchment inorganic load (kg ha^{-1}) for the 1988 water year. This was computed from continuous discharge observations and water quality samples at intervals ranging from 15-minutes during storm events to a maximum of 24-hours. It is interesting that the annual nutrient loads (for NO_3^- and PO_4^{3-}, only) computed from this intensive water quality sampling data did not differ significantly from those computed from weekly water samples (Heathwaite *et al.*, 1989). Suspended sediment and NH_4^+ loads, however, were grossly underestimated by the weekly data because they are closely controlled by stream discharge.

For the two intensively-farmed catchments, Gara and Start, high loads are shown for all elements. Gara has a particularly high SS load which may be related to steep slopes there. Start has a high NO_3^- load which may relate to greater arable land use in this catchment; NH_4^+ and P loads are similarly high.

TABLE 1 SLAPTON catchments inorganic load (kg ha^{-1}) from October 1987 to September 1988.

Catchment	Area (ha)	Runoff (mm)	Land Use Grass (%)	Arable (%)	NH_4^+	NO_3^- (kg ha^{-1})	PO_4^{3-}	Suspended sediment
Gara	2362	920	11.9	81.2	1.79	68.03	0.38	503.34
Slapton Wood	93	581	36.1	32.1	0.16	63.60	0.21	66.15
Start	1079	950	34.2	52.6	1.39	103.93	0.58	224.89
Stokeley Barton	153	148	66.0	28.8	0.23	19.51	0.21	23.37

The annual total inorganic nutrient and SS loss from each subcatchment was: 6 t (NH_4N), 282 t (NO_3N), 2 t (P), and 1440 t SS. There has been concern that the nutrient load from the Slapton sewage works may be a major point source of pollution owing to its proximity to the Lower Ley (Johnes & O'Sullivan, 1989; Burt *et al.*, 1990). However, the sewage works formed less than 0.5%, 0.04% and 1.3% of the total NH_4^+, NO_3^- and PO_4^{3-} input to the Lower Ley respectively, so its contribution to eutrophication may be minimal. These results do not take into account seasonal variations in the nutrient output from the sewage works, which is greatest in summer when the Slapton village population almost doubles from tourism. In summer, the Lower Ley is least able to assimilate this nutrient input because lake flushing is minimal. Furthermore, it is estimated that only 50% of the village is connected to mains sewerage so the sewage load from other sources, such as septic tanks, could be high.

For all inorganic solutes and SS, the majority of the annual load is delivered in January and February, when the discharge is high. For NO_3^-, 64% of the Gara, and 54% of the Start load is delivered in these two months. Furthermore, the Start stream exceeds the WHO NO_3^- limit (11.3 mg l^{-1} NO_3-N) for at least 4-months of the year. For SS, 93% and 70% of the Gara and Start load is delivered in winter (November to March). The winter load of NH_4^+ and PO_4^{3-} is at least 70% for both catchments. Sediment and solute transport in these catchments appears to be strongly controlled by discharge.

The impact of monthly loads on lake water quality is determined by the ability of the Lower Ley to assimilate the inputs. The Lower Ley has a flushing rate of twenty times per year (Van Vlymen, 1979). At peak winter flow at least one third of the lake volume may be displaced in 24 hours. This suggests that a high proportion of the winter sediment and solute load will be displaced from the lake, thus having little impact on lake water quality and eutrophication. It is perhaps the summer inputs, when lake flushing is low, that are of most importance. Here the role of the Higher Ley reedbed in modifying the inputs of two of the subcatchments, Gara and Slapton Wood, becomes important. The balance between monthly solute and sediment input and output to the Higher Ley is presented in Table 2. From October through to March, all elements show a net gain in the Higher Ley. So the Higher Ley acts as a N, P, and SS sink for the winter months. Furthermore, any input to the Lower Ley from the Higher Ley is likely to be rapidly discharged from the Lower Ley because the lake flushing rate over this period is high. From April to July the Higher Ley has a net loss of most elements. It, therefore, acts as a sediment and solute source for the summer period.

This reverts to a net gain in the autumn. On balance, the Higher Ley is an important sink of NH_4^+ (3 t), NO_3^- (95 t) and SS (1080 t) for the 1988 water year. For P, the Higher Ley shows a net annual export, particularly in March and April. As P is commonly thought of as the limiting nutrient in the eutrophication process, this source of P is important. This is even more so considering that the input occurs in spring and summer when the flushing rate of the Lower Ley is minimal, which means that most of the P will remain within the lake system. It is possible that this net P export from the Higher Ley is the result of saturation of the lake sediments with P. Gehrels & Mulamoottil (1989) suggest that wetlands have a limited capacity to retain nutrients: if the P input cannot be used fast enough, i. e. P retention by chemical precipitation or adsorption, P will remain in solution. Trudgill *et al.* (1990) suggest that wetlands may be as a source of P.

