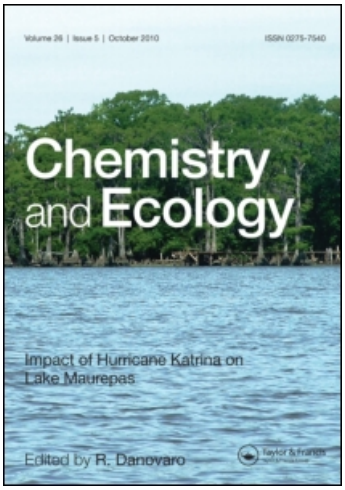

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THE ROLE OF MACROPHYTES IN THE RETENTION OF PHOSPHORUS IN THE RIVER THAME, ENGLAND

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The effects of the growth of the dominant species of macrophytes on phosphorus transport in the River Thame, a nutrient enriched lowland clay catchment in southern England, were assessed using a mass-balance approach. Macrophyte abundance was estimated between late March and early June at three sites along the river. The plant biomass of phosphorus and the total phosphorus content of sediments in the main part of the river channel and sediments associated with the plant roots were measured on each occasion. Total phosphorus concentrations in the river water were measured at weekly intervals at a gauging station at the lower end of the study reach.

The results showed that the phosphorus content of plants at the site most impacted by sewage derived phosphorus was < 1% of the flux of total phosphorus estimated for the water column in April and May. Phosphorus contained in the total standing crop of macrophytes at the least impacted site was estimated as approximately 3% of the mean daily flux of total phosphorus in the water. Although no trends were found in the total phosphorus contents of the roots, shoots or sediments through the season, differences in the phosphorus content of the sediments were found between sites with different phosphorus loading. Higher porewater and Equilibrium Phosphate Concentrations (EPC_0s) were recorded at the site most impacted by sewage effluent when compared to an upstream sampling site.

Keywords: Phosphorus; Eutrophication; Macrophytes; Rivers; Chemical fluxes

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INTRODUCTION

Inorganic phosphorus is an essential and potentially limiting nutrient for the growth of plants in fresh waters. The concentration of soluble phosphorus in water bodies is the result of the hydraulic loading and the various sources of phosphorus *e.g.*, point-inputs from sewage treatment works, diffuse inputs from urban and agricultural areas, and multiple interactions of phosphorus within the system. The latter usually consist of exchanges between different phosphorus fractions, *e.g.*, dissolved organic compounds and inorganic compounds, interactions with suspended- and bottom-sediments, and as biological assimilation and release by organisms and plants (Grobbelaar and House, 1995).

There is considerable information about the interactions of phosphorus with sediments (Stabel and Geiger, 1985; Poilles and Moody, 1992; House *et al.*, 1997) but little data on how the growth of aquatic macrophytes affect water column, sediment porewater and sediment concentrations of phosphorus (Westlake, 1973; Carr and Chambers, 1998; Pelton *et al.*, 1998; Sand-Jensen, 1998). Macrophytes have a key role in the ecology of streams not least because they provide microhabitats for microorganisms, invertebrates and fish (Dawson, 1988). Submerged macrophytes change the flow patterns in streams and lead to sediment deposition within plant-beds in low-flow conditions, and contribute to the stability of the bottom sediments (Westlake, 1973; Dawson, 1978; Kern-Hansen and Dawson, 1978; Sand-Jensen, 1998).

Previous work has concentrated on chalk streams in lowland catchments in the UK that are dominated by groundwater inputs, *e.g.*, Casey and Downing (1976). In contrast, the present study examines the relationship between phosphorus and macrophytes in a lowland river draining a clay-dominated catchment. The study sites are affected, to varying degrees, by point-inflows of soluble phosphorus. The main objective of the study was to assess the consequences of macrophyte growth on phosphorus concentrations in the water column and river bed-sediments. Although macrophytes have a role in the accumulation and stabilisation of bottom-sediments during periods of low river-flow, the implications for the phosphorus budget are not dealt with here.

