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A model-based assessment of non-compliance of phosphorus standards for lakes in England and Wales

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Abstract

High phosphorus concentrations causing eutrophication will prevent many lakes in England and Wales from reaching good ecological status by 2015 according to the EC Water Framework Directive (WFD). The aim of this study was to estimate the percentage of lakes in England and Wales that are likely to fail recently agreed WFD phosphorus standards. As measured lake phosphorus concentrations are only available for a small number of lakes a model-based approach was adopted. This involved estimating phosphorus loads from a wide range of sources including agricultural loads, sewage effluents, septic tanks, diffuse urban sources, atmospheric deposition, groundwater and bank erosion. Lake phosphorus concentrations were predicted using the Vollenweider model, and the model framework was satisfactorily tested against available observed lake concentration data. Applying the model to all lakes in England and Wales greater than 1 ha, it was estimated that under current conditions, roughly two thirds of the lakes would fail good ecological status with respect to phosphorus. According to our estimates, agricultural phosphorus loads represent the dominant source for the majority of catchments, but diffuse urban runoff also is important in many lakes and sewage effluents are the most frequent dominant source for lake catchments greater than 100 km². Required reductions of phosphorus loads to increase the number of lakes achieving good ecological status and potential delays because of internal loading and biological resistances are briefly discussed.

Keywords: lakes; phosphorus; Water Framework Directive; modelling; source apportionment.

1. Introduction

Phosphorus is widely accepted as the most frequently limiting nutrient for biological productivity in most lakes (Schindler, 1977; OECD, 1982; Reynolds and Davies, 2001). Increasing population densities, use of inorganic fertilizer and intensive livestock agriculture have all increased phosphorus loads to lakes and have led to accelerated eutrophication. Eutrophication is characterised by increased growth of phytoplankton and can often lead to undesirable changes in the ecosystem structure, such as loss of macrophytes and frequent cyanobacteria blooms.

The EC Water Framework Directive (WFD) (Directive 2000/60/EC) requires member states to improve or maintain good chemical and ecological quality in all surface water bodies. This involves the classification of the current status of surface water bodies according to the deviation from their reference state (a condition associated with negligible or minor human impact). The WFD also requires the establishment of management plans to maintain or restore good status. Reference total phosphorus (TP) concentrations for UK lakes have recently been

established by Carvalho *et al.* (2006), thereby permitting an assessment of the phosphorus status of lakes in England and Wales.

The GB Lakes Inventory (Bennion *et al.*, 2002; Hughes *et al.*, 2004) lists 6309 lakes in England and Wales with an area greater than 1 ha. However, currently only 109 lakes are monitored by the Environment Agency in contrast to more than 7,000 monitoring sites at rivers and canals. Due to the lack of monitoring data an evaluation of phosphorus status which aims at including all lakes in England and Wales greater than 1 ha requires a modelling approach.

Compared to previous lake assessments (Carvalho *et al.*, 2003) which were based on preliminary TP standards, this study uses the recently agreed TP standards, applies a more detailed methodology of estimating phosphorus loads and makes a source apportionment of phosphorus inputs into lakes. A scenario analysis was carried out to investigate to what extent reductions in i) agricultural phosphorus loads only and ii) phosphorus loads from all sources would increase the number of lakes achieving good ecological status in terms of the revised TP standards.

2. Methods and data

2.1 Estimation of phosphorus loads

Phosphorus loads were estimated for lakes in the GB Lakes Inventory with a size greater than 1 ha. This included lakes smaller than 50 ha, for which WFD reporting is not statutory. Some lakes were excluded because i) data in the GB Lakes Inventory was inconsistent with a lake surface area greater than the catchment area; ii) some lakes on the coast and on islands were located beyond the available national land use maps; or iii) a typology, needed to define the phosphorus standards, was not available. The study finally considered 5,536 of the 6309 lakes greater than 1 ha in area.

Phosphorus loads from diffuse sources were estimated at a spatial scale of 1 km². The loads impacting on an individual lake were calculated by intersecting the loads maps with the lake catchment boundaries provided by the GB Lakes Inventory. The lake boundaries were originally extracted from Ordnance Survey PANORAMA mapping at a scale of 1:50,000, and the boundaries of the lake catchment areas were derived automatically from the Institute of Hydrology digital terrain model with a spatial resolution of 50 by 50 m².

The estimates of pollutant loads for individual lakes are uncertain, given the statistical nature of pressure data and the small catchment sizes of the majority of lakes. Catchment areas are for example often similar or smaller than the spatial resolution of the source data for the agricultural and population census, which determine the loads associated with manure and septic tanks. While the pollutant load models therefore are not reliable for estimating loads to individual lakes, the summary statistics of the proportion of the lake population that is at risk should be robust.

2.1.1 Diffuse sources

Agriculture including rough grazing and forest

Agricultural phosphorus inputs to rivers were estimated using the PSYCHIC (Phosphorus and Sediment Yield CHaracterization In Catchments) model (Collins *et al.*, 2007; Davison *et al.*, 2008; Stromqvist *et al.*, 2008). The PSYCHIC model is a monthly time-step model with explicit representation of surface and drain flow hydrological pathways, particulate and solute

mobilisation, and incidental losses associated with fertiliser and manure spreading. It calculates total phosphorus losses from all agricultural land, including rough grazing and runoff from hard standings and takes account of landscape retention. Compared to simpler export-coefficient based approaches this type of process-based model is better suited to represent the impact of spatially variable key environment factors.

The PSYCHIC model has been integrated with the soils, climate and agricultural census data held in the MAGPIE Decision Support System (Lord and Anthony, 2000) using 1961 - 1990 climate data and 2004 agricultural census and land cover data. The baseline output from the PSYCHIC model assumes that landowners implement no mitigation methods that might reduce phosphorus losses. The output was therefore modified to take account of mitigation methods already implemented, using a methodology described in Anthony (2006).

