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Contributions of diffuse and point sources to the phosphorus loads in the River Main over a 22-year period

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Time series from 1974 to 1995 of the soluble reactive phosphorus (SRP), soluble organic phosphorus (SOP) and particulate phosphorus (PP) annual loads from the River Main, Northern Ireland (NI), were compared with changes in sewage derived phosphorus (P) loadings and the manure P load produced by farm animals in the catchment. A P reduction programme at the largest sewage treatment works in the catchment from 1980 had only a limited impact on river SRP loads from 1981 to 1984. River loads then increased, so that by 1995 they were 15 tonnes P higher than in 1974 despite a net 18 tonnes P reduction in the sewage derived P load over that period. When allowance was made for SRP inputs from towns and rural septic tanks, the remaining river SRP loads showed a pronounced upward trend from 1974 to 1995 with the rate of increase accelerating after 1986. This change point coincided with a change point in the manure P production time series which also showed an upward trend after 1986. Prior to that 1996 manure P production had been relatively constant form 1974. The increase in diffuse SRP loads from 1974 to 1986 was attributed to increasing soil P. A P budget for NI agriculture from 1974 to 1995 showed that the cumulative surplus was 28 tonnes P km^{-2}, while over the same period background or diffuse river loads increased by 0.058 tonnes P km^{-2} from 0.024 tonnes P km^{-2} in 1974 to 0.082 tonnes P km^{-2} in 1995**.** Annual flow was positively correlated with river loads of SRP, SOP and PP. Changes in sewage derived P were significantly correlated with SRP but not with either SOP or PP loads. Neither SOP nor PP loads showed any trend with time.

Introduction

Phosphorus (P) loss from agriculture to water has come under increasing scrutiny as a determining factor in the eutrophication of freshwater lakes and rivers (Sharpley and Withers, 1994, Tunney *et al*. 1997). In contrast to point sources of P, which typically enter surface waters via a pipe and are thus easily identified, agricultural P sources are a set of complex and varied inputs, in terms of their origin, timing and spatial distribution. Two factors may considered as influencing the P loss processes from agriculture: (a) P losses associated with animal manures, and (b) losses which reflect the accumulation of P in soils. They are not independent factors, as regions with high rates of animal manure production usually rely on imported foodstuffs and as a consequence have substantial P surpluses, leading to P accumulation in soils.

Point source P inputs from sewage treatment works (STWs) in the catchment of Lough Neagh, a large eutrophic lake in North-eastern Ireland, were reduced in the early 1980s. However from 1974 to 1991, there was a steady increase in non-point source inputs of soluble reactive P (SRP) loads to rivers draining into the Lough and observed reductions in river SRP loads, reflecting reduced point source P inputs, were of short duration (Foy *et al*. 1995, Smith *et al*. 1994). This background increase in SRP loadings was observed in each of the six rivers entering Lough Neagh and was considered to originate from diffuse or agricultural sources. Foy and Withers (1995) presented parallels between the diffuse SRP loading increase and the accumulation of P in Northern Ireland soils.

This paper presents an analysis of trends in the P loadings from one of the rivers entering Lough Neagh, the River Main, from 1974 to 1995. Loadings are compared with the changes in point source P inputs from STWs, the potential P loading from rural septic tanks, animal manure P loads to land and the likely accumulation of P in soils in the catchment. In addition to extending the data set already published for SRP, the paper presents long term changes of the two other P fractions which make up the total P (TP) load: soluble organic phosphorus (SOP) and particulate phosphorus (PP).