DESCRIPTION OF SITES

The River Thame, in the Vale of Aylesbury, is a lowland river draining much of East Oxfordshire and parts of Buckinghamshire. Its catchment area to the Environment Agency gauging station at Wheatley (NGR 46122050) is 533 km^2 (Fig. 1). It flows in a southwesterly direction from its source northwest of Aylesbury, and joins the River Thames six miles south of Oxford. Three sampling sites were chosen for the study as detailed in Table I. The most upstream site (U) was situated in a reach not impacted by major sewage discharges, whereas the other two sites were below the main sewage inflows. The middle site (M) was downstream of the Aylesbury sewage treatment works (STW) but above the STW at Thame, while the

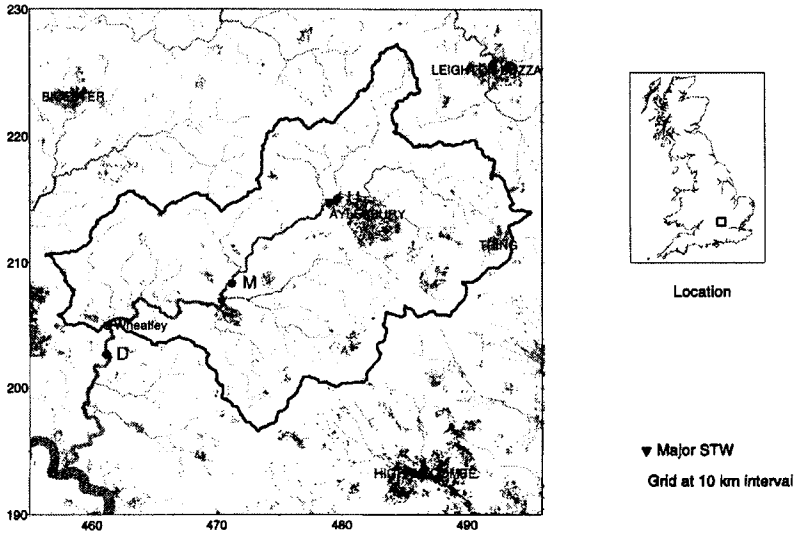

FIGURE 1 Outline of the catchment boundary for the River Thame showing the main sampling sites (D, M and U) and towns in the region.

TABLE I Sampling site locations

Site location	*Site code*	*National grid reference*	*Distance from site U (km)*
Aylesbury	U	SP 4796152	0
Drake's farm	M	SP 4712084	12.7
Cuddesdon Mill	D	SP 4611027	33.3

downstream site (D) was influenced by effluent from both of the major sewage works. The sites were chosen to represent the vegetation typical of the river, Type II (Holmes *et al.*, 1998), and also for their ease of access to the 100 m sections of the river needed for the plant quality assessment of Mean Trophic Ranking (Holmes *et al.*, 1999). The sites varied greatly in width, depth and flow but gradients were shallow ($< 1:1000$) and the sites were all below 40 m in altitude. The geology of the catchment is dominated by clays and Jurassic limestone with chalk present along the southeastern boundary.

METHODS

Routine Monitoring

River-water samples were collected at weekly intervals at the Environment Agency gauging site at Wheatley (Fig. 1), which is 2 km upstream of site D. The samples were returned to the laboratory and analysed for their total phosphorus concentration, as described below. Mean daily discharges for the river on the day of sampling were provided by the Environment Agency. Similar river discharge data were not available for site U and so these were estimated from spot field measurements.

Field Surveys

The sites were visited on three occasions during the macrophyte growing season, *i.e.*, on the 29 March, 11 May and 2 June, 1999. Site M was not sampled in March because of difficulties in access. At each site, a 100 m section of river that was open and as free from shade as possible was selected for the macrophyte survey. A similar section of river was also found, either downstream or upstream of this section for sampling bed-sediments and macrophytes. The river sites were surveyed using the standard Mean Trophic Rank methodology (Holmes *et al.*, 1999) in which the areal coverage of each species and its species trophic rank gave an estimate of the eutrophic status of the sites. Photographs of the sections were recorded for future reference.