Urban

Phosphorus inputs from road runoff and diffuse urban sources to watercourses were estimated based on a volume-concentration approach, where average annual runoff is multiplied by event mean concentrations (Mitchell, 2005; Ellis and Mitchell, 2006). It has been shown that the event mean concentration of a site is not correlated to annual runoff. Average annual runoff was estimated by the Wallingford Procedure (NERC, 1975). Representative total phosphorus event mean concentrations for roads and different types of urban areas were taken from the database compiled by Mitchell *et al.* (2001) and were in the range of 0.2 – 0.4 mg l⁻¹ TP.

Bank erosion

River bank erosion was calculated using a prototype national scale bank erosion index (Collins and Anthony, 2008). This model estimates bank erosion as a function of the duration of excess bank shear stress following the general methodology of Julian and Torres (2006). It was previously calibrated against measurements of the bank erosion contribution to catchment sediment yield derived from sediment fingerprinting studies (Collins and Anthony, 2008).

Bank erosion estimates for sediment were available for catchments in England and Wales and ranged from 10 to 670 kg ha⁻¹ of the local catchment area, with a national average value of 30 kg ha⁻¹. The associated phosphorus loss was calculated using data on the average topsoil TP content of the dominant soil series for individual river catchments. The model output was then interpolated onto a 1 km² grid for summarising to lake catchment areas. Using the topsoil TP content is likely to overestimate phosphorus losses by bank erosion as the vertical variability of the TP content in the soil profile is not taken into account. As bank erosion is however only a small contribution of the total phosphorus load this was considered acceptable.

Groundwater

In river catchments dominated by groundwater flow, concentrations in the order of 0.01 to 0.02 mg l⁻¹ P would be sufficient to contribute an additional annual phosphorus load of up to 0.1 kg ha⁻¹ P and can therefore locally be a significant phosphorus source to rivers feeding lake systems. However, routine measurements by the Environment Agency have regionally varying and relatively high detection limits, and measurements for research projects only cover a limited number of catchments. Available measurements show, nonetheless, that significant concentrations can be reached. For example, Neal *et al.* (2004) reported average concentrations of 0.01 to 0.04 mg l⁻¹ P for borehole samples in the Kennet and Pang catchments and Jarvie *et al.* (2005) reported concentrations with an average value of 0.05 mg l⁻¹ for the groundwater in the Avon catchment, southern England. The phosphorus

concentrations in these agriculturally dominated groundwater catchments are assumed to be higher than average for England and Wales. Phosphorus concentrations in groundwater will be influenced by land use, soil, subsurface properties and hydrogeology, but, as data allowing a spatially variable estimation were not available, this study used a constant input value of $0.01 \text{ mg l}^{-1} \text{ P}$ as a preliminary estimate. The groundwater phosphorus estimate was integrated with the PSYCHIC model calculations of vertical soil drainage to groundwater to give an approximate groundwater phosphorus load.

Atmospheric deposition

The direct deposition of phosphorus over the water surface area for each lake catchment was calculated by integrating annual average rainfall data with estimates of the total phosphorus concentration in rainfall. In the UK soluble reactive phosphorus (SRP) in rainfall is regularly monitored by the Environmental Change Network (ECN, 2008), and there are also measurements from research catchments (Neal *et al.*, 2003; Neal *et al.*, 2004). Reported values for average SRP concentrations in rainfall in the UK range from 0.004 to $0.06 \text{ mg l}^{-1} \text{ P}$. As they could not be related to catchment characteristics, a constant value for the SRP concentration in rainfall was applied. Using the average SRP concentration based on the ECN sites of $0.022 \text{ mg l}^{-1} \text{ P}$ and assuming an average ratio of SRP to TP of 0.5 as reported by Neal *et al.* (2004) the TP concentration in rainfall was fixed at $0.045 \text{ mg l}^{-1} \text{ TP}$.

2.1.2 Point sources

Sewage effluent

Phosphorus loads in sewage effluent discharges were calculated using a database provided by the Environment Agency which had been developed as part of a national water quality model framework (Kelly *et al.*, 2006). This database provided estimates of consented annual average flows for c. 3,550 effluent discharges with a population equivalent greater than 250.

For some discharges the database included estimates of annual average orthophosphate concentrations in the effluent based on compliance monitoring. Missing concentration data were replaced with averages, derived separately for each Environment Agency region and for effluent discharges in three flow bands centred on population equivalents in the ranges 0 to 2,000; 2,000 to 10,000; and greater than 10,000 (Table 1). The total phosphorus load in the sewage effluent discharges was calculated on the basis of an average ratio of orthophosphate to TP in effluent discharges of 0.85 (Demars *et al.*, 2005).

Table 1 Annual average orthophosphate concentrations at freshwater discharge consents with measured effluent quality data (Environment Agency; data for 2000 to 2004).

Environment Agency Region	Population Equivalent		
	<2000 ($\text{mg l}^{-1} \text{ P}$)	2,000-10,000 ($\text{mg l}^{-1} \text{ P}$)	>10,000 ($\text{mg l}^{-1} \text{ P}$)
East Anglia	6.1	5.9	5.2
Wales	4.7	4.0	3.4
Midlands	6.5	6.2	4.3
North East	5.1	4.8	2.9
North West	4.8	4.4	3.0
South West	5.4	6.0	2.1
Southern	6.0	5.0	2.6
Thames	5.3	5.2	3.8

Table 2 Numbers of properties connected to mains sewerage within each service company area of England and Wales (OFWAT, 2008), and the corresponding estimated percentage of unconnected properties.

Service Company	Connected Properties (10 ⁶)	Total Property Count (10 ⁶)	Unconnected Properties (%)
Anglian & HPL	2.4	2.5	0.5
Northumbrian, Essex & Suffolk	1.2	1.2	1.0
Severn Trent	3.7	3.9	4.9
South West	0.6	0.7	11.7
Southern	1.8	1.9	7.9
Thames	5.3	5.8	7.3
United Utilities	3.1	3.1	1.9
Wales	1.3	1.5	8.4
Wessex	1.1	1.2	12.0
Yorkshire & York	2.1	2.1	0.2
England and Wales	22.7	23.9	5.1

The impact of tertiary phosphorus stripping was taken into account using an Environment Agency database that identified 227 individual sites for which treatment was in place by the end of 2005 (Nowosielski, pers. comm.). The given maximum permitted TP concentrations in the effluent discharges were used in place of the compliance monitoring data as appropriate.