Study area

The River Main is the second largest river in the Lough Neagh catchment and it drains an area of 709 km^2 (Smith 1976, Wood and Smith 1992). Human population, animal numbers and agricultural land-use categories for 1974 and 1995 are summarised in Table 1. A P reduction programme has been operational since 1981 at the largest STWs complex in the catchment at Ballymena. The urban population within the P removal programme represents 74% of the catchment sewered population. Over the study period there was a modest increase of 1619 in the remaining sewered population but the rural population declined slightly by 572. Sewage treatment and disposal of the rural non-sewered population is via septic tanks. Land use is dominated by grassland which, when combined with upland rough grazing, accounted for over 90% of the farmed area. Apart from the area under grass which increased by 8%, all other land use categories declined between 1974 and 1995. From 1974 to 1995 cattle numbers declined by 1.2% but the sheep flock increased by 240%. The poultry and pig sectors, which relied on imported cereal foodstuffs, showed contrasting trends, with pig numbers down by 41% and poultry numbers up by 65%. The latter increase reflected a large percentage increase of 230% in chickens raised for meat production, while the egg laying flock declined by 22%.

Methods

P loadings

Grab water samples were taken from the River Main on a weekly basis from 1974 to 1995 at a location close to where the river enters Lough Neagh (Smith 1977). Three phosphorus fractions were measured on these samples using standard methodology: SRP, total soluble P (TSP) and total P (TP) (Murphy and Riley 1962, Eisenreich *et al*. 1975). The soluble P fractions were defined as those measured after filtration through a 0.45 µm membrane filter. Annual P loadings were calculated for each of these P fractions using log P concentration vs log flow regression equations, each regression equation employing the P concentrations measured in the calendar year (*see* Foy *et al.* 1995 for references). River flows were derived from a continuous river level record. The method of P load calculation employed in this paper differs slightly from that used previously, as a factor has been incorporated into the regression equations to correct for the inherent bias towards underestimating loadings of equations based on log transformed data (Ferguson 1987, Lennox *et al.* 1997). In this paper three sets of annual P loadings are presented: the SRP loading, the SOP loading, which is the difference between the TSP and SRP loads, and the PP loading which is the difference between the TP and TSP loads.

Annual TP loadings for Ballymena STWs, based on regular 24 hour composite samples, were provided by the operator of the works from 1981 but, prior to 1981, were available only for 1974 and 1979–80. TP loadings from STWs were converted to SRP loadings using conversion factors based on short-term studies on the Ballymena STWs, given by Storey (1990), which computed the SRP fraction in the effluent to be 64.8% of TP loading when P reduction was not operational and 38.5% when it was operational. Because of the proportion of SRP in treated effluent was lower post P reduction, the SRP reduction rates were proportionally greater than TP reduction rates when P reduction was operational (Foy *et al.* 1995). Loadings of TP from the next two largest towns, Randalstown and Cullybackey, are those given by Smith (1976) for 1974 and loadings measured in 1994 by the operator of the STWs.

Table 1. Land use, animal numbers and human populations in the River Main catchment 1974–1995.

		1974	1995	Change (%)
Agricultural land (km^2)				
Grass		384.3	415.8	8.2
Rough grazing		152.5	113.6	–25.5
Arable crops		46.1	30.8	–33.2
Woods		5.9	3.9	–33.3
Other land		22.8	8.9	–61.1
Animal numbers (nos.)				
Bulls		542	864	59.4
Dairy cows		23 934	24 821	3.7
Beef cows		17 316	14 638	–15.5
Other cattle	> 2 yr. old	5 685	5 939	4.5
	1–2 yr. old	19 223	20 613	7.2
	0–1 yr. old	26 181	24 904	–4.9
Total cattle		92 881	91 779	–1.9
Sheep	Breeding	23 667	73 132	209.0
	< 1 yr. old	1 663	3443	107.0
	0–1 yr. old	19 218	74 761	289.0
Total sheep		44 548	151 336	239.7
Pigs		72 296	42 427	–41.3
Poultry ($\times 10^3$)	Laying flock	942	736	–21.9
	Broilers	500	1 649	229.5
Total poultry		1 443	2 385	65.3
Human populations				
Sewered	Ballymena	28 495	31 619	11.0
	Randalstown	2 771	3 846	38.8
	Cullybackey	1 956	2 116	8.1
	Other centres	5 041	5 325	5.4
Total sewered		38 263	42 906	12.1
Unsewered		19 374	18 802	–3.0

