PHOSPHORUS LOADING FROM A RURAL CATCHMENT – RIVER DEEL, CO. MAYO, IRELAND, – A TRIBUTARY OF LOUGH CONN

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ABSTRACT
Total phosphorus (TP) loading to Lough Conn from the Deel River, Co. Mayo, Ireland was measured in detail over a 2-year period: 1998–1999. The TP load emanating from a 227 km^2 catchment was measured by analysing TP in daily composite water samples (six sub-samples/day) and multiplying the resultant TP concentrations (µg P/l) by the corresponding daily flow (m^3/s) measurements. Three smaller agricultural sub-catchments were sampled on a weekly basis in 1998 and 1999 and two of these were also sampled on a daily basis during 1995. Routine monitoring phosphorus data were also available for the major sewage works in the catchment (p.e. 1100) – i.e. in the river both upstream, downstream of the plant and also for the inflow to and outflow from the sewage works. The TP loads for 1998 and 1999 were 18.4 t P and 15.9 t P, respectively. The phosphorus loading was apportioned to different sources by reference to detailed GIS data for individual sub-catchments and by measurement of the major point source discharge. Diffuse agricultural losses accounted for an average of 59% of the total measured TP loss from the catchment in 1998 and 1999.

Keywords: agricultural pollution, phosphorus loading, source apportionment

INTRODUCTION
The apportionment of diffuse phosphorus loading to aquatic systems back to its individual sources is a difficult task. Accurate measurements of P loading to the river or lake in question are required. Kronvang and Iversen (2002), for example, demonstrate that infrequent fortnightly or monthly sampling in small catchments (<100 km^2) can lead to greater than 100% underestimation of phosphorus loading in comparison with 'true' loads measured with fully automated flow-proportional sampling. The tendency of P concentration to be positively correlated with river discharge in regions where diffuse agricultural losses dominate the P loading means that it is critically important to sample frequently during flood events, when a significant proportion of total P losses can occur. The second important requirement in apportioning the end-of-catchment P loading back to its individual sources is a detailed knowledge of the catchment concerned. All potential sources of P losses must be known in as much detail as possible. A detailed knowledge and understanding of the pathways by which phosphorus reaches watercourses is also desirable.

This study used time-proportional automatic samplers (six sub-samples/day) in order to produce an accurate record of average daily TP concentrations at the end of the Deel River catchment over the 2-year period 1998–1999. Daily flow measurements were also available over the period from an automatic flow gauge located at Knockadangan Bridge.

The second requirement – that for detailed catchment information – was dealt with in this study by use of a combination of GIS-based land-use maps, agricultural and population census data, measurement of point source loadings and an estimate of 'background' loadings. While in theory there is an infinite number of ways of apportioning the loading to individual sources, in practice some are more likely than others. It is possible to put upper and lower limits on point sources, for example, relatively easily if chemical analyses of the quality of the effluents discharged are available together with effluent volume information or by reference to standard per-capita figures for treatment plant discharges.

Modelling techniques also provide additional possibilities for improving source apportionment estimates through a more detailed modelling of pathways by which P is lost to water (e.g. Daly *et al.* 2002). Such modelling was not used in this study but a large research project currently under way in Ireland – a €3.4M Teagasc/EPA-funded study entitled 'Eutrophication from Agricultural Sources' is developing models for use in Irish catchment management (see www.epa.ie).

METHODS
The Deel River catchment is a predominantly rural catchment with a population of just under 2900 persons (38% sewered population and 62% in houses using septic tanks) averaging almost 13 persons/km^2. The total cattle population in the catchment was estimated from the agricultural census as 12,800 and the sheep population as 18,400. Forestry and peat harvesting are the only other significant activities within the catchment that have a bearing on TP loading. There are no important industrial activities that discharge significant effluents to water within the catchment. The catchment is shown in Fig. 1 and characterised in Table 1.

Table 1. Catchment characteristics for Deel River and its sub-catchments.