Septic tanks

Phosphorus losses from households not connected to mains sewerage are potentially very significant in rural areas. The number of unconnected properties for each of the eight sewerage company areas operating in England and Wales was calculated by the difference of the number of properties connected to sewerage in 2002 as reported to the Office of Water Services (OFWAT, 2008) and the number of properties in each service area, estimated from Ordnance Survey Address Point data for 2001. The percentage of unconnected properties ranged from 0.5 to 12 % (Table 2).

The unconnected properties were expected to be concentrated in rural areas. A national map of Rural and Urban Area Classification (Bibby and Shepherd, 2004) defines settlement area types and density of properties. Available service data for the North West region were summarised by each of the settlement types (Table 3). The percentage of properties unconnected varied from 27 % in areas of sparse hamlets and isolated dwellings, to less than 0.1 % within densely populated urban areas. The septic tank population within each service company area was therefore distributed across a map of the Rural and Urban Area Classification in proportion to the number of properties in each 1 km² cell and a weight was given to each of the area classification types based on the North West summary data (Table 3).

Table 3 Average percentage of properties not connected to mains sewerage within the North West service area, by Rural and Urban Area Classification (Bibby and Shepherd, 2004).

Rural and Urban Area Classification	Percentage of Unconnected Properties
Hamlet and isolated dwelling - sparse	27
Hamlet and isolated dwellings - less sparse	16
Village - sparse	14
Village - less sparse	10
Town and fringe - sparse	0.3
Town and fringe - less sparse	1.3
Urban >10k - sparse	0.1
Urban >10k - less sparse	0.1

Based on the ratio of population to the number of properties from the national census data it was assumed that each unconnected property was occupied by an average of 2.1 people. The total phosphorus load from the mapped septic tanks was estimated as 0.3 kg capita⁻¹ (Carvalho *et al.*, 2003).

2.2 Catchment retention

A proportion of the phosphorus input to the contributing lake catchment area is retained in the river system above the lake. Processes involved are sedimentation in floodplains during overbank flooding, deposition of particulate phosphorus in the river channel under low flow conditions, sorption of SRP to the sediment and biological uptake. Phosphorus gets released through decomposition of organic matter, sediment remobilisation (Collins and Walling, 2007), or desorption of phosphorus from the bed sediment at decreased phosphorus concentration in the river water. Phosphorus retention and remobilisation can vary considerably over the year, with phosphorus retention both at high and at low flow conditions, and either retention or remobilisation at moderate flows (House, 2003). While biological uptake and channel bed storage are assumed to be transitory at the annual time-scale, phosphorus sorbed to sediments can be retained over longer periods (depending on sorption capacity and the development of the phosphorus concentrations in the water column), and floodplain deposition results in long term storage.

For this study the annual average proportion of phosphorus retention in the river system was estimated using the empirical model of Behrendt and Opitz (2000). This model is based on statistical analyses of modelled TP inputs and measured outputs from c. 100 catchments in Central Europe and assumes that retention is higher for smaller catchments with a low specific runoff. The model requires estimates of the river and lake surface area within a catchment. River surface area was estimated as a function of the total catchment area (Behrendt and Opitz, 2000) and lake surface area was taken from the GB Lakes Inventory. Modelled retention for individual lake catchments was generally in the range of 5 to 40 % with the highest values associated with large catchments of low annual rainfall or with other lakes located in the headwaters.

2.3 Estimation of phosphorus concentrations

The OECD lakes model (OECD, 1982) is an empirical model predicting annual average lake TP concentrations as a function of the lake phosphorus load and hydraulic residence time:

$$P = 1.55 \cdot \left(\frac{L}{Q} \cdot \frac{1}{1 + \sqrt{\tau}} \right)^{0.82} \quad (\text{EQ 1})$$

Where P is the average lake total phosphorus concentration ($\mu\text{g l}^{-1}$), L is the annual phosphorus load (mg y^{-1}), Q is the annual discharge ($\text{m}^3 \text{y}^{-1}$) and τ is the hydraulic residence time (y).

A high number of similar empirical steady state mass balance models have been developed (e.g., Brett and Benjamin, 2008) but the OECD model has been calibrated against the widest range of data and has achieved the highest r^2 , with a value of 0.86 for log transformed predicted and measured concentrations. The model ignores differences between lakes in the proportions of soluble and particulate phosphorus load, stratification, seasonal variation of phosphorus fluxes and the morphology of the water bodies and is not applicable for lakes with high internal loading which are not in a steady state (Hakanson, 1999). With a 95 % prediction confidence interval spanning a five-fold variation in concentration its use as a predictive management tool for individual lakes has been questioned (for example, Reynolds and Davies, 2001). More complex lake models with a higher number of parameters, however,

require calibration to individual lakes and have a high predictive uncertainty. Therefore, as the focus in this study was on calculating population statistics for a large number of lakes, the OECD model was chosen.

The discharge and hydraulic residence time were calculated on the basis of lake catchment area, annual average runoff for the period 1995 to 1997, lake surface area, and lake depth from the GB Lakes Inventory. Measured depth data were only available for a small percentage (2 %) of the lakes, for all other lakes a crude depth estimate provided by the GB Lakes Inventory was used, which is based on a multiple regression relationship to lake surface area, altitude and perimeter.

2.4 Phosphorus concentration data for model testing

In order to evaluate both the framework for estimating the lake phosphorus loads and the applicability of the OECD model, calculated and measured concentrations were compared. Annual average phosphorus concentrations for a limited number of lakes were provided by the GB Lakes Inventory. The data were limited to lakes with a measured depth and with phosphorus concentrations which were based on at least four regularly spaced sampling occasions throughout the year (Carvalho *et al.*, 2003). A study by Carvalho *et al.* (2006) indicates that this sampling frequency gives an estimate of annual mean TP concentrations ± 14 %.

Of the 79 lakes with suitable data, 4 lakes were excluded from the analysis because they had no outflow (White Mere, Moss *et al.*, 1997), measurement data pre-dated implementation of phosphorus stripping at contributing sewage effluent works (Lyn Penrhyn) or the sewage had been re-directed out of the catchment (Rostherne Mere and Alderfen Broad).