The loading of TP from the remaining towns has been estimated from population and annual P *per capita* values. The latter were calculated as given by Foy *et al*. (1995) and vary according to changes in detergent and dishwasher P *per capita* and assume a 10% retention of P as sludge in the STWs. Estimates of the P loading for the rural population are also based on the product of population and the annual P *per capita* but with a weighting factor to allow for removal by sub-soil soakaways. Although the septic tanks which serve the rural population are supposed to discharge to sub-soil soakaways, it is generally assumed that a significant number do not use an efficient soakaway and discharge in part to surface drains. In this study a weighting factor of 0.6 has been used to allow for removal by soakaways. This factor is derived from regression equations of annual SRP loads vs urban and total populations for the Lough Neagh rivers presented by Smith (1977). Non-sewered or rural population densities in these rivers was less variable than urban population densities so that the slopes of the SRP loads vs urban and total population densities equations were similar but the intercepts differed. The intercept difference reflects the contribution of the rural population and can be shown to be equivalent to the non-sewered population having a SRP *per capita* of 1.0 g P person^{-1} day^{-1}. This, in turn, represents 60% of the 1.5 g P daily *per capita* value estimated for the sewered population in that study.

Table 2. Manure P animal *per capita* (Anon. 1996).

	kg P head^{-1} yr^{-1}
Cattle	
Bulls	13
Dairy cows	13
Beef cows	10
Heifers (> 2 yr. old)	10
Heifers (< 2 yr old)	8
Other cattle (> 2 yr. old)	10
Other cattle (1–2 yr. old)	8
Other cattle (< 1 yr. old)	3
Sheep	
Breeding flock	1
Sheep (> 1 yr. old)	1
Sheep (< 1 yr. old)	0.5
Pigs	2.75
Poultry	
Laying birds	0.22
Broiler	0.19

Land use, animal and human population numbers

Human population statistics were obtained from the population censuses of 1971, 1981 and 1991. Between census population estimates were based on changes in the electoral rolls which are revised annually. Land-use and animal numbers were obtained from the annual farm census of the Department of Agriculture for Northern Ireland (DANI). Historically this data is presented by rural districts which cover comparatively large areas. To convert rural district values to catchment based values, weighting factors for the five rural districts in the Main catchment were based on the area of each in the catchment: 0.824 × Ballymena, 0.172 × Antrim, 0.128 × Ballymoney, 0.046 × Larne and 0.005 × Ballycastle. An exception to this was the numbers of broiler chickens which were only presented by county, a larger administrative unit than rural district, up to 1980. For this period catchment broiler chicken numbers were based on a county weighting factor which reflected the proportion of broilers in the Main catchment in 1981 relative to the County Antrim total for that year. The farm census outputs categorise animal numbers by age, sex and type (e.g. beef and dairy cows) and this breakdown was used to estimate manure P weightings based on the product of animal numbers times a manure P *per capita*. The manure P *per capita* employed are listed in Table 2 and are those produced by the Department of Agriculture in the Republic of Ireland for use in nutrient management planning on farms (Anon. 1996). The value given for pigs is based on per sow place and assumes that, for each sow, there were seven other pigs. External inputs of P to agriculture in Northern Ireland (NI) are imported fertilisers and foodstuffs and statistics on these inputs are also collected by the DANI, which also monitors production outputs. These inputs and outputs have been used to calculate a P balance for NI from 1974 to 1995. This balance is available only for Northern Ireland (NI) and not for specific river catchments.

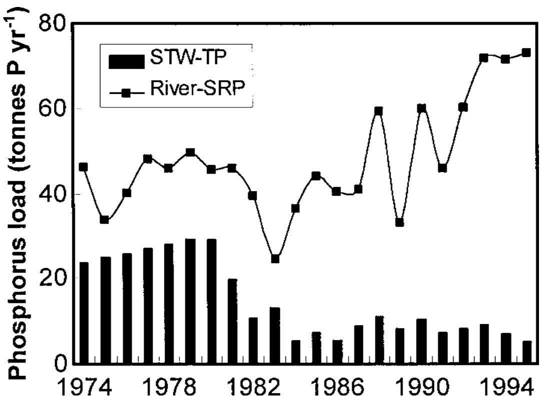

Fig. 1. Annual River Main SRP loads and TP loads from Ballymena STWs 1974–1995.