		Catchment						
		Deel	Upper Deel	Mid Deel	Rappa	Tooreen	Rath-namagh	Lecarrow
Catchment Area (km^2)		227	152	11	23	13	14	14
Population								
Total Population	1	2,860	890	290	730	400	275	275
Estimated Rural Population	1	1,760	610	40	730	100	185	95
Estimated Urban Population (Crossmolina) in each catchment	3	1100	280	250	0	300	90	180
Agricultural Census								
Total Cattle	2	12,867	5,021	1,194	2,812	1,079	1,543	1,218
Total Sheep	2	18,424	13,728	1,001	1,306	779	643	967
No. Farms	2	431	199	40	84	31	39	38
No. Tractors	2	324	149	23	63	27	31	31
Milking Equipment Units	2	63	7	7	20	10	14	5
Silage area (% catchment)	2	6	3	13	14	10	12	9
Rough Grazing (% catchment)	2	17	20	4	11	16	8	17
Tillage land (% catchment)	2	1	0	4	3	1	2	1
CORINE Land Cover (% catchment)								
Intensive Pasture	5	16	2	55	54	31	33	33
Low intensity Pasture	5	7	5	25	13	12	0.22	10
Mixed Intensity	5	9	1	9	7	46	42	38
Natural grasslands	5	2	3	0	0	0	0	0
Worked Bog	5	2	3	0	0	0	0	0
Native Peat Bog	5	51	70	8	18	10	10	19
Soil Type (% catchment)								
High level blanket peat	6	4	6	1	0	0	0	0
Low level blanket peat	6	58	83	0	0	12	0	41
Peaty podzols	6	2	4	0	0	0	0	0
Lithosol 4	6	1	1	5	0	0	0	0
Degraded Grey Brown Podzols	6	28	6	79	59	88	69	59
Basin peat	6	7	0	15	41	0	31	0
Soil Drainage Type (% catchment)								
Well Drained	6	29	7	92	58	88	69	59
Poor Drainage	6	68	89	8	42	12	31	41
Excessive Impedance	6	3	4	0	0	0	0	0
Bedrock Geology (% catchment)								
Lower Avonian/Carboniferous	7	33	51	0	0	0	0	0
Quartzite	7	9	14	0	0	0	0	0
Schist / Gneiss	7	7	11	0	0	0	0	0
Upper Carboniferous Limestone	7	51	24	100	100	100	100	100
Forest Cover (1998) % of catchment								
Broadleaf forest	4	1	0	5	2	0	5	0
Coniferous forest	4	6	8	0	0	0	0	2
Mixed forest	4	0	0	0	0.1	0	0	0
Other forest	4	0	0	1	0.3	0.02	0.2	0
Clear-felled	4	5	7	0	0.1	0	0	0
Planting Grant Applied for	4	3	4	1	1	0	1	0
Mature Plantation	4	2	2	5	2	0	5	0
Young Plantation	4	7	11	1	1	0	1	2
Total Forest Cover	4	24	32	13	6.5	0.02	12.2	4

Data Sources:
1. Estimated from Central Statistics Office 1996 and 2002 Census data
2. CSO Agricultural Census (1991)
3. Mayo County Council
4. FIPS – DMNR/Coillte National Forestry Inventory & Planning System 1998
5. CORINE landcover 1990
6. Teagasc - Soil Survey data
7. Geological Survey of Ireland Geology of Ireland Bedrock Map