TABLE 2 Effect of the Higher Ley on sediment and solute delivery (t) to the Lower Ley; O = output; I = input; and B = balance (I-O).

	NH_4^+			NO_3^-			PO_4^{3-}			Suspended sediment		
Month	I	O	B	I	O	B	I	O	B	I	O	B
Oct	0.190	0.012	+0.178	6.27	0.46	+5.81	0.037	0.006	+0.031	32.7	0.1	+32.6
Nov	0.570	0.058	+0.512	18.96	6.67	+12.29	0.097	0.021	+0.076	198.2	1.5	+196.7
Dec	0.320	0.046	+0.274	14.88	7.64	+7.24	0.024	0.014	+0.038	76.0	1.8	+74.2
Jan	1.350	0.046	+1.304	63.75	13.92	+49.83	0.304	0.048	+0.256	520.2	7.4	+512.8
Feb	1.200	0.227	+0.973	42.91	24.54	+18.37	0.159	0.128	+0.031	198.3	56.3	+142.0
Mar	0.300	0.119	+0.181	7.75	4.63	+3.12	0.114	0.650	-0.536	119.9	13.9	+106.0
Apr	0.090	0.139	-0.049	4.73	7.99	-3.26	0.044	0.661	-0.617	15.7	15.1	+0.6
May	0.070	0.080	-0.010	2.90	3.22	-0.32	0.042	0.038	+0.004	7.3	14.2	-6.9
Jun	0.005	0.047	-0.042	0.90	0.80	+0.10	0.014	0.016	-0.002	1.4	2.3	-0.9
Jul	0.060	0.077	-0.017	0.87	0.33	+0.54	0.038	0.017	+0.021	6.1	2.2	+3.9
Aug	0.010	0.002	+0.008	1.02	0.58	+0.44	0.013	0.008	+0.005	6.8	1.6	+5.2
Sep	0.050	0.038	+0.012	1.64	1.19	+0.45	0.021	0.077	-0.056	12.4	0.7	+1.7
Total	4.215	0.891	+3.324	166.58	71.97	+94.61	0.907	1.684	-0.777	1195.0	117.7	+1077.9

So far, the pattern of catchment sediment and solute loads and the role of the Higher Ley reedbed in modifying these loads has been examined. To interpret these results further, the hydrological pathways and relative importance of different catchment land uses must be evaluated. Heathwaite *et al.* (1990a,b) measured the sediment and solute production in surface runoff for representative Slapton catchment land use types using a series of rainfall simulation experiments. Surface runoff from overgrazed permanent grassland doubled that from lightly grazed areas and at least twelve times that of ungrazed areas or arable land use. Additionally, lack of vegetation cover owing to severe poaching led to an increase in loss of SS, total N and total P. Over 90% of total N delivered was in inorganic NH_4-N form, whereas for PO_4-P, 80% was in organic or particulate form. Plot studies also established that preferential soil water movement down structural pathways can account for a high proportion of surface applied NO_3^- fertilizer in soil drainage waters (Coles & Trudgill, 1985).

Delayed subsurface flow has been shown to be an important hydrological pathway for NO_3^- leaching, with saturated hillslope hollows forming point sources of N within the whole hillslope system which contributes a diffuse NO_3^- load (Burt & Arkell, 1987). Catchment losses of NH_4^+, PO_4^{3-} and SS appear to be largely derived from an overland flow pathway, with peak concentrations of these elements at peak stream discharge (Heathwaite *et al.*, 1989). Land use is particularly important where overgrazing or mechanical compaction of the soil surface has occurred. This increases the likelihood of infiltration-excess overland flow and hence the importance of this nutrient and sediment hydrological pathway. Infiltration capacities falling below 1 mm h^{-1} have been recorded in severely overgrazed fields, whereas values around 30-40 mm h^{-1} are common in lightly grazed areas (Heathwaite *et al.*, 1990a).

Land use in riparian zones is predominantly grazed permanent grassland (Heathwaite, 1990b). This land use is thought to be an important source of stream sediment and solute loads, especially where it is heavily grazed. The high SS load for the Gara catchment (Table 1) may be explained by the combination of steep slopes and grazed permanent grassland in riparian zones. The nutrient load and transport pathways from manure-amended grasslands is the focus of current research efforts.