2.5 Lake ecological standards for phosphorus

The WFD requires that environmental standards are set according to the deviation from a lake-type-specific reference state. For the UK, lake types were defined by mean depth and alkalinity, and in terms of phosphorus standards, high alkalinity lakes were further subdivided by specific geology (distinguishing Marl lakes in limestone catchments from the rest) and by geographic region (lakes in England and Wales are in the Northern or Central European Geographic Intercalibration Group) (Carvalho *et al.*, 2006). Lake types were estimated for 5,536 lakes in England and Wales using information provided in the GB Lakes Inventory dataset. England and Wales are dominated by very shallow, high alkalinity lakes with very few deep lakes.

Phosphorus standards were preferentially defined as site-specific, using a model which relates phosphorus reference concentrations to site-characteristics, or else as type-specific, from statistics of a population of reference lakes. A European version of the Morpho-Edaphic Index (MEI) by Vighi and Chiaudani (1985) was developed from a database of more than 500 European reference lakes (Cardoso *et al.*, 2007) for site-specific standards. Site specific standards were available for about 160 lakes in England and Wales with known depth and alkalinity data. All lakes used the clear-water MEI model outlined in Cardoso *et al.* (2007). Where depth and alkalinity were not known, type-specific standards were used.

Type specific phosphorus concentrations for good ecological status were developed by Cardoso *et al.* (2007) from a database of over 500 European reference lakes. The phosphorus good/moderate boundary was set based on ecologic impact and derived from the chlorophyll

Table 4 Type specific annual mean total phosphorus concentrations ($\mu\text{g l}^{-1}$ TP) at lake status boundaries used in this study (Carvalho *et al.*, 2006).

Alkalinity (meq l^{-1})	Depth (m)	Region	Type Reference ($\mu\text{g l}^{-1}$ TP)	High / Good ($\mu\text{g l}^{-1}$ TP)	Good / Moderate ($\mu\text{g l}^{-1}$ TP)	Moderate / Poor ($\mu\text{g l}^{-1}$ TP)	Poor / Bad ($\mu\text{g l}^{-1}$ TP)
Low (<0.2)	Very shallow (<3)	Central and North	7	9.3	13.7	27.4	54.8
	Shallow (3 - 15)	Central and North	5	6.7	9.8	19.6	39.2
	Deeper (>15)	Central and North	4	5.5	8.5	17	34
Medium (0.2 - 1.0)	Very shallow (<3)	Central and North	12	15.8	23.1	46.2	92.4
	Shallow (3 - 15)	Central and North	8	10.7	15.7	31.4	62.8
	Deeper (>15)	Central and North	6	8.1	12.5	25	50
High (>1.0)	Very shallow (<3)	Central	28	35.9	49.1	98.2	196.4
		North	18	23.1	31.6	63.2	126.4
	Shallow (3 - 15)	Central	20	25.6	35.7	71.4	142.8
		North	13	16.7	23.2	46.4	92.8
Marl	Very shallow (<3)	Central		10	24	48	96
	Shallow (3 - 15)	North		9	20	40	80

good/moderate boundary using TP-Chlorophyll regression relationships (Phillips *et al.*, 2008). The chlorophyll good/moderate boundary was based on secondary effects of increased phytoplankton concentrations on the depth distribution of submerged macrophytes. The boundaries between the lake types used in this study are indicated in Table 4.

2.6 Scenario: reductions in phosphorus loads

In order to quantify the relationship between reductions in phosphorus loads and increase in the number of lakes reaching good ecological status, the required percentage reduction to reach good ecological status has been calculated based on current and good ecological status for each lake. After reducing phosphorus inputs from point sources in reaction to the Habitats and Urban Wastewater Directive there is now a stronger focus on tackling diffuse sources from agriculture, which are particularly important for lakes, as many are in headwaters above the main inputs from sewerage. Scenario analysis was therefore performed to represent i) reducing all phosphorous loads equally and ii) reducing agricultural loads only.

3. Results

3.1 Model validation

A strong positive correlation was observed between the predicted and measured annual average total phosphorus concentrations (Fig. 1) explaining 68 % of the observed variance (EQ 2).

$$\text{Log}_{10}(\text{Measured TP}) = 1.349(\pm 0.108) \times \text{Log}_{10}(\text{Modelled TP}) - 0.393(\pm 0.159) \quad (\text{EQ 2})$$

The regression model intercept was statistically significant ($P < 0.02$), when the intercept was set to zero the slope of the model was $1.092(\pm 0.030)$ indicating that the model underestimated at high measured concentrations.

Fig. 1 Modelled and measured annual average total phosphorus concentrations using the OECD (1982) model for selected lakes in the GB Lakes Inventory.

3.2 Load apportionment

The analysis revealed that diffuse agricultural sources are the dominant sources of phosphorus within the lake catchments, with diffuse urban runoff the next most important source (Fig. 2). Sewage effluents are only important in large catchments; they are the most frequent dominant source in lakes with a catchment area greater than 100 km², but according to the available database only 6 % of the catchments smaller than 100 km² have sewage effluent inputs (with

Fig. 2 Number of modelled lake catchments in which each of the modelled pollutant sectors is the dominant source, by catchment size across England and Wales.

a population equivalent greater than 250). Overall, groundwater, bank erosion and atmospheric deposition each account for only a small percentage (generally less than 10 %) of the total phosphorus input. Atmospheric deposition is, however, significant for very small lake catchments in upland areas. Diffuse urban runoff is dominant in areas of high population density, principally in the Midlands and South East. Lakes where sewage effluents were the dominant source had the lowest chance of reaching good ecological status. 99 % of these lakes were predicted not to comply with phosphorus standards. The likelihood of failing good ecological status was lower where agriculture or diffuse urban runoff were the dominant source, with 71 % and 78 %, respectively, and where bank erosion, atmospheric deposition or groundwater contributions were the dominant source this generally indicated low pressure and a high probability of achieving good ecological status.