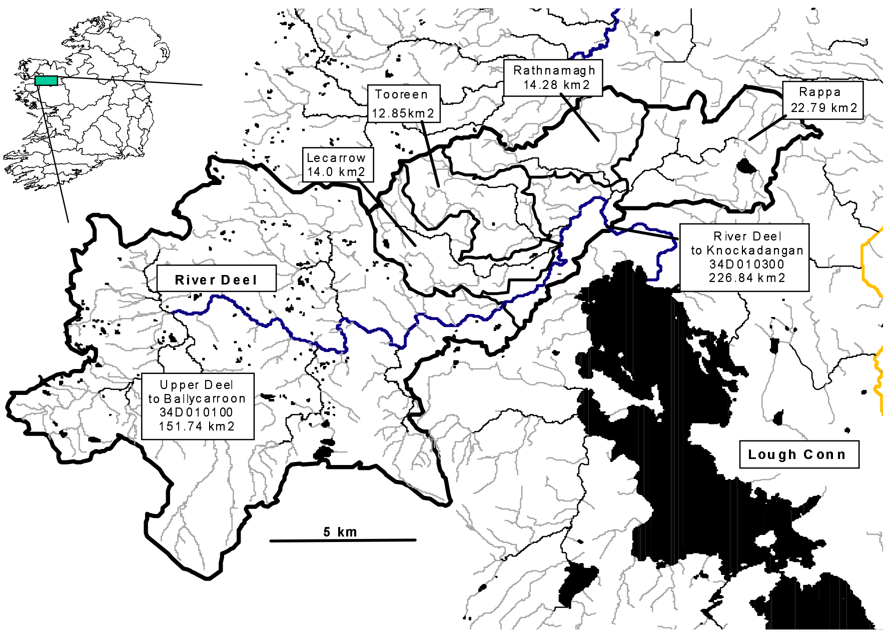


Fig. 1. The Deel River and sub-catchments included in the study.

During 1998 and 1999, time-proportional daily composite samples were taken at Knockadangan Bridge (34D010300, NG 115760, 319245) on the River Deel, upstream of the confluence with Lough Conn, but downstream of Crossmolina, using a Sigma autosampler. The autosampler was programmed to take a sample once very 4 hours and to combine six such sub-samples into one container each day in order to create a single composite sample per day. Some 483 composite samples were obtained over the 2-year period equivalent to almost 3000 individual water samples. TP concentrations for missing samples (e.g. due to low battery or other malfunction) were interpolated. Weekly grab samples were also taken at the lowermost bridges in the catchments of the Tooreen, Rathnamagh and Rappa rivers. Continuous daily flow (m^3/s) measurements were made by a continuous flow recorder on the River Deel at Knockdangan Bridge which is maintained by Environmental Protection Agency (EPA) hydrometric staff. On the other tributaries, water level was read from flow-rated staff gauges on a weekly basis when water samples were being taken. Samples were analysed for TP using acid digestion on a high-temperature block followed by ascorbic/molybdate colorimetric analysis on a Technicon autoanalyser. To ensure maximum accuracy, eight standards were run at the beginning, middle, and end of each analysis batch over the concentration range 0 to 200 µg/l P. The lowest limit of detection was 1 µg/l with a precision of ±1µg/l P (Donnelly, 2001). Additional information was available for the inflow and outflow of Crossmolina sewage treatment works from regular sampling and analysis carried out by the EPA since 1979. These data included corresponding upstream and downstream samples on the Deel River. This enabled the impact of the discharge from the Crossmolina sewage treatment works (population equivalent 1100) to be assessed quite accurately. Biological assessment of the river Deel downstream of the sewage treatment works has also been carried out since the early 1980s. Monthly EPA ambient monitoring data for unfiltered molybdate reactive phosphate (MRP) concentrations, were also available for the Deel River at Ballycarroon, 2.5 km upstream of the town of Crossmolina and these were converted to TP values by use of TP:MRP ratios. An additional year-long continuous monitoring programme for TP was also carried out during 1995 for two rural catchments, the Tooreen and Rappa rivers. This dataset was used to demonstrate the pattern of the diffuse agricultural runoff in the Lower Deel catchment, downstream of Crossmolina. Daily rainfall values were obtained from Met Éireann for three nearby rainfall stations (Lahardane, Straide and Ballina). These were used in interpolating flow values on the sub-catchments that were sampled weekly rather than daily and also as quality control on flow readings generally. Precipitation ranged from 1322 to 1775 mm/year at the three stations with amounts quite similar in both 1998 and 1999.

Geographical Information System (GIS) data for the catchments surveyed included, *inter alia,* CORINE land cover data (1990), Agricultural Census Data (1991), Population Census (1996), Teagasc soil survey data, bedrock data from the Geological Survey of Ireland and forestry data from the national Forestry Inventory and Planning System.