TABLE 3 Predicted losses[1] of N (t year^{-1}) from the Slapton catchments.

Year	Inorganic	Farmland Organic	Total	Sewage	Total[2]
1905	3.1	34.8	37.9	6.4	48.1
1935	2.9	43.2	46.1	6.4	56.4
1945	13.3	32.2	45.6	6.2	55.7
1950	8.8	46.7	55.5	6.2	65.6
1955	12.2	58.4	70.5	6.2	80.7
1960	18.9	69.6	88.6	6.2	98.9
1965	20.0	80.4	100.4	6.6	110.9
1970	28.3	97.0	125.3	6.9	136.1
1975	35.7	95.1	130.8	7.3	142.0
1980	39.0	72.6	111.3	7.9	123.1
1985	48.9	100.3	149.2	8.5	161.6

[1] after Acott (1989)

[2] totals assume fixed losses (t year^{-1}) from woodland of 2.27, from settlement of 0.12, and from precipitation 1.56.

LONG TERM TRENDS IN LAND USE AND WATER QUALITY

Three sources of long term catchment information exist: (1) land use records, which date back to the 1860s (Public Records Office, Kew); (2) sediment cores from the Lower Ley which can be dated using ^{210}Pb; and (3) water quality records dating back to the 1970s.

The lake sediment and nutrient history is described in Heathwaite & O'Sullivan (1990). There is clear evidence for increased erosion of detrital material, primarily allogenic K, Al and Si, from the catchment since 1950. Allogenic P influx also has increased and is presumably derived from sediment-associated sources. These changes are thought to reflect post-1945 intensification of agriculture. Lake eutrophication and catchment erosion have increased since 1950 as indicated by increased biogenic silica (which is an index of primary productivity) and a change in diatom flora in the upper lake sediments.

The land use and livestock changes over the period 1905-1990 for the Slapton catchments are shown in Fig. 1. A major increase in the proportion of temporary grassland after 1955 is observed. This probably resulted from agricultural intensification after World War II, when permanent grassland and rough grazing was ploughed and re-seeded. The area of temporary grassland has decreased since 1975. In part, this is a result of temporary grass falling into the permanent grassland category (the cut-off is 7 years). Accordingly, the proportion of permanent grassland in the catchment has increased significantly since 1970. The proportion of arable land in the catchment has not increased as much as anticipated given national trends (Oakes *et al.*, 1981). This may be because flat plateaux areas suitable for arable land use are restricted. However, the general land use patterns shown in Fig. 1 disguise the disproportionate increase in arable land use in some subcatchments, notably the Start. Here catchment topography is more suitable for arable land use, and may in part explain the high sediment and solute loads recorded in Table 1. Livestock has increased since 1905 (Fig. 1b). Assuming that a substantial proportion of livestock occupy the permanent grassland, an increase in stocking density has taken place from less that four livestock ha^{-1} between 1905 and 1950 to over fifteen stock ha^{-1} in 1965. These results suggest that the increase in livestock may be an important cause of changes in stream water quality. The application of N fertilizer in the Slapton catchments generally has increased since 1905 (Fig. 1). The application has decreased in the past 5 years but again these changes are likely to have resulted in an increase in the stream NO_3^- load caused by transport along subsurface and preferential flow pathways discussed above.

TABLE 4 Land use (ha), livestock and inorganic fertilizer application ($t\ year^{-1}$) in the Slap ton Wood catchment from 1905 to 1990.

	Grassland		Arable		Rough	Livestock		Fertilizer	
Year	Temporary	Permanent	Cereals	Roots	Grazing	Cattle	Sheep	N	P
1905	39	40	25	19	-	65	229	1.49	1.15
1935	26	46	26	11	13	62	164	1.32	1.00
1945	21	44	29	19	9	61	67	6.12	3.75
1950	31	39	28	17	9	86	173	3.78	4.05
1955	36	36	24	14	8	82	286	4.83	3.64
1960	45	35	23	15	8	120	394	7.20	3.78
1965	48	32	25	12	4	118	423	8.13	2.94
1970	49	36	18	13	3	226	667	12.09	3.23
1975	32	50	18	9	4	164	457	12.74	2.67
1980	29	50	22	11	3	154	391	15.32	2.50
1985	29	52	27	10	0	137	474	18.81	2.21
1990	32	30	10	20	0	0	440	37.87	4.80

(after Acott 1989; Warren 1990)