3.3 Lake ecological status

Modelled concentrations were compared with the relevant phosphorus thresholds for good ecological status and Figure 3 summarises the percentage distribution of modelled lake systems achieving phosphorus standards for good ecological status under present day agricultural census and practices. Overall, 68 % of lake systems were predicted to fail phosphorus standards for good ecological status. The percentage of lakes predicted to fail good ecological status varies by region and is clearly better, with a lower proportion failing than the national average, in the Anglian and Welsh regions (Fig. 3).

3.4 Scenario: reductions in phosphorus loads

The percentage phosphorus load reduction required to achieve good ecological status was calculated for each of the failing lake systems. This calculation assumed either i) that the load from all sectors was reduced equally; or ii) that only the diffuse agricultural (including forestry) load was reduced (**Fig. 4**). The analysis revealed that, if loads from all sources were for example reduced by 50 %, the percentage of lakes achieving good status would potentially increase from 32 % to 58 %. Reducing loads from agriculture by 50 % would increase the percentage of lakes reaching good status to 43 %. If the agricultural loads were completely removed, then 37 % of lakes would continue to fail good ecological status. The remaining lakes are most likely located in urban and semi-urban areas with a high diffuse urban runoff component to the total phosphorus load.

Fig. 3 Modelled lake status by Environment Agency Region.

Fig. 4 Predicted percentage of lake catchments achieving good ecological status in terms of TP standards after a reduction of phosphorus loads from all sources or phosphorus loads from agricultural sources only, summarised across England and Wales.

4. Discussion

4.1 Model framework

The results of testing the model framework were satisfactory, but it was not possible to demonstrate conclusively that it has provided unbiased estimates of total phosphorus loads to the lake systems. A possible underestimation at high phosphorus concentrations needs to be taken into account in the interpretation of results. The correlation between simulated and observed concentrations was comparable to a study by Heathwaite *et al.* (2005), who applied the OECD model to UK lakes; their model explained 66 % of the observed variation.

The under-estimation of measured phosphorus concentrations may have reflected an under-estimation of modelled phosphorus loads by the PSYCHIC model, which is known to predict lower loads than published export coefficient models. However, the under-estimation was more striking only for the very polluted lake systems where the calculated dominant sources of phosphorus were often sewage effluent outfalls, septic tanks or diffuse urban runoff. Phosphorus loads from these sources may have been under-estimated in these specific catchments due to the statistical average data used to characterise effluent discharges and concentrations, density of septic tanks and the connectivity of urban areas. Improved measurements of actual loading (rather than consented values) from these sources are clearly required to help improve the characterisation of pollutant pressures. Underestimation might also be partly due to internal loading. Stock numbers generally have declined over the last 10 to 20 years (Defra, 2007) and many large STWs or those discharging into Sites of Special Scientific Interest have implemented P-stripping. Particularly in shallow lakes phosphorus is expected to be released from sediment which has been exposed to higher phosphorus concentrations in the past.

The results of the full model could not be approximated with a simple relationship between lake phosphorus concentrations and catchment characteristics, such as the percentage of arable, grassland and urban land cover, livestock stocking rates or population densities. In contrast, Davies and Neal (2007), for example, were able to establish a simple regression relationship between phosphorus concentrations and percentage urban land use for river water quality sites from the Harmonised Monitoring Scheme in England and Wales. Establishing simple regression relationships seems to be possible for large river catchments where sewage effluents are more likely to be the dominant source and show a stronger correlation to the population density or the percentage urban land use. For the lake catchments in this study however, the small size of many catchments precluded establishing a relationship between population density and loadings from sewage effluents as sewage effluents are often not returned to the river within the catchment. Also, in these smaller catchments agricultural sources were more important, but the predicted agricultural loads were difficult to mimic by a simple relationship as they are highly influenced by interactions between land use, climate and soil type (in particular soil erodibility and assisted drainage assumptions).

4.2 Source apportionment

Even though the absolute phosphorus loads from sewage effluents summarised over England and Wales are very high they only impact on a small percentage of lakes and for the majority of sites failing the TP standards for good ecological status diffuse agricultural sources are the dominant source (Table 5). In terms of what source should be targeted by management for most lakes, diffuse agricultural sources therefore are very important and clearly need to be tackled in order to increase the number of lakes reaching good status. This will also benefit small headwater streams, which are often not appropriately represented when the status of rivers is assessed, even though these small streams make up the majority of water courses by stream length and have a high ecological value (Bishop *et al.*, 2008).

Regarding uncertainties the phosphorus loads from agriculture, urban sources, STWs, septic tanks and atmospheric deposition require attention as these sources frequently represented the dominant source. However, catchments where STWs are dominant tend to fail good ecological status because of the high phosphorus loads, so that in terms of reaching good ecological status an error in the magnitude of loads will only be significant in very few cases. The uncertainties in the remaining sources are assumed to be in a similar order of magnitude. For example for agricultural loads, a comparison between 5 different models for P loss from agricultural land indicated an average coefficient of variation of 67 % (Kronvang *et al.*, 2009). For atmospheric deposition the largest source of uncertainty lies in the TP concentration in rainfall. Using the ECN data (ECN, 2008) the lower and upper quartile of the SRP

Table 5 Source apportionment of phosphorus loads to lakes, percentage of all lakes where a source is the dominant source, and percentage of lakes failing good ecological status where a source is the dominant source.

Source Type	% of total load summed over all catchments	Related to all lakes: % of lakes where dominant source	Related to failing lakes: % of lakes where dominant source
Sewage effluent	84	10	14
Diffuse agricultural	10	52	54
Diffuse urban	3	14	16
Septic tanks	3	8	9
Groundwater	0.5	1	0
Bank erosion	0.5	2	1
Atmospheric deposition	0.2	13	5

concentration in rainfall are c. 50 % below and above the mean value. Besides uncertainties due to the connectivity of urban areas a large part of the uncertainty results from variations in the event mean concentration, and values for the upper and lower quartile are at c. 50 % below and 100 % above the mean value (Mitchell *et al.*, 2001). Uncertainties in septic tank loads relate mostly to maintenance issues, location, age and method of discharge of the systems, and are currently difficult to quantify due to insufficient data.

