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A review of the significance of non-point source agricultural phosphorus to surface water¹

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Introduction – international perspective

Release of phosphorus (P) from terrestrial environments undermines water quality by contributing to eutrophication in lakes and rivers (Daniel *et al.*, 1998; de Clercq *et al.*, 2001; Watson and Foy, 2001; Withers *et al.*, 2000). Eutrophication arises from a complex interrelationship between nutrient status and ecological circumstances (Haygarth *et al.*, 2000a) that results in accelerated growth of algae or water plants (Pierzynski *et al.*, 2000). There is no internationally accepted ‘critical’ P concentration for water, but the Environment Agency for England and Wales proposed standards of 85 µg total P (TP) l⁻¹ (annual geometric mean) for standing fresh waters and 200 µg soluble reactive P (SRP) l⁻¹ (annual mean) for running fresh waters (Environment Agency, 1998). Presence of algae causes significant limitations on water use for drinking and fishing, as well as for industrial and recreational uses (Carpenter *et al.*, 1998). In Europe, 55% of river stations reported annual average dissolved P concentrations in excess of 50 µg P L⁻¹ over the period 1992-96 (Crouzet *et al.*, 1999). A report on the state of New Zealand’s environment revealed that approximately 10% of shallow lakes were classified as eutrophic (20-50 µg total P L⁻¹) or hypereutrophic (>50 µg total P L⁻¹) (Cameron *et al.*, 2002). The protection of water quality is, therefore, a major international environmental problem. In recent years, the level of focus and attention on point sources* has diminished, because of the relative ease by which they have been identified and subsequently controlled. In contrast, and partly due to the success with point sources, the perceived and actual relative importance of non-point source agricultural pollution has increased. In the European Union, the Water Framework Directive (2000/60/EC) is a key legislative driver behind this and aims to restore all waters to ‘good ecological status’ by 2015.

* See note at end of article concerning the definition of non-point sources

Generic mechanisms of non-point source phosphorus release from agriculture

The P release from agricultural soils is generally small compared with the amounts of P added to soil as mineral fertiliser and organic manure. These can exceed 25 kg P ha⁻¹ yr⁻¹ in many agroecosystems (Cameron *et al.*, 2002; de Clercq *et al.*, 2001; Haygarth *et al.*, 1998; Sibbesen and Runge-Metzger, 1995). Data from a wide range of field and catchment studies have shown that, in most cases, annual total P transfer from soil is less than 1 kg ha⁻¹, although higher rates of transfer (2-6 kg P ha⁻¹ yr⁻¹, up to 17 kg P ha⁻¹ yr⁻¹) have been recorded from soil under intensive pastoral or arable farming, especially when animal manure is applied (Gillingham and Thorrold, 2000; Haygarth and Jarvis, 1999; Hooda *et al.*, 2000; McDowell *et al.*, 2001; Nash *et al.*, 2000; Turner and Haygarth, 2000). To help achieve a balanced perspective on non-point source P release from agriculture, it is necessary to consider:

Sources ⇒ mobilisation (by solubilisation and detachment) ⇒ transport.

Sources

Sources reflect the input of P to the agricultural and soil reservoirs that will represent the long term potential for transfer to the wider environment. This can be natural (indigenous soil P and atmospheric deposition) and anthropogenic (fertilisers and animal feed to the farm, fertilisers and manure to the soil). Phosphorus transfer from land to water cannot occur without ‘sources’ of P, which come from (i) indigenous soil P which relates to soil parent material (i.e. background), (ii) fertilisers, and (iii) imported livestock feed concentrates, which are returned to the land via direct excretion during grazing or, after storage, as spread manure. Haygarth *et al.* (1998) compiled comprehensive P budgets for intensive dairy and extensive upland sheep farming systems in the UK and determined an annual accumulation rate of 26 kg P ha⁻¹ under dairying compared with only 0.28 kg P ha⁻¹ under sheep. Withers *et al.* (2001b) determined an average P surplus on arable and grassland farms in the UK of 1000 kg P ha⁻¹ over the 65 years from 1935 to 2000 (15 kg P ha⁻¹ yr⁻¹). High levels of P accumulation in soil have also been reported under intensive farming systems in other parts of Europe and North America (de Clercq *et al.*, 2001; Sibbesen and Runge-Metzger, 1995; Sims *et al.*, 2000), together with consequent increases in plant available P (Tunney *et al.*, 1997). The accumulation of P in soil from imported feed is particularly important in areas of

intensive livestock production (e.g. pigs, poultry, dairy) where large quantities of manure are applied to land (Sharpley and Tunney, 2000).