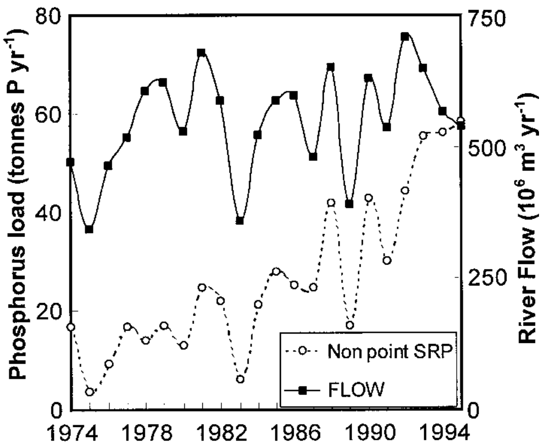

Fig. 2. Computed diffuse River Main SRP load and annual river flows 1974–1995.

Results

River P loadings

Long term changes in the River Main SRP loads and in the TP loadings from the Ballymena STWs are shown in Fig. 1. STWs TP loadings from 1975 to 1978 are estimated by interpolation between TP loadings measured in 1974 and 1979–80. Although SRP is the dominant P fraction in the TP load from STWs, reducing STWs P loads from 1981 onwards only resulted in reduced river SRP loads from 1981 to 1983. From 1984, river SRP loads increased so that, by 1995, the annual SRP loading was 26.7 tonnes P higher than measured in 1974, despite a reduction of some 18.4 tonnes P in the TP loading from Ballymena STWs over the same period. Changes in TP loads from point sources show that the loadings from the other towns in the catchment altered little over the period, as did the estimated loading from the non-sewered rural population (Table 3). Therefore, the river increase in SRP cannot have originated from either towns or from the rural population.

Measured SRP loadings have been reduced by the estimated SRP contribution from Ballymena STWs, small towns and the rural populations (Fig. 2). Annual loadings for the small towns and the rural population were calculated by interpolating between the 1974 and 1995 loads and assuming that the proportion of SRP in the effluent was 0.648. The resulting loading, representing diffuse SRP sources, is shown to have been increasing from the commencement of the study period in 1974 and this increase appears to have accelerated after 1987. The considerable year on year variation evident in loads around the upward trend can, in part, be related to changes in flows; for example, the low flow years of 1975, 1983 and 1989 had markedly reduced diffuse SRP loadings (Fig. 2).

In contrast to SRP, loadings of SOP and PP showed no discernible trend over the study period (Fig. 3). Both SOP and PP loadings were positively correlated with annual flow, $R^2 = 0.39$ and 0.61 respectively. The regression of annual SRP load with flow gave an R^2 value of 0.39. Of the three TP fractions, the least abundant fraction was SOP, with a mean load of 13.7 tonnes P yr^{-1}, followed by 22.4 tonnes P yr^{-1} of PP and 48.1 tonnes P yr^{-1} of SRP.

Table 3. Computed changes in the TP load (tonnes P yr^{-1}) in the River Main catchment from the human population.

	1974	1995
Sewered population		
Ballymena	23.7	5.3
Other towns	10.4	9.3
Non sewered population	11.3	10.0
Total	45.4	24.6

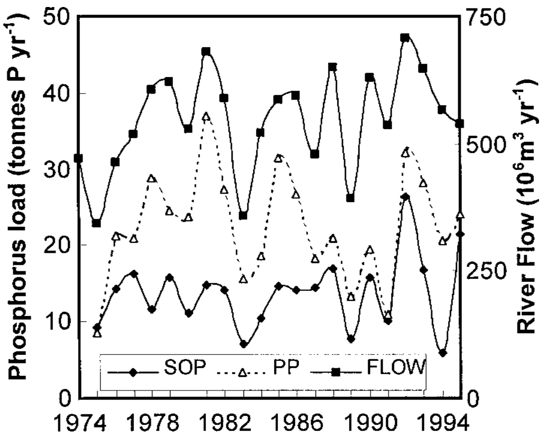

Fig. 3. River Main SOP and PP loads and annual river flows 1974–1995.