Preliminary attempts to link the land use changes to stream sediment and solute loads used Vollenweider's export coefficient approach, described in Jorgensen (1980) and Johnes & O'Sullivan (1989). Table 3 indicates the predicted losses of N for the Slapton catchments over the period 1905-1985 based on export coefficients for the different land uses. A trend of increasing total N losses is shown, with organic N as the main source of N loss. This pri-

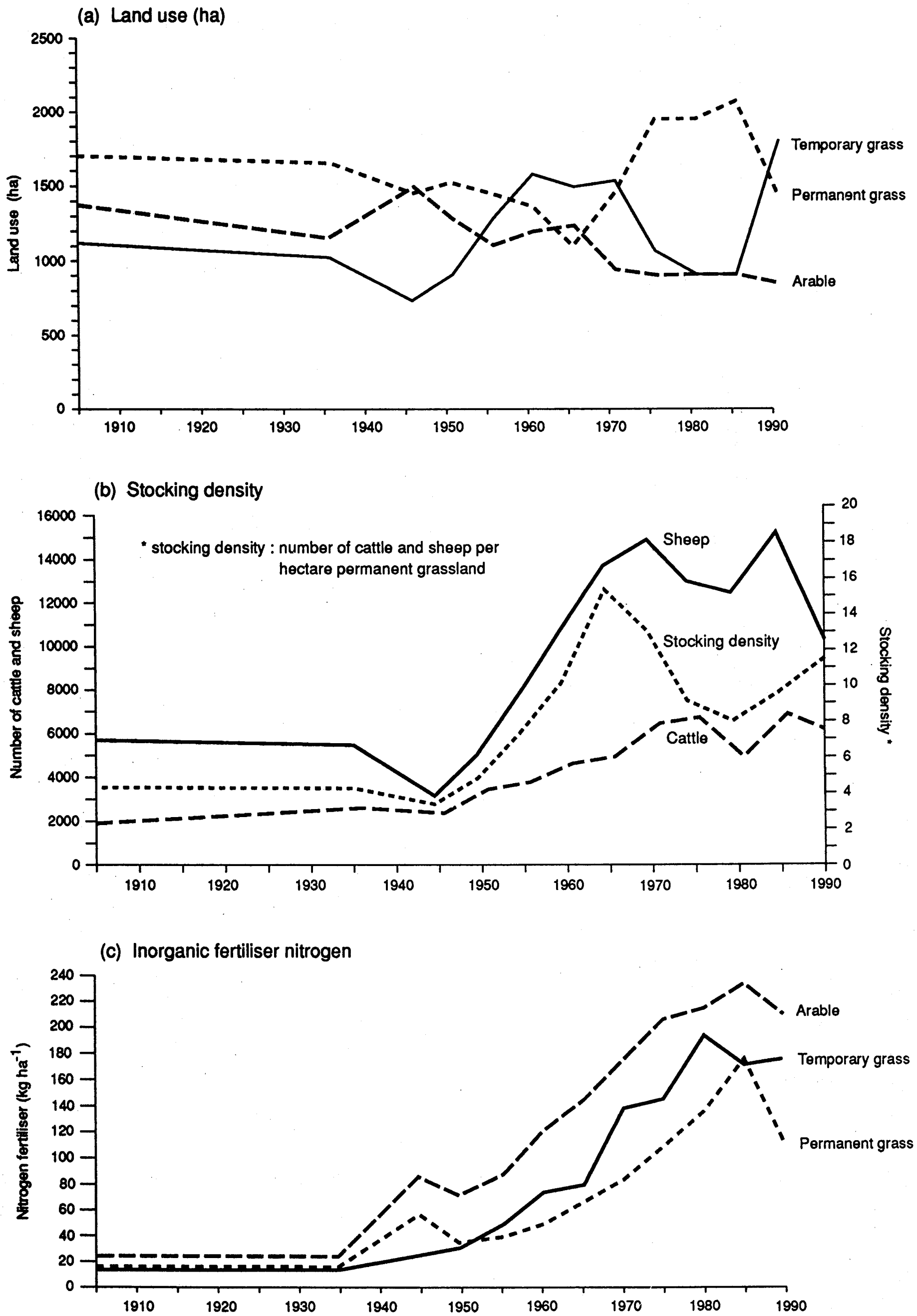

FIG. 1 Land use, livestock and inorganic N fertilizer application in the Slapton catchments from 1905 to 1990.

TABLE 5 Rainfall, runoff and NO_3N concentration and loads in the Slapton Wood catchment (after Burt et al., 1988).