4.3 Lake ecological status

Carvalho *et al.* (2003) suggested that 88 % of lakes in England and 56 % of lakes in Wales would fail to achieve good ecological status under present day conditions; estimates very similar to the results of this study.

Evaluating lake ecological status for the data set of the 75 lakes used for model validation based on measured concentrations results in 64 % of the lakes failing good ecological status with respect to phosphorus. However, the percentage of lakes with measurements is only small and the selection of lakes for measurements might be biased towards pristine lakes on the one hand and lakes with known eutrophication problems on the other hand. Modelling results as in this study are therefore very useful to make assessments for a very large number of lakes to complement results based on measurements.

4.4 Required reductions of phosphorus loads to achieve good ecological status

Substantial reductions in phosphorus loads are needed to increase the number of compliant lakes. The predicted phosphorus concentrations under current conditions result in a high number of lakes classified as poor or bad status. The moderate/poor and poor/bad class boundaries are defined as doublings of the good/moderate class. A lake in the poor status class needs on average to improve by 1.5 classes in order to reach the good/moderate boundary, which corresponds to a reduction in phosphorus concentrations by 66 %.

Potential reductions of agricultural losses by increasing the uptake of mitigation methods are likely to fall short of the large reductions required. Anthony *et al.* (2008) have investigated different options for reducing agricultural phosphorus losses in Wales. Implementing all available measures from the existing environment schemes resulted in a reduction of phosphorus delivery to watercourses of 35 % at a substantial annual cost to the agricultural sector of c. 140 M GBP y⁻¹. Including only those measures which were presumed enforceable, estimated reductions in phosphorus loss were only 15 %.

In order to further reduce phosphorus losses, reductions in the intensity of agriculture, including caps on fertilizer input and stocking rates and taking land out of production could be considered. Johnes *et al.* (2007) investigated a drastic scenario, which was region specific and included fertilizer reductions between 50 % and 80 %, reductions in animal numbers by 25 % and conversion of part of the arable land to grassland. Using an export coefficient model they estimated an overall reduction of phosphorus losses to watercourses in England and Wales of 40 % compared to a 1991 baseline. Even though this number might be an overestimate as the export coefficient approach relates the losses linearly to animal numbers or fertilizer input, it illustrates the severe changes in agriculture that are required to reduce agricultural phosphorus loads sufficiently for ensuring compliance.

To reduce further phosphorus loads to lakes, other sources, such as urban diffuse losses and septic tanks, also need to be considered. Both estimates are affected by large uncertainties and should be quantified in greater detail. High losses from septic tanks to watercourses are known to be associated with lack of maintenance and with older septic tank installations which sometimes discharge directly into watercourses (Frost, 1996). The scale of poor

maintenance and installation is largely unknown, although surveys in Northern Ireland suggest poor performance is not uncommon (Phil Jordan, pers. comm.).

4.5 Delay of water quality improvements after load reduction

The Vollenweider model simulates the phosphorus concentrations as a function of phosphorus load for a system in steady state. However, many studies have observed a lag effect following a reduction of external nutrient inputs from a catchment to a lake, and lake recovery can take many years, if not decades to occur (Jeppesen *et al.*, 2005; Sas, 1989). This is especially true of shallow lakes where the sediment to lake volume ratio is lower than in deeper lakes (Sas, 1989).

This transient recovery period is caused by gradual re-equilibration of phosphorus stored in the lake bed sediments with the overlying water column following a reduction in external loading (Spears *et al.*, 2006; Søndergaard *et al.*, 2005). Sediment phosphorus concentrations, and therefore the expected length of the transient period, are regulated largely by the pollution history, i.e. intensity and time period, and a lake's flushing rate (Spears *et al.*, 2007). A low flushing rate and extended pollution history will result in high sediment phosphorus content and, therefore a long recovery period, and vice versa.

A synthesis of 35 case-studies from around the world demonstrated that in most lakes a new equilibrium for total phosphorus was reached after 10 to 15 years (Jeppesen *et al.*, 2005). Therefore the actual time required for many lakes (especially shallow lakes) to respond to reduced nutrient loading may extend beyond the most immediate important timelines of the WFD (i.e. 2015 and 2021).

4.6 Ecological responses to reduced phosphorus concentrations

Plants and algae are actually responsive to concentrations of bioavailable phosphorus. Therefore, if soluble, more bioavailable phosphorus losses are more strongly reduced than particulate losses, this may result in a greater ecological response. This should for example be the case for reduction in phosphorus loads from sewage effluents, which have a high SRP:TP ratio. Also, many available agricultural mitigation methods are focussed on the control of soluble phosphorus losses from fertiliser and manures, and may, therefore, have a stronger impact on ecology than inferred simply from the total phosphorus losses.

A lag in the ecological response to changing phosphorus concentrations must also be considered. Of the limited ecological studies available, most have focused on responses of chlorophyll concentrations to nutrient load reductions. These case-studies (Carvalho and Kirika, 2003; Ferguson *et al.*, 2008; Jeppesen *et al.*, 2005; Moss *et al.*, 2005; Phillips *et al.*, 2005) all indicate strong ecological resilience to reduced in-lake phosphorus concentrations, with limited improvements observed in chlorophyll concentrations or algal blooms even following large reductions in both external loads and in-lake phosphorus concentrations. One of the reasons for ecological resilience is that even following reductions of in-lake phosphorus concentrations, phosphorus may still be in excess of plant and algal requirements and production may, therefore, be limited by other factors, such as nitrogen or light availability (Moss *et al.*, 2005). In shallow lakes, which can exist in a macrophyte or a phytoplankton dominated state, negative feedback loops can be significant and may delay or impede the ecological response to reduced phosphorus concentrations.

5. Conclusions

The modelling framework described for estimating phosphorus loads in combination with the Vollenweider model is a sufficiently robust method to estimate lake phosphorus concentrations from which non-compliance for lake phosphorus standards could be inferred. It must be emphasised that uncertainties for individual lakes can be very high, although the statistics across the population of lakes are demonstrated to be reasonably robust. Regarding the source apportionment future work should refine the load estimates for urban loads and septic tanks, which have been studied less than diffuse agricultural loads.