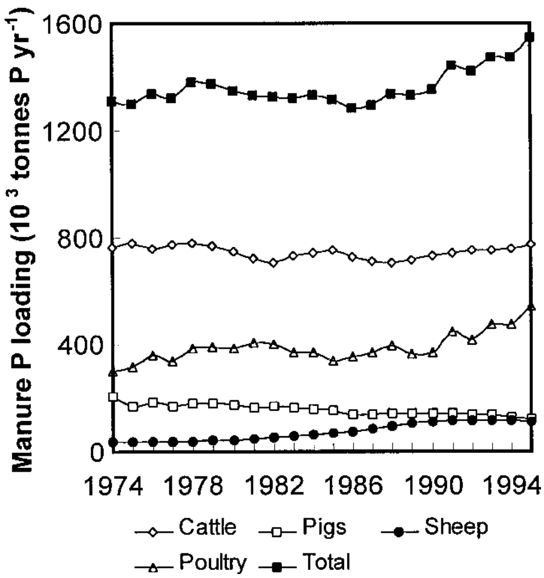

Fig. 4. Animal manure P loads in River Main catchment 1974–1995.

Agricultural P inputs

Annual manure P loads in the Main catchment increased by 18.2% or by 238 tonnes P from 1974 to 1995, due primarily to a higher poultry manure P load which had increased by 240 tonnes P (Fig. 4). Changes in the contributions from other animal categories were minor in terms of their impact on the total manure P loading. Cattle, the largest fraction of the animal manure P load, increased by only 1.1% and, although sheep numbers trebled (Table 1), they contributed less than 9% of the manure P total. From 1974 to 1986, there was not a consistent period of increasing manure P loadings and the manure P load in 1986 was 1.7% lower than in 1974. The expansion of the broiler chicken sector after 1986 caused the total manure P load to increase and this increase therefore parallels the period when river diffuse SRP loadings began to increase more rapidly (Figs. 2 and 4).

Since 1945 the principal features of the P budget for NI agriculture have been (a) the large P inputs from imported animal foodstuffs, which approach in magnitude the fertiliser P input, and (b) the modest scale of P exported as a percentage of agricultural P inputs (31% of P inputs). From 1974 to 1995, this imbalance between P inputs and outputs resulted in an average annual P surplus of 12 650 tonnes P yr^{-1} (Fig. 5). As the agricultural land area devoted to agriculture, including rough grazing, in NI is 10^4 km^2, this surplus is equal to an annual surplus of approximately 1.3 tonnes P km^{-2}. From 1974 to 1995, the accumulated agricultural P surplus was therefore 28 tonnes P km^{-2} which compares with the much smaller increase in the background SRP losses in the River Main over the same period. These increased from 0.024 tonnes P km^{-2} in 1974 to 0.082 tonnes P km^{-2} in 1995, an increase of 0.058 tonnes P km^{-2}.

Regression analyses

Annual flow, TP loading from Ballymena STWs, annual manure P load for the Main catchment and time were employed as independent variables in multiple regression analyses with annual SRP, SOP and PP loads as dependent variables. Time was employed as surrogate variable to represent the linear accumulation of P in soils presented in Fig. 5. The regression analyses include the measurements for the years 1979 to 1995, when there was a continuous record for the TP loadings from the Ballymena STWs. Apart from annual flow, no other variable was significantly correlated at the $P < 0.05$ level with either the SOP or PP loads and only the results of the SRP multiple regression analyses have been presented here.