Total phosphorus loadings for the River Deel were calculated on a daily basis at Knockadangan Bridge. This was calculated by multiplying the daily discharge in the river (m^3/s) by the corresponding average daily concentration (µg/l) and correcting to give load as kg P/day. Daily load values were then summed over each entire 365-day period to give annual P loading. For those sub-catchments where grab samples were taken and spot-flow measurements were made, concentrations and flows were interpolated to give a 365-day flow concentration record for each year. Because total phosphorus was positively correlated with flow (i.e. highest concentrations tend to occur during the highest flows), in many of these streams a flow model based on soil moisture deficit and recent rainfall was used to predict flow, particularly for the winter months.

Table 2. Measured TP loading from River Deel sub-catchments for 1998 and 1999.

	Annual Total Phosphorus Loading (kg/year)			
Catchment	Deel (226.84 km^2)	Rappa (22.79 km^2)	Rathnamagh (14.28 km^2)	Tooreen (12.85 km^2)
Year				
1998	18452	1419	626	1339
1999	15887	1695	742	1372
	Annual Phosphorus Export rates (kg/ha/year)			
1998	0.813	0.623	0.438	1.042
1999	0.700	0.744	0.520	1.068

RESULTS AND DISCUSSION

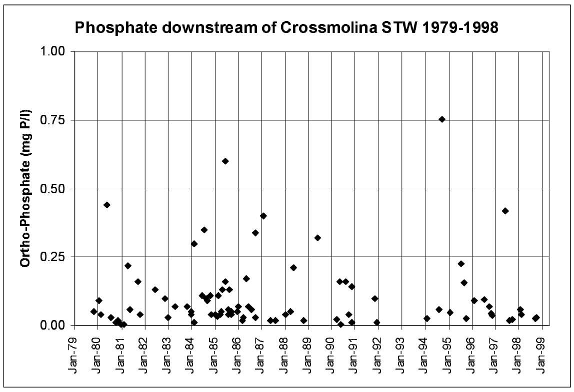
Table 2 gives the measured and calculated loads for the entire Deel catchment upstream of Lough Conn and for the three important agricultural catchments downstream of Crossmolina. Export rates for TP (kg/ha/year) from the individual measured catchments are also shown.

The Upper Deel catchment has a relatively low intensity upper catchment (151.7 km^2). This portion of catchment upstream of Crossmolina Town is dominated by bog and forestry with poorly drained low level blanket peats on a predominantly Carboniferous bedrock and a population density of approximately 5 persons/km (Table 1). While the upper catchment is generally one of low agricultural intensity, a number of high concentration phosphorus episodes were noted in the routine monitoring carried out by the EPA at Ballycarroon Ford. This included one event when the ortho-phosphate concentration reached 150 µg P/l. On the same day (20 Oct 1998) the composite sample from the autosampler at Knockadangan Bridge, some 5 km further downstream, gave a TP concentration of 200 µg P/l – an extraordinarily high value for this river system. Thus, two independent sampling and analysis programmes confirmed that an extreme phosphorus event occurred on that day in the upper Deel River. A number of other phosphorus 'events' of lesser scale were also noted for the samples from the Upper Deel, particularly in 1998, giving rise to unexpectedly high loss rates from the upper catchment.

Mayo County Council estimate that Crossmolina had a population of approximately 1100 people connected to the sewage treatment works in the 1998–1999 period. The population in Crossmolina has dropped slightly since 1996 so the 1100 population estimate may now be slightly too high. There were no significant industries connected to the sewer during the study period. A small caravan park adds to the load during the summer months. At the time of the survey the sewage treatment works had not yet been replaced but a new treatment works is currently (2003) under construction. This will include a new secondary treatment plant and a phosphorus removal stage. This followed recommendations by, *inter alia,* the Lough Conn Committee (McGarrigle *et al.,* 1993, 1997). The town is below the threshold for phosphorus removal under the EU Urban Waste Water Directive but a P-removal stage was sanctioned by the Department of the Environment and Local Government for the plant due to the need for a cross-sectoral approach to P load reduction.

Figure 2 shows a 20-year record of ortho-phosphate concentrations in the outflow from Crossmolina sewage treatment works and also phosphorus concentrations in samples taken from the left-hand bank sampling point, just downstream of the Crossmolina sewage treatment works. This graph demonstrates quite clearly that no significant change has occurred in the quality of the discharged effluent from the Crossmolina sewage works since monitoring began in 1979. While the works is not particularly efficient, its efficiency level has not varied significantly over the period. No statistically significant trends were apparent in the outflow or at the sampling location downstream of the discharge point on the Deel River ($P >> 0.05$). Thus, it is concluded that the loading of phosphorus to the River Deel discharged by the population of the town of Crossmolina from 1979 to 1999 has not changed dramatically over this time period. This supports an earlier, similar, conclusion based on an analysis of data for the 1979–1992 period (McGarrigle *et al.* 1993).