Mobilisation

Mobilisation describes the start of the transport process and includes chemical, biological and physical processes that we call as 'solubilisation' and 'detachment'.

Solubilisation

The term 'solubilisation' refers to the release of molecules or macromolecules of P from soil surfaces and soil biota into soil water, for potential transfer. Levels of P in soil leachate following solubilisation have been shown to be sufficiently high to contribute to eutrophication if transferred to watercourses. Solubilisation reflects long-term management history and there is strong evidence that solubilisation potential increases with soil P status. Several studies have demonstrated that biological processes also play an important role in determining the amounts and forms of P transfer from soil. For example, Turner and Haygarth (2001) found that the process of wetting and drying resulted in accelerated release of soluble organic P from soil biomass. This is confirmed by findings from several studies which revealed that a significant proportion of soluble P and P in subsurface and overland flow from grassland soils is present as organic P (Haygarth and Jarvis, 1997; Heathwaite and Dils, 2000; MacLaren, 1996; Turner and Haygarth, 2000; Turner *et al.*, 2002).

Detachment

Detachment of soil particles with P attached, often associated with soil erosion, is a physical mechanism for mobilising P from soil into waters (Kronvang, 1990; Sharpley and Smith, 1990). Soil erosion *per se* has been much described (Burnham and Pitman, 1986; Elliot *et al.*, 1991; Evans, 1990; Heathwaite and Burt, 1992; MAFF, 1997; Morgan, 1980; Quinton, 1997) as has the role of particle transfer in P loss (Catt *et al.*, 1994; Kronvang, 1990; Sharpley and Smith, 1990; Zobisch *et al.*, 1994). Various size thresholds have been used to operationally define detachment, with most examples using $>0.45 \mu\text{m}$, although in some cases $>0.4 \mu\text{m}$ or even $>0.2 \mu\text{m}$ have been used for the threshold between 'dissolved' and 'particulate' P (Haygarth *et al.*, 1997). These filter sizes are somewhat arbitrary as P can occur in a continuum of particulate and colloidal sizes down to near molecular sizes (Aiken and Leenheer, 1993; Buffle *et al.*, 1978; De Haan *et al.*, 1984; Fox and Kemprath, 1971; Hannapel *et al.*, 1963; Mayer and Jarrell, 1995; Nanny *et al.*, 1994).

Transport

Transfers from the hillslope to the stream are mainly controlled by a combination of hydrological factors that include the intensity and duration of rainfall (or irrigation) events, together with the spatial variables of scale and pathways (Haygarth *et al.*, 2000b). Slope (topography) and drainage (substrate permeability) mainly influence P transfer pathways at the field scale. Phosphorus transfer to surface water occurs via overland flow and/or subsurface flow (interflow, drainflow) as base-flow and storm-flow, while transfer to groundwater occurs via a combination of throughflow (percolating water) and preferential flow. Critical transport pathways from hillslope to stream are so called 'incidental transfers' that occur when applications of manure or fertiliser coincide with discharges (Haygarth and Jarvis, 1999), resulting in direct transfers to watercourses without the opportunity for the P molecule to be incorporated into the soil matrix (Preedy *et al.*, 2001). The interaction between the hydrology and the agricultural management practice is clearly important with incidental transfer mechanisms (Haygarth *et al.*, 2000b). Despite the proliferation of anecdotal evidence, there are only a few robust scientific studies providing evidence for incidental mechanisms (Harris *et al.*, 1995; Haygarth and Jarvis, 1997) and an obvious opportunity exists for some scientific criteria to define and manage these occurrences.

Current state of knowledge of point and non-point sources of P in Europe

Separating the importance of point and non-point source of P in catchments remains difficult and encompasses much uncertainty (de Wit *et al.*, 2002). A wide diversity (from complex process and distributed approaches to simpler less data intensive approaches) of modelling approaches alongside empirical approaches have been developed to assess these, such as:

- Export coefficient approach, which has been used to determine the origin of nutrient loads to the North American lakes (Beaulac and Reckhow, 1982). The approach has been further developed and applied at catchment scale studies (Johnes, 1996) and allows the scaling up from plot scale studies to larger catchment size and to account for complex land-use systems. Export coefficients represent the rate of nutrient loads (mostly $\text{kg ha}^{-1} \text{yr}^{-1}$) that are transported from a particular source.
- Mass balance and material flow analysis, that are simple approaches based on the analysis of nutrient inputs (sources in the catchment) and outputs (river load at basin outlet) enabling large scale nutrient balances to be constructed and nutrient fluxes determined (de Wit *et al.*, 2002; Droic and Koncan, 2002).
- Empirical approaches that use experiments and observations of the sources, mobilisation and transport processes of P are made at various spatial scales. Withers *et al.* (2001a) compared P transfer from soil following application of sewage sludge, fertiliser and manure and observed that the risk of P transfer to watercourses was higher through the addition of inorganic P fertiliser or liquid cattle manure compared to liquid and dewatered sewage sludge. Their results demonstrated that large fertiliser top dressings to agricultural land pose a significant eutrophication risk. The timing and method of addition of P supplements are important, with the incorporation of the P amendment into the soil leading to the lowest P release in runoff (Withers *et al.*, 2001a). The transport of point and non-point sources can be observed through the use of microbiological and chemical tracers, an example of this approach has been the use of boron as a conservative marker for sewage effluent (Jarvie *et al.*, 2002).

A summary table of assembled information on non-point sources of P is presented in Table 1 and detail of case studies is presented in the text below. The percentage values presented in Table 1 are the contribution of non-point source agricultural sources e.g. surplus P transported to drainage network unless stated. Although, in this document, we have tried to confine the examples presented to non-point source agricultural P, it must be emphasised that not all non-point source pollution necessarily comes from agriculture, as other non-point sources may be rural, urban and atmospheric in nature. Where this is not specified, we have followed the original authors definitions and thus the reader is advised that some variation in the exact terminology may exist.

Table 1. Estimated contribution of non-point* source phosphorus to river loads in Europe

Region	Year	P(%)	Reference
Po	Early 1990s	22-25	(de Wit <i>et al.</i> , 2002)
Rhine	Early 1990s	13-21	(de Wit <i>et al.</i> , 2002)
Elbe	Early 1990s	11-16	(de Wit <i>et al.</i> , 2002)
Rhine	1993-1997	42	(Behrendt, 1999)
Elbe	1993-1997	44	(Behrendt, 1999)
Danube	1996	44	(Zessner and van Gils, 2002)
Frome	1998	60	(Hanrahan <i>et al.</i> , 2001)
River Thames	1996	15	(Cooper <i>et al.</i> , 2002)
River Thames ¹	1999	36-53	(Cooper <i>et al.</i> , 2002)
Krka, Slovenia	1996-7	41	(Drovc and Koncan, 2002)
Kennet	1997	2	(Jarvie <i>et al.</i> , 2002)
Kennet ²	1998-9	29-45	(Jarvie <i>et al.</i> , 2002)
Avon	2000-1	24	(Hilton <i>et al.</i> , 2002)

¹ After P-stripping introduced at Aylesbury sewage treatment works (STW).

² Tertiary P treatment installed in summer 1997 Marlborough STW.

* See note at end of article concerning the definition of non-point sources

The River Frome case study (Hanrahan *et al.*, 2001)

Non-point and point sources can be spatially combined allowing the relative significance of non-point and point sources to be examined and the impact of differing management options (Hanrahan *et al.*, 2001). This work demonstrated that an export coefficient model in Southern England, could be used to predict total P loading from point and non-point sources in the River Frome catchment on both a seasonal and annual basis. Modelled annual total P from the Frome catchment showed non-point sources associated with land use to be the primary factor accounting for the inputs. A simple sensitivity analysis of the Frome export coefficient model indicated that nutrient export from STWs followed by tilled land were the most sensitive factors controlling the export of P from the Frome catchment (Hanrahan *et al.*, 2001).

Rhine and Elbe case study (Behrendt, 1999)

The MONERIS (Modelling Nutrient Emissions in River Systems) model was used to estimate the nutrient inputs into the Rhine and Elbe river basins from point and a range of non-point sources. The inputs of P into the Rhine and Elbe were estimated in 1993-1997 to be half that compared to their values in the mid eighties due to the reduction in discharges from municipal wastewater treatment plants. In line with this decrease, the relative contribution of non-point agricultural sources increased from 16 to 42% and 19 to 44% for the Rhine and Elbe basins respectively. Soil eroded from soils and transported to the river systems was the dominant non-point source pathways modelled.