At each visit unfiltered river water samples were collected for the analysis of total phosphorus content. The pH, and electrical

conductivity were measured in the field (Ciba-Corning M90 field meter). In addition, a 60 ml water sample was filtered in the field through a 0.45 μm cellulose nitrate membrane, returned to the laboratory and analysed for soluble reactive phosphorus (SRP) content and alkalinity, as described below.

Bed-sediment was sampled to ca. 5 cm depth using a stainless steel scoop or, if the water was deep, using a Freshwater Biological Association 100 mesh net. The samples were sieved to a maximum size of 2 mm into a stainless steel tray, allowed to settle, excess water decanted off and then transferred to a 500 ml wide-necked plastic bottle for transport to the laboratory. Representative sediments from each section were sampled and, if clear visual differences in the texture of some of the sediments were apparent, these were sampled separately. In the March survey, bed-sediments were taken at sites U and D to assess differences in the Equilibrium Phosphate Concentration (EPC_0) of the sediments in the main river-channel and sediments between the roots of plants. Two different sediments from the riverbed were selected – (a) the dominant sand/gravel textured sediment and (b) softer sand/clay material typical of marginal zones.

The three most abundant macrophytes were sampled in triplicate by removing all of the plants, including their roots, from within a 1 metre quadrat. The plants were washed with river water to remove adhering sediment and animals, drained and placed in plastic bags for transport back to the laboratory.

Chemical Analysis

Solutions were all prepared using ultra-pure water of conductivity $< 0.1\,\mu S\,cm^{-1}$ at 20°C (Purite, Analyst HP). Total alkalinity was measured by titration to pH 4.5. Soluble reactive phosphorus was determined by Flow-Injection-Analysis (FIA) (Tecator, 1983). Total phosphorus content of the river water was determined by digesting filtered sub-samples, with acidic potassium persulphate in an autoclave at 121°C, then reacting with acid ammonium molybdate reagent to produce an molybdenum-phosphorus complex. This intensely coloured compound was then quantified spectrophotometrically at 880 nm (Eisenreich *et al.*, 1975). Procedural blanks and quality assurance samples were included in the analysis.

Plant material was washed with tap water to remove fine sediments and any animals that remained from the previous wash in river water. The roots and shoots were separated, sorted in plastic baskets and weighed with a spring balance. Subsamples of root and shoot material from each species (obtained from mixed subsamples from the triplicate quadrats of the same species) were put into meshed-bottomed trays. The wet weight was recorded, the subsamples were dried at 70°C for 48 h and then dry weight recorded. Subsamples were ground, with a grinder for the soft plant material and with a grater followed by a grinder for the hard materials such as the tubers and rhizomes, and stored in 100 ml plastic bottles.

Sediment and plant tissues were analysed for total phosphorus content by acid oxidation using a method modified from Allen *et al.* (1974). All glassware was soaked in chromic acid (50 g dm^{-3} $K_2Cr_2O_7$ in 50% v/v H_2SO_4), then triple washed in ultra-pure water before use. The objective of the method is to degrade all organic and inorganic material (except siliceous material) to liberate phosphorus as inorganic phosphate in solution. The dissolved phosphate was then determined by reaction with ammonium molybdate reagent using the method of Murphy and Riley (1962). In brief, the method consisted of digesting 0.15–0.25 g of dry plant tissue or 0.35–0.45 g of dry sediment in 5 ml of concentrated nitric acid at 100°C for ca. 30 mins using a programmable temperature controlled block digester (Techne DG-1). After cooling the digest, 5 ml of digestion reagent (360 ml of concentrated sulphuric acid, 0.42 g selenium powder, 9.41 g lithium carbonate and 420 ml hydrogen peroxide in 1 dm^3 and stored at 0°C) were added and the temperature was raised to 200°C for 30–45 minutes. After 10 minutes of cooling, 4 ml of concentrated nitric acid followed by 4 ml of 100 vol hydrogen peroxide were mixed with the digest and heated to 200°C for a further 1 h period. After cooling for 10 minutes, a further 2 ml of concentrated nitric acid and 2 ml of 100 vol hydrogen peroxide were added and the mixture heated to 220°C for 1 hour. When cool, the sides of the digestion tube were carefully washed with 10–15 ml of ultrapure water and then heated until white or brown fumes had ceased or greatly reduced. The digest was then cooled and transferred to a 100 ml volumetric flask for SRP analysis. The performance of the digestion method was checked by analysing 6 replicate samples of sediment, 6 samples of plant material