Water year load	Rainfall (mm)	Runoff (mm)	Mean NO_3-N concentration (mg l^{-1})	Stream NO_3-N load (t)	Catchment NO_3-N (kg ha^{-1})
1971	1024	540	5.14	2.6	28
1972	832	333	5.94	1.8	20
1973	930	436	5.62	2.3	25
1974	1029	484	5.89	2.7	29
1975	921	538	6.40	3.2	34
1976	576	168	6.93	1.1	12
1977	1212	689	8.29	5.3	57
1978	970	569	7.66	4.1	44
1979	1063	580	6.82	3.7	40
1980	1089	557	6.85	3.5	38
1981	1162	601	6.69	3.7	40
1982	1119	607	7.75	4.4	47
1983	1108	654	6.80	4.1	44
1984	895	488	6.91	3.1	34
1985	1135	630	8.32	4.9	52
1986	1110	656	10.05	6.1	66
1987	997	531	9.20	4.5	49
1988	1253	581	8.65	5.9	64
1989	892	493	6.44	3.0	32
1990	1046	574	8.33	4.4	48

marily is caused by an increase in livestock. Note that these predictions relate only to potential N losses. Actual losses will be modified by land use location in relation to the stream. For example, land use in riparian zones is likely to be more significant than that in plateau areas. Furthermore, N losses will be modified by the various physical and biochemical mechanisms discussed earlier.

To assess the accuracy of these export coefficients for stream water quality change, predicted nutrient losses were compared with observed water quality changes in the Slapton Wood catchment This catchment has the longest water quality record (1970-1990) which is described further in Burt *et al.* (1988). Table 4 lists the land use, livestock and fertilizer application for the Slapton Wood catchment over the period 1905-1990. The proportion of temporary grassland, in line with changes in the Slapton catchments as a whole, increased from 1935 to 1975 and is reflected in an increase in permanent grassland. The proportion of arable land has fluctuated consistent with grassland changes, with root crops increasing in recent years. Livestock generally has increased over the period, but decreased since 1985, which may have been caused by milk quotas. The amount of fertilizer N and P applied has increased significantly over the period of study.

Table 5 lists the NO_3^- concentration and load over the period 1970-1990. A significant increase in stream NO_3^- concentration occurred during the study period (Burt *et al.*, 1988). Recently, the NO_3^- load has decreased. This may be linked to decreasing livestock and grassland area (Table 4). Changes in fertilizer use cannot be the cause because application rates increased during the period. The predicted Slapton Wood stream NO_3^- concentration based on export coefficients and the observed stream NO_3^- concentration are listed in Table 6. It appears that predicted concentration of inorganic N underestimate observed inorganic

TABLE 6 Predicted and observed long-term total N and NO_3^-N concentrations (mg l^{-1}) in the Slapton catchments.

Year	Predicted Total N[1] (all catchments)	Predicted NO_3-N[1] (all catchments)	Predicted NO_3-N[2] (Slapton Wood)	Observed NO_3-N (Slapton Wood)
1905	1.98	-	-	-
1935	2.33	-	-	-
1945	2.29	0.55	1.60	-
1950	2.71	0.36	2.32	-
1955	3.32	0.50	3.04	-
1960	4.08	0.78	3.77	-
1965	4.57	0.83	4.96	-
1970	5.62	1.17	5.22	5.14
1975	5.86	1.47	5.95	6.40
1980	5.07	1.60	6.67	6.85
1985	6.67	2.01	7.40	8.32

1 after Acott (1989)
2 after Burt *et al.* (1988)

N, whereas the predicted total N concentration is similar to the observed value. Two possible conclusions can be drawn from these results. First, total N derived from the catchment is readily transformed to inorganic NO_3^- in the stream. Second, hillslope physical and biochemical processes modify the potential land use export coefficient before it reaches the stream. In the case of the Slapton Wood catchment, these processes would have to transform organic N forms to inorganic N before they reach the stream.

CONCLUSIONS

Long term trends of catchment land use, livestock and fertilizer application have been examined in relation to observed water quality changes. An export coefficient approach for predicting the effects of land use on water quality falls short of accurately predicting stream water quality because it fails to account for the effect of physical and biochemical hillslope processes in modifying the potential sediment and nutrient export from different land uses.

Although hillslope hydrological pathways are fairly clearly delineated in the Slapton catchment, the relative importance of physical and biochemical modification, both down the hillslope and at different times of year, requires further research. Extension of export coefficient models to a more "process-based" approach, such as that described in Lee *et al.* (1989), is not possible until these "modifying" mechanisms are more clearly understood.

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