Two multiple regression analyses are presented, the first of which employed the measured values for individual years (Table 4). In this regression (a), the flow and time variables were included as significant at the $P < 0.05$ level, and the flow variable was significant at the $P < 0.001$ level. The flow coefficient can be considered as an estimate of the river SRP concentration from diffuse sources in 1979, with a value of 0.066 mg P l^{-1}. The regression coefficient of 1.9 tonnes P yr^{-1} for the time variable gives an estimate of the annual rate of SRP load increase in the River Main. If this value is divided by the mean annual river flow of 547×10^6 m^3, the resulting concentration of 3.5 µg P l^{-1} provides an estimate of annual underlying increase in river SRP concentration. The coefficient of 0.64 for the STW TP load variable indicates that a change in 1 tonne P in the loading of TP from the STWs results in a 0.64 tonne P in the measured river SRP load. The significance level ($P = 0.063$) for this coefficient was slightly greater than the critical significance level of $P = 0.05$. The coefficient of 0.64 for STW TP was much larger than the value of 0.053 for the manure P load variable, indicating that river SRP changed by only 0.053 tonne for each 1 tonne of manure P produced in the river catchment. However the significance level for this variable was poor at $P < 0.12$.

A theoretical objection against this treatment of time series is that the data points in the series may not be independent from each other (e.g. Pankratz 1991). For example, the manure P load in any year is very likely to be similar to that in the preceding year. This can be over-come by detrending the data, so that the regression analysis is performed on observations which are the year-on-year changes. That is, the observations used for 1980 are calculated as differences between the measurements for 1979 and 1980 and so the number of observations is reduced by 1. As the series are detrended there is no time variable to be included in the regression analysis (Table 4b).

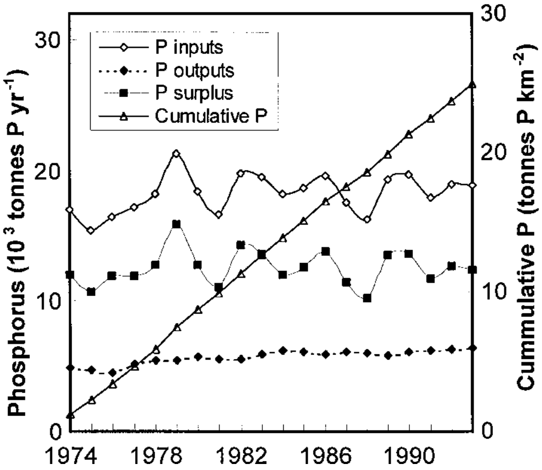

Fig. 5. A phosphorus balance for agriculture in Northern Ireland 1974–1995.

Flow was the dominant variable in the detrended regression analysis but, in contrast to the standard multiple regression, the regression coefficient for STW TP load was significant at the $P < 0.05$

Table 4. Summary of SRP multiple regression analyses (1979–1995 data) (STW TP = Ballymena STW TP load).

Variable	Regression coefficient	95% Confidence limits	Significance level (P)	R^2
(a) not detrended (17 observations)				
Flow (10^6 m^3 yr^{-1})	0.066	± 0.31	< 0.001	
STW TP (tonnes P yr^{-1})	0.64	± 0.68	0.063	
Time (1979 = 1)	1.89	± 1.40	0.012	
Manure P load (tonnes P yr^{-1})	0.054	± 0.07	0.117	
Intercept (tonnes P yr^{-1})	–86.5	± 81.8	0.040	0.898
(b) detrended (16 observations)				
Flow (10^6 m^3 yr^{-1})	0.079	± 0.024	< 0.001	
STW TP (tonnes P yr^{-1})	1.01	± 0.80	0.018	
Manure P load (tonnes P yr^{-1})	0.028	± 0.09	0.509	
Intercept (tonnes P yr^{-1})	3.07	± 3.56	0.084	0.851

level. In contrast the significance level of the manure P variable decreased to $P = 0.50$ in the detrended analysis. The intercept is an indication of the underlying rate of annual increase, but the value 3.07 tonnes P yr^{-1} was only significant at $P = 0.084$. When the manure P variable was excluded from the regression analysis, this had little impact on either the R^2 value which was reduced from 0.851 to 0.846 and the regression coefficients for the STW TP and flow variables. The intercept of this regression increased to 3.42 tonnes P yr^{-1} and was significantly different from zero ($P = 0.043$). These two intercepts, 3.07 and 3.42 tonnes P yr^{-1}, when divided by annual flow, gave estimates of 5.6 and 6.2 μg P l^{-1} yr^{-1} for the rate at which river SRP concentrations were increasing.