This study confirmed previous estimates that the majority of lakes in England and Wales will fail to reach good ecological status and that substantial measures to reduce phosphorus inputs into these lakes are required. Even though the national load from sewage effluents is large, for the majority of catchments diffuse agricultural phosphorus loads represent the most important source. For agriculture, required changes would have to go beyond improvements of agricultural practise, and need to include reducing the intensity of land use. As it is likely that in many cases phosphorus concentrations cannot be reduced to limiting levels, measures to reduce nitrogen concentrations should also be considered. The results of this work are being used to support government in assessing the impact of changes in agricultural practise under supportive policy instruments.

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References

- ANTHONY, S. (2006). "Cost effectiveness of policy instruments for reducing diffuse agricultural pollution," Final report to Defra, project code WQ0106 and ES02025, 119 pp.
- ANTHONY, S., TURNER, T., ROBERTS, A., HARRIS, D. AND WITHERS, P. (2008). "Evaluating the extent of agricultural phosphorus losses across Wales," Final project report to Defra and WAG, project WT0743CSF, 281 pp.
- BEHRENDT, H. AND OPITZ, D. (2000). "Retention of nutrients in river systems: dependence on specific runoff and hydraulic load," *Hydrobiologia*, 410, 111-122.
- BENNION, H., HILTON, J., HUGHES, M., CLARK, J., HORNBY, D., KERNAN, M. AND SIMPSON, G. (2002). "Development of a risk based prioritisation protocol for standing waters in Great Britain based on a georeferenced inventory – Phase 2," Final Project report to the Environment Agency, 109 pp.
- BIBBY, P. AND SHEPHERD, J. (2004). "Developing a new classification of urban and rural areas for policy purposes – the methodology," http://www.statistics.gov.uk/geography/downloads/Methodology_Report.pdf, 27 pp.
- BRETT, M. AND BENJAMIN, M. (2008). "A review and reassessment of lake phosphorus retention and the nutrient loading concept," *Freshwater Biology*, 53, 194-211.
- CARDOSO, A., SOLIMINI, A., PREMAZZI, G., CARVALHO, L., LYCHE, A. AND REKOLAINEN, S. (2007). "Phosphorus reference concentrations in European lakes," *Hydrobiologia*, 584, 3-12.
- CARVALHO, L. AND KIRIKA, A. (2003). "Changes in shallow lake functioning: response to climate change and nutrient reduction," *Hydrobiologia*, 506, 789-796.

- CARVALHO, L., MABERLY, S., MAY, L., REYNOLDS, C., HUGHES, M., BRAZIER, R., HEATHWAITE, L., LIU, S. *ET AL.* (2003). "Risk Assessment Methodology for Determining Nutrient Impacts in Surface Freshwater Bodies," Final R&D Technical Report P2-260/9 to the Environment Agency and Scottish Environment Protection Agency, 171 pp.
- CARVALHO, L., PHILLIPS, G., MABERLY, S., CLARKE AND R. (2006). "Chlorophyll and Phosphorus Classifications for UK Lakes," Final Report to SNIFFER, Project WFD38, 81 pp.
- COLLINS, A.L. AND ANTHONY, S.G. (2008). "Assessing the likelihood of catchments across England and Wales meeting 'good ecological status' due to sediment contributions from agricultural sources," *Environmental Science & Policy*, 11 (2). 163-170.
- COLLINS, A.L. AND WALLING, D.E. (2007). "Fine-grained bed sediment storage within the main channel systems of the Frome and Piddle catchments, Dorset, UK," *Hydrological Processes*, 21, 1448-1459.
- DAVIES, H. AND NEAL, C. (2007). "Estimating nutrient concentrations from catchment characteristics across the UK," *Hydrology and Earth System Sciences*, 11(1). 550-558.
- DAVISON, P., WITHERS, P., LORD, E., BETSON, M. AND STROMQVIST, J. (2008). "PSYCHIC A process-based model of phosphorus and sediment mobilisation and delivery within agricultural catchments. Part 1: Model description and parameterisation," *Journal of Hydrology*, 350(3-4). 290-302.
- DEFRA (2007). "Agriculture in the United Kingdom," ISBN 978-0-11243095-7, 132 pp.
- DEMARS, B., HARPER, D., PITT, J. AND SLAUGHTER, R. (2005). "Impact of phosphorus control measures on in-river phosphorus retention associated with point source pollution," *Hydrology and Earth System Sciences*, 9, 43-55.
- ELLIS, J.B. AND MITCHELL, G. (2006). "Urban diffuse pollution: Key data information approaches for the Water Framework Directive," *Water and Environment Journal*, 20 (1). 19-26.
- ECN (2008). Environmental Change Network, www.ecn.ac.uk.
- FERGUSON, C., CARVALHO, L., SCOTT, E., BOWMAN, A. AND KIRIKA, A. (2008). "Assessing ecological responses to environmental change using statistical models," *Journal of Applied Ecology*, 45, 193-203.
- FROST, A. (1996). "Loch Leven and diffuse pollution," *In:* Petchey, A., D'Arcy, B. and Frost, C.(eds.), *Diffuse pollution and agriculture*, Scottish Agricultural College, Aberdeen, 174-182.
- HAKANSON, L. (1999). "On the principles and factors determining the predictive success of ecosystem models, with a focus on lake eutrophication models," *Ecological Modelling*, 121, 139-160.
- HEATHWAITE, A.L., DILS, R., LIU, S., CARVALHO, L., BRAZIER, R.E., POPE, L., PHILLIPS, G., MAY, L. (2005). "A tiered risk assessment approach to predicting diffuse agricultural phosphorus losses," *Science of the Total Environment*, 344, 225-239.
- HOUSE, W.A. (2003). "Geochemical cycling of phosphorus in rivers," *Applied Geochemistry*, 18, 739-748.
- HUGHES, M., HORNBY, D., BENNION, H., KERNAN, M., HILTON, J., PHILLIPS, G. AND THOMAS, R. (2004). "The development of a GIS-based inventory of standing waters in Great Britain together with a risk-based prioritisation protocol," *Water Air and Soil Pollution: Focus*, 4, 73-78.
- JARVIE, H.P., NEAL, C., WITHERS, P.J., WESCOTT, C. AND ACORNLEY, R.M. (2005). "Nutrient hydrochemistry for a groundwater-dominated catchment: The Hampshire Avon, UK," *Science of The Total Environment* , 344, 143-158.
- JEPPESEN, E., SONDERGAARD, M., JENSEN, J., HAVENS, K., ANNEVILLE, O., CARVALHO, L., COVENEY, M., DENEKE, R. *ET AL.* (2005). "Lake responses to reduced nutrient loading