Rhine, Elbe and Po case study (de Wit *et al.*, 2002)

Agriculture's contribution to the P loads entering the Rhine, Elbe and Po rivers was estimated for the period 1970-1995. Two models differing in complexity were compared and modelled five-year averages river loads were validated with river loads derived from discharge and measurements from a large number of monitoring stations. Non-point source (indirect) loads of P were calculated based on average surpluses at the soil surface upstream of the sampling point and the fraction transferred by the soil and groundwater system to the river network. De Wit *et al.*, (2002) estimated with a mass balance approach that the average contribution of agriculture to the total P load was 13-21 % (Rhine), 11-16% (Elbe), and 22-25% (Po).

Rhine case study (Farmer and Braun, 2002)

International co-operation through the Rhine Commission has resulted in marked reductions in the discharges of P to the Rhine over the last fifty years. The Rhine catchment states (France, Germany, Switzerland and the Netherlands) established the International Commission for the Protection of the Rhine (ICRP) in Basel on 11th July 1950. Since this date a number of internationally agreed measures have successfully reduced the P inputs to the Rhine leading to a reduction in the total P input dropping from 73,738 tonnes yr⁻¹ in 1985 to 26,793 tonnes yr⁻¹ in 1996 (Farmer and Braun, 2002). These reductions have been mainly through management of urban and industrial point sources. In 1996 it was estimated that non-point sources contribute 47% to this total P load.

The Thame case study (Cooper et al., 2002)

Phosphorus stripping was introduced in 1998 at one major STW in the Thame catchment at Aylesbury, UK. Annual catchment budgets were created based on a range of characteristic flow conditions. The annual contribution of point and non-point sources was estimated based on several sets of monitoring data (Cooper *et al.*, 2002). A number of point sources were identified, including 21 STWs and approximately 300 septic tanks. Information on non-point sources was gathered from the Environment Agency and catchment survey data. Non-point source inputs were calculated based on identified inputs to the catchment and the difference between inputs and outputs from the catchment. The STW at Aylesbury contributed half of the total point source discharges prior to the introduction of P-stripping. Following the introduction of P-stripping at Aylesbury STW, STWs were estimated to contribute one half of total P inputs. Significant non-point sources of P, including particulate P transport during winter months were identified. The difference between P leaving the catchment and the input from STW was found to be an inaccurate estimator of the non-point P load; it may be used to estimate the joint influence of non-point sources and in-stream processes (Cooper *et al.*, 2002).

Loch Leven, Scotland (Foy and Bailey-Watts, 1998) taken from Haygarth et al. (2000a)

Loch Leven in Kinross, Scotland is a eutrophic lake that suffers from problems of reduced water clarity and regular blue-green algal blooms. The Loch Leven catchment is mainly agricultural with minor industrial and sewage based P inputs and drains an area of 13.3 km². Through the removal of P in discharges from a woollen mill and upgrading of existing and new STWs, the annual point source TP inputs were reduced by 40% (Table 2). In addition the soluble inorganic P loading was reduced by 46%, as point source inputs were proportionally richer in molybdate reactive P than non-point source inputs. The presence of significant non-point source P inputs in the catchment (42% in 1985 and 59% in 1995) has resulted in the reduction in point sources not delivering the expected environmental improvements. A large proportion of this agriculturally derived P is believed to enter the Loch in the form of particulate P. Consequently, the Loch Leven Catchment Management Project was set up in 1995 to bring together those organisations with responsibilities for planning and development, rural land use, water quality and pollution prevention, and nature conservation issues within the catchment. Four Working Groups developed a catchment management plan, and implementation of the plan began in 1998.

Table 2. Inputs of total phosphorus to Loch Leven, Kinross, Scotland in 1985 and 1995, adapted from Foy and Bailey Watts (1998).

Source	Tonnes total P year ⁻¹	
	1985	1995
Industry	6.4 (31%)	0.4 (3%)
STWs	5.3 (26%)	3.5 (27%)
Rainfall	0.4 (2%)	0.4 (3%)
Geese	0.4 (2%)	0.4 (3%)
Non-point source	8.1 (39%)	8.1 (64%)
Total	20.6	12.6

Lough Neagh, N. Ireland (Foy and Bailey-Watts, 1998)