Discussion

The data presented here has confirmed earlier studies showing increasing SRP loss rates in the River Main catchment (Foy *et al.* 1995, Foy and Bailey-Watts 1998, Smith *et al*. 1994). Although loadings presented for the contribution of P from septic tanks and small villages are not based on direct measurements, the human populations covered by these sources showed little change over the study period. Therefore it is highly unlikely that they could have been the source of the observed increase in SRP loss rate. Moreover, the magnitude of this increase is such that it exceeds the P loadings from either septic tanks or small towns. In contrast to SRP, neither the SOP nor PP loads showed any evidence of change with time. The predominance of SRP as a fraction of TP loading, as observed in the River Main, can be taken as an indication of high sewage derived P inputs to a river (Cooke 1976, Muscutt and Withers 1996). However, there is now a substantial body of field derived evidence showing that SRP is a large, and often the largest, component of the TP lost in drainage from grassland, particularly from fertile grassland, which is the dominant land use in the Main catchment (e.g. Dils and Heathwaite 1996, Haygarth *et al*. 1998, Lennox *et al*. 1997, Nash and Murdoch 1997, Nelson *et al*. 1996).

Examples of increasing diffuse P sources inputs with time are comparatively limited, but this may simply reflect a paucity of long term data sets and, where long term time series do exist, it can be difficult to separate the impacts of diffuse and urban point sources (Muscutt and Withers 1996). Johnes *et al.* (1996) showed that P concentrations increased over a 60 year period in ten, largely rural, English and Welsh rivers. These increases were attributed primarily to greater stock numbers on farms. TP concentration increases in small Finnish streams, observed over a 15 year period, were greatest in streams with a high proportion of arable land (Rekolainen 1991). In Northern Ireland the increase in SRP load reported in the Main catchment was observed in all the major rivers draining into Lough Neagh (Foy *et al.*, 1995). Anderson (1997) used the diatom sedimentary record of six lowland rural lakes in Northern Ireland, to produce diatom inferred lake TP concentrations, and the reconstructed TP history of each lake showed that lake TP concentrations began to increase after 1950.

Differing sources for observed increases in diffuse P loads in rivers have been proposed. The catchment export coefficient model of Johnes *et al.* (1996) employs land-use types and catchment manure P production and is similar to a model given by Bilaletdin *et al.* (1991) for TP concentrations in Finnish catchments. Both models place particular emphasis on the impact of increased manure P production on P losses to water. The importance of manure application rates on P export is evident from measurements of P in drainage from a small grassland catchment close to the Main catchment in NI which have shown dramatic increases in SRP and TP loss rates immediately after the application of animal manure slurry (Jordan and Smith 1985; Lennox *et al.* 1997). However studies on the same site have shown that, over a ten year period, median SRP concentrations increased at a rate of approximately 1 μg P l^{-1} yr^{-1}. This increase was attributed to the P accumulation in soils in the drainage area leading to higher SRP concentrations in the leachate (Smith *et al.* 1995). Elevated soil P, caused by an imbalance between P inputs and outputs, was associated with enhanced SRP in drainage water from an arable experimental site in England (Heckrath *et al.* 1995). The importance of accumulating soil P as a water quality issue has been highlighted by Sharpley *et al*. (1994), while programmes to limit agricultural P losses to water in Denmark, Netherlands and Sweden include measures to bring agricultural P inputs and outputs into balance (Archer and Marks 1997). Reviewing the effectiveness of non-point source control measures introduced in Wisconsin USA, Garrison and Asplund (1993) attributed their failure to halt an increase in lake TP concentrations to a continued build-up of soil P.