Phosphorus loading from the sewered population in Crossmolina was calculated by a number of different methods including standard per-capita figures for biological treatment such as the 1.7 g/person/day used recently by SEPA in the Loch Lomond catchment (SEPA, 2002). A wider range of 1, 2 and 3 g/person/day was also included, as was done also in an earlier study (McGarrigle *et al.,* 1993), in order to ensure that all likely loads were considered in the calculations. Average phosphorus concentrations in the effluent (Fig. 2) together with average flow volume estimates for the effluent gave an annual loading figure of approximately 700 kg P/year. This gave very good agreement with the middle range per-capita estimates.



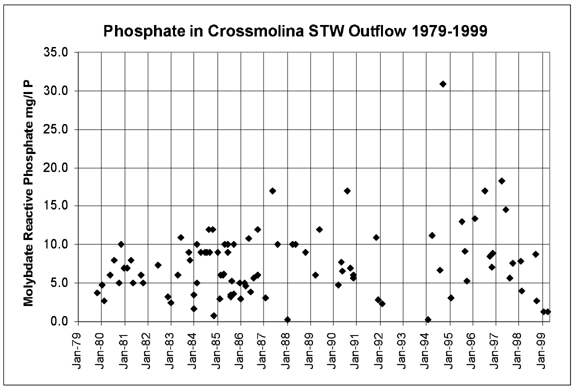


Fig. 2. Phosphorus concentration in the effluent discharged from Crossmolina sewage treatment works and in the River Deel downstream over the period 1979–1999.

Table 3 gives a phosphorus balance for the catchment as a whole and for the various sub-catchments. The load at Keesaun Spring is negative as it represents the underground loss of water downstream of Ballycarroon Ford, which reappears at Keesaun Spring. The maximum SEPA (2002) runoff coefficient for urban areas of 1.9 kg/ha/year is used to estimate diffuse losses from the hard surfaces in Crossmolina, rather than using an agricultural runoff coefficient for this area.

Table 3. Deel Catchment phosphorus balance

		Total Phosphorus Loading (kg P/year)		
	km^2	1998	1999	Methods
Deel River Catchment to Knockadangan Bridge	226.84	18,452	15,887	Precise load based on continuoussampling and flow measurements
Upper Deel	151.74	12378	8259	Based on monthly MRP samples and MRP:TP ratios
Keesaun (underground loss)		-862	-845	Weekly TP (Keesaun Spring)
Rappa	22.79	1,419	1,695	Weekly TP
Rathnamagh	14.28	626	742	Weekly TP
Tooreen	12.85	1,339	1,372	Weekly TP
Lecarrow (P load estimated)	14.00	1,459	1495	Tooreen export coefficient
Rural mid-Deel (P load estimated)	8.68	904	927	Rathnamagh export coefficient
Urban surfaces	2.50	475	475	SEPA max 1.9 kg/km^2
Crossmolina STW		803	803	@ 2 g P/person/day discharged
Total:	226.84	18,541	14923	
'Deficit' or error		-89	964	Errors - due to measurement uncertainties especially in Upper Deel

Table 4 apportions the measured TP loading at Knockadangan Bridge. A background loss rate of 0.1 kg P/ha is taken as the reference state or unavoidable loss rate from a near-pristine catchment – approximately 13% of the total load currently measured. This loss rate, for example, agrees with recent measurements made in the Lough Mask catchment (Donnelly, 2001). A wide range of potential values is given for Crossmolina sewage works ranging from 2 to 7% of the measured TP loss from the Deel catchment. Bord na Móna peat bog losses and forestry losses are estimated in similar fashion to the method used by McGarrigle *et al.* (1993) with a modification for improved forestry practice. Septic tanks are quantified by use of SEPA (2002) per-capita loss rate to Loch

Table 4. Source apportionment of Total phosphorus loss to Deel River.