- an analysis of contemporary long-term data from 35 case studies," *Freshwater Biology*, 50, 1747-1771.
- JOHNES, P.J., FOY, R., BUTTERFIELD, D. AND HAYGARTH, P.M. (2007). "Land use scenarios for England and Wales: evaluation of management options to support 'good ecological status' in surface freshwaters," *Soil Use and Management*, 23 (Suppl. 1), 176-194.
- JULIAN, J. AND TORRES, R. (2006). "Hydraulic erosion of cohesive riverbanks," *Geomorphology*, 76, 193-206.
- KRONVANG, B., BEHRENDT, H., ANDERSEN, H. E., ARHEIMER, B., BARR, A., BORGVANG, S. A., BOURAOUI, F., GRANLUND, K. ET AL. (2009). " Ensemble modelling of nutrient loads and nutrient load partitioning in 17 European catchments," *Journal of Environmental Monitoring*, 11, 572 - 583.
- KELLY, S., DEMPSEY, P. AND CRABTREE, R. (2006). "Production of SIMCAT model structures for England and Wales," Final Report to the Environment Agency, No. UC7189, 84 pp.
- LORD, E.I. AND ANTHONY, S. G. (2000). "MAGPIE: A modelling framework for evaluating nitrate losses at national and catchment scales," *Soil Use and Management*, 16, 167-174.
- MITCHELL, G. (2005). "Mapping hazard from urban non-point pollution: a screening model to support sustainable urban drainage planning," *Journal of Environmental Management*, 74, 1-9.
- MITCHELL, G., LOCKYER, J. AND McDONALD, A. (2001). "Pollution hazard from urban nonpoint sources: a GIS-model to support strategic environmental planning in the UK," Technical Report, School of Geography, University of Leeds, UK, 120 pp.
- MOSS, B., BARKER, T., STEPHEN, D., WILLIAMS, A., BALAYLA, D., BEKLIOGLU, M. AND CARVALHO, L. (2005). "Consequences of reduced nutrient loading on a lake system in a lowland catchment: deviations from the norm?," *Freshwater Biology*, 50, 1687-1705.
- MOSS, B., BEKLIOGLU, M., CARVALHO, L., KILINC, S., MCGOWAN, S. AND STEPHEN, S. (1997). "Vertically challenged limnology, contrasts between deep and shallow lakes," *Hydrobiologia*, 342-343, 257-267.
- NERC (1975). "Flood Studies Report (in five volumes)," Natural Environment Research Council.
- NEAL, C., REYNOLDS, B., NEAL, M., HUGHES, S., WICKHAM, H., HILL, H., ROWLAND, P. AND PUGH, B. (2003). "Soluble reactive phosphorus levels in rainfall, cloud water, throughfall, stemflow, soil waters, stream waters and groundwaters for the Upper River Severn area, Plynlimon, mid Wales," *The Science of The Total Environment*, 314-316, 99-120.
- NEAL, C., SKEFFINGTON, R., NEAL, M., WYATT, R., WICKHAM, H., HILL, L. AND HEWITT, N. (2004). "Rainfall and runoff water quality of the Pang and Lambourn, tributaries of the River Thames, south-eastern England," *Hydrology and Earth System Sciences*, 8, 601-613.
- OECD (1982). "Eutrophication of waters: monitoring, assessment and control," Organisation for Economic Cooperation and Development, 154 pp.
- OFWAT (2008). Office of Water Services, <http://www.ofwat.gov.uk/aptrix/ofwat/publish.nsf/Content/navigation-jr06-all-tables>.
- PHILLIPS, G., KELLY, A. PITT, J. AND SANDERSON, R. TAYLOR, E. (2005). "The recovery of a very shallow eutrophic lake, 20 years after the control of effluent derived phosphorus," *Freshwater Biology*, 50, 1628-1638.
- PHILLIPS, G., PIETILAINEN, O., CARVALHO, L., SOLIMINI, A., SOLHEIM, A. AND CARDOSO, A. (2008). "Chlorophyll - nutrient relationships: a statistical evaluation of typed lakes using a large European data set," *Aquatic Ecology*, 42, 213-226.

- REYNOLDS, C.S. AND DAVIES, P.S. (2001). "Sources and bioavailability of phosphorus fractions in freshwaters: a British perspective," *Biological Reviews*, 76, 27-64.
- SAS, H. (1989). "Lake Restoration by Reduction of Nutrient Loading," Academic Verlag Richarz.
- SCHINDLER, D.W. (1977). "The evolution of phosphorus limitation in lakes," *Science*, 195, 260-262.
- SPEARS, B., CARVALHO, L. AND PATERSON, D. (2007). "Phosphorus partitioning in a shallow lake: implications for water quality management," *Water and Environment Journal*, 21, 47-53.
- SPEARS, B., CARVALHO, L., PERKINS, R., KIRIKA, A. AND PATERSON, D. (2006). "Spatial and historical variation in sediment phosphorus fractions and mobility in a large shallow lake," *Water Research*, 40, 383-391.
- STROMQVIST, J., COLLINS, A., DAVISON, P. AND LORD, E. (2008). "PSYCHIC A process-based model of phosphorus and sediment transfers within agricultural catchments. Part 2. A preliminary evaluation," *Journal of Hydrology*, 350, 3-4, 303-316.
- SØNDERGAARD, M., JENSEN, J. AND JEPPESEN, E. (2005). "Seasonal response of nutrients to reduced phosphorus loading in 12 Danish lakes," *Freshwater Biology*, 50, 1605-1615.
- VIGHI, M. AND CHIAUDANI, G. (1985). "A simple method to estimate lake phosphorus concentrations resulting from natural, background loadings," *Water Research*, 19, 987-991.