In the River Main catchment, diffuse SRP losses increased up to 1986, despite a stationary manure P load, suggesting that increasing soil P is an important driver of environmental change. The accelerated rate of increase in P losses observed after 1986 coincides with increased manure P production. The initial multiple regression analysis produced a coefficient for the manure P variable for which losses were equivalent to 5% of inputs, which is close to the range of values proposed by Johnes *et al.* (1996). However in neither of the regressions in Table 4 was the manure P variable included at the $P = 0.05$ level and, in the detrended analysis, the impact of the manure variable on SRP loss rates was slight. Overall, it is difficult to argue that the modest increase in manure P in the catchment observed since 1974 has been the dominant driver for the much larger percentage increase in SRP loss rates.

The estimates given for the rate of river SRP increase were in the range of 3.5 μg P l^{-1} yr^{-1} to 6.0 μg P l^{-1} yr^{-1} and are substantially higher than the rate of 2 μg P l^{-1} yr^{-1} estimated using the pre-1992 data set of the River Main and other Lough Neagh major rivers (Foy *et al*. 1995). This latter value is in agreement with the range of 0.3–2.3 μg P l^{-1} yr^{-1} for five of the six lake TP increases given by Anderson (1997). Anderson (1997) speculated that sixth lake, which had an increase rate of 11 μg P l^{-1} yr^{-1}, reflected the impact of point source inputs of manures. However, as recorded farm pollution incidents in NI have declined since 1987, it is difficult to argue that farm-yard pollution is the cause of recent SRP load increases observed in the Main (Lennox *et al*. 1998).

There are two additional points to be made with regard to the high SRP loss rates observed from the Main. The first is that the Main may indeed be expected to have a higher than average P loss rate as it has a disproportionate share of the poultry industry in Northern Ireland, with 16% of poultry numbers compared to 5% of the farmed area. Proportions of cattle, sheep and pigs are broadly in line with the farmed area. As the poultry sector relies on imported foodstuffs, the Main catchment P surplus will be greater than average. The second point relates to the SRP loads from 1993 to 1995 which were over 10 tonnes P higher than recorded in any previous year. These high loads reflect more scatter than normal in the SRP concentration vs river flow regressions used to determine loads and in each of these years one or two observations had a large impact (> 10%) on the computed annual SRP loads. The 1996 river SRP loading of 60 tonnes P, although considerably higher than loads in the mid 1980s, was 13 tonnes P less than the 1995 value despite a higher river flow in 1996. Unfortunately TP loadings from the Ballymena STW were not available to include in this paper.

Conclusions

The results from the Main catchment have shown that P losses rates from diffuse sources have increased over a 20 year period to the extent that the reduction of a major point source of P now appears as a comparatively minor change in the time series of river loadings. The annual increase is small but the cumulative effect measured over decades will have dramatic effects on the trophic status of lakes and rivers. It is argued here that the increase in SRP inputs from diffuse sources was due primarily to an increase in soil P, as there was not a dramatic increase in manure P application rates. As the imbalance between P inputs and outputs is a standard feature of livestock farming in Europe and the USA, the effects on the River Main P loadings suggest that these regional surpluses provide a long term threat to water quality.

The management of lakes will therefore increasingly have to look to the agricultural sciences and it will be necessary to examine the use of P in agriculture in terms of environmental impact. Soil P tests which are appropriate for agriculture may not give a good indication of environmental risk and new tests for assessing risk may be required (Edwards *et al.* 1997). P recommendations for agriculture have tended not to consider the effects of P on water quality, arguing that it is immobile in the soil (Cooke 1976). The results from the Main have shown that that this is true only up to a point given the differences in scale between P accumulation and increases in river SRP loads. To date, measures adopted in European agriculture for protecting the aquatic environment have focused on restricting nitrate and sediment loss. These may not be appropriate for P, especially in situations where soluble P fractions predominate. For example buffer strips may be of limited use in grassland farming where a large proportion of the P is in soluble forms. Maximum manure application rates imposed to protect against excessive nitrate leaching will inevitably oversupply with P, as manures are relatively richer in P than nitrogen.

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