		Total Phosphorus Loading (kg P/year)			
	Population	Km^2	1998	1999	%
Deel River Catchment to Knockadangan Bridge (EPA Code 34D010300)		*226.84*	18,452	15,887	
		Kg P/ha			
Background losses (includes atmospheric deposition on land)		0.1	2,268	2,268	13
Crossmolina Sewage Works (pe 1100)		g P/p/day			
Low estimate	1100	1.0	402	402	2
Middle Estimate	1100	2.0	803	803	5
High Estimate	1100	3.0	1,205	1,205	7
Most Likely	1100	1.7	683	683	4
Urban surfaces (1.9 kg/ha/year)			475	475	3
Bord na Móna peat bogs			256	256	1
Forestry			2141	2,095	12
Scattered Rural Dwellings	1762	1.9	1,222	1,222	7
Sub-total of non-agricultural P Loading			7,045	6,999	41
Total agriculture losses (by difference)			11,407	8,888	59

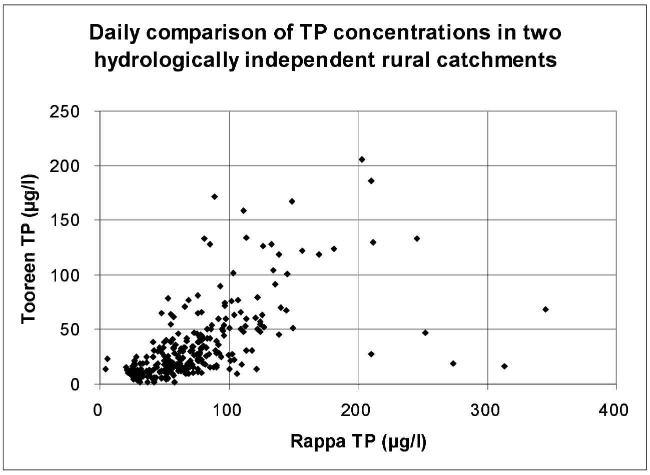


Figure 3. Daily comparison of TP concentrations in two hydrologically independent, rural sub-catchments, Tooreen and Rappa, downstream of Crossmolina.

Lomond. The quantifiable non-agricultural P losses tabulated in Table 4 amount to 41% of the measured TP loss at Knockadangan Bridge. The estimates are quite conservative in that, for example, it is likely that the losses from Crossmolina sewage works are less than indicated in Table 3. Thus, the remaining 59% of the measured loss, which has to emanate from farming activities, is likely to be an underestimate.

CONCLUSIONS

Agriculture is the dominant source of phosphorus loading within the Deel River accounting for an average of 59% of the measured phosphorus loading in 1998 and 1999. Most of this emanates from the better quality farmland downstream and just upstream of Crossmolina where the bulk of the cattle numbers are found. Loss rates of over 1.0 kg/ha/year have been measured in some of these catchments. A striking feature is the tendency for TP concentrations to be higher during wet weather and high flow events. Figure 3 compares TP concentrations on a daily basis in two adjacent catchments for 315 separate days during 1995. The day-to-day positive correlation between TP concentrations in these two hydrologically independent catchments is very obvious. High TP concentrations in both catchments generally coincide with wet days when stream flow was also high. Bearing in mind that there are very few houses in either of these catchments and little forestry or other industrial activities, this is a clear signature of diffuse agricultural runoff from fields and farmyards. Figure 3 strongly suggests that agriculture is the prime source of the phosphorus, particularly at the higher concentrations observed in these catchments. Two further points support the hypothesis that most of the TP loading in these catchments is from agricultural sources. First, this type of positive correlation between concentration and flow is not seen in 'cleaner' rural catchments that have lower in-stream TP concentrations. Second, the opposite effect is seen downstream of point sources – i.e. lower concentrations at higher flows.

The intensive daily measurement programme described here strongly supports conclusions reported previously regarding a change in the diffuse runoff pattern in the River Deel and its impact on Lough Conn (McGarrigle, 1993; McGarrigle *et al.*, 1993, 2000; McGarrigle and Champ, 1999).

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