Lough Neagh is a large eutrophic lake in north-east Ireland covers 386 km². The main catchment land uses in 1991 were grassland (77%) and rough grazing (14%). A molybdate reactive P budget was calculated by Foy *et al.* (1982), who estimated that STWs contributed 48% of inputs to the Lough in 1979, 4% was from creameries and the remaining 48% originated from non-point sources. Between 1981 and 1983 P removal was commissioned at ten STWs serving seven major towns (63% of the urban population) in the catchment. The impact of this phosphorus removal on lake TP concentrations was evident, with mean annual values decreasing from about 140 µg L⁻¹ in 1982 to 100 µg L⁻¹ in 1988. After 1988, the upward trend resumed as a result of a combination of factors including contributions from non-point sources, including septic tanks (Foy *et al.*, 1995), reflecting an annual increase in molybdate reactive P river loading of between 1.9 and 2.3 kg P km⁻¹. The continuing surplus of P in Northern Ireland agriculture since 1995, equivalent to a soil P accumulation rate of around 10 kg P ha⁻¹yr⁻¹, is thought to be the most likely cause of the increase (Foy and Bailey-Watts, 1998).

Krka case study (Drolc and Koncan, 2002)

The major inputs of total P into the lower Krka catchment were analysed and a P budget was developed through the use of material flow analysis. Material flow analysis focuses on the stocks and flows of nutrients within the catchment, enabling emissions from point and non-point sources to be compared. The Krka river basin contains a range of land uses with forest covering almost half of the basin. The main sources of P were found to originate from waste water management (52%), with agricultural inputs estimated at 45% of the total P emissions with 41% being classified as P arising from non-point agricultural sources (Drolc and Koncan, 2002).

River Kennet, UK (Jarvie *et al.*, 2002)

The Kennet is a major tributary to the River Thames, Southeast England, with an estimated catchment area of 1200 km². The system is groundwater fed with approximately 787 mm annual rainfall, with only 34% of this being converted to river flow, due to the high permeability of the catchment. The loads of P through the catchment were studied using in-stream monitoring at a network of river site in combination with analysis of effluent discharges at Marlborough STW to assess the relative importance of point and non-point sources on in-stream P concentrations. In August 1997 tertiary treatment was installed to reduce the P concentration in the effluent at Marlborough STW, which resulted in a significant drop in the SRP concentration in the effluent. Non-point source inputs to the catchment in the summer of 1997, before tertiary treatment was installed was estimated at 2%, whereas in 1998 and 1999 non-point sources contributed 45 and 29% of P inputs, respectively. The results demonstrated that point source treatment was successful in reducing the in-stream soluble reactive P load by an estimated 72%, based on direct measurement of soluble reactive P and the use of boron as a conservative marker for sewage effluent (Jarvie *et al.*, 2002).

Danube case study (Zessner and van Gils, 2002)

Zessner and van Gils (2002) recently used emission estimates and water quality data to investigate and quantify the sources, pathways and sinks of nutrients in the Danube basin using the Danube Water Quality Model. The approach takes into account retention processes of P which include net storage in the sediments of lakes, flood plains and wetlands. The most important pathways in the Danube basin are for P erosion and runoff (36%, mainly from agriculture) and sewage treatment works (33%) (Lampert and Brunner, 1999). The uncertainties associated with average values of emission estimates from different countries and different years were estimated to be +/- 20% (Zessner and van Gils, 2002). There has been an estimated and observed decrease in both N and P levels in the Danube between 1988 and 1997, due to the reduction in manure discharges in Romania and Bulgaria in the early 90s, following political changes. A challenge will be to ensure that the economic recovery of these countries can proceed without increasing nutrient emissions to the Danube (Zessner and van Gils, 2002). Validation of the results with monitoring data from Reni showed that the model significantly overestimated monitored TP. It was suggested that the TP concentrations were not representative of the river load due to the low sampling frequency (Zessner and Kroiss, 1999).

Conclusions

In general, non-point sources* of P are at least as an important a source of P as sewage, particularly where point source reduction strategies have been implemented through the use of treatment technologies. There are difficulties and thus uncertainties in providing non-point source estimates, but several European case studies have been used to demonstrate that non-point sources of P contribute between 29 and 60% of the total P load to European catchments.

*** NOTE: Definition of non-point sources:** *Non-point sources are generally read as being approximately equivalent both to (a) the part of phosphorus coming from all sources other than sewage and industrial wastewaters and (b) to the part of phosphorus coming from agricultural activities and the soil. However, depending on the author/data, non point sources may also include uncollected waste waters (discharged directly to water or via septic tanks) and point sources may include agricultural phosphorus in manure from farmyards and animal production units.*

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