(*Sparganium*) and 6 samples of phytic acid (17.3 w/w % phosphorus). The phytic acid was supplied by Sigma and the phosphorus content, as determined by the method used here for TP analysis of the river water, was in agreement with the expected value (Denison *et al.*, 1998). A sample of phytic acid was included in all the analysis batches to monitor the performance of the analytical method.

Equilibrium Phosphate Concentration (EPC_0) was measured by the method previously described by House and Denison (2000), using 2.0–2.5 g of wet sample in 200 ml of 2 mM calcium chloride mixed with water containing different concentrations of SRP, for 24 h at 10°C. Porewater concentrations were measured on return to the laboratory by decanting the supernatant off the sediment samples after centrifuging ($g_{average} = 6000$), and filtering through 0.45 μm cellulose nitrate membrane before analysis by FIA (Tecator, 1983).

RESULTS AND DISCUSSION

Method Performance

All results are given in terms of the dry weight of material analysed. The total phosphorus analysis of the sediment was compared with the results obtained in previous studies (House and Denison, 1998; Bowes and House, 2000) using the method of Anderson (1976). The TP content of the sediment sample by the Anderson method was 79.9 $\mu mol\, g^{-1}$ compared with a mean value of 85.2 $\mu mol\, g^{-1}$ ($\pm$ 11.4 $\mu mol\, g^{-1}$; se: standard error) by the procedure employed here. The analysis of phytic acid produced a mean value of 5019 $\mu mol\, g^{-1}$ ($\pm$ 660 $\mu mol\, g^{-1}$; se) indicating a recovery of 90% for phosphorus. The variability for the analysis of the plant tissue was slightly less than that for the sediment with a result of 91.8 $\mu mol\, g^{-1}$ ($\pm$ 5.5 $\mu mol\, g^{-1}$; se) compared with a slightly higher result obtained using the Anderson (1976) method of 129 $\mu mol\, g^{-1}$.

Total Phosphorus Concentrations in the River

The weekly total phosphorus concentrations showed a general increase from slightly below 400 $\mu g\, l^{-1}$ at the beginning of January to a maximum of 1990 $\mu g\, l^{-1}$ in July (Fig. 2). This is consistent with the

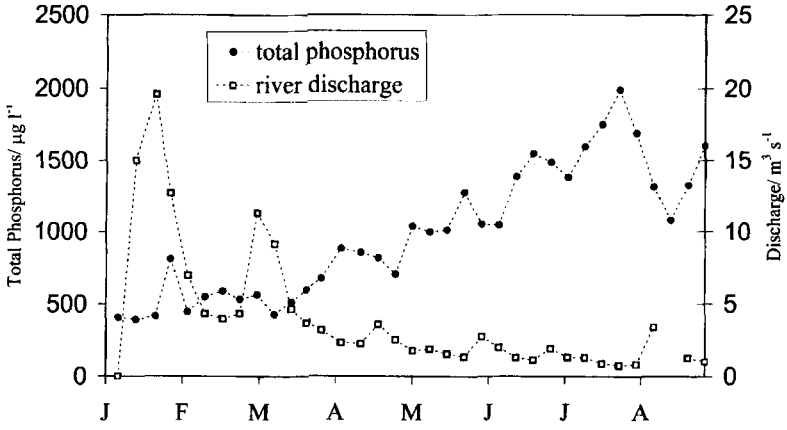

FIGURE 2 Mean daily discharge and weekly in-stream total phosphorus concentration in the River Thame at Wheatley over the study period.

dilution of a point source (in this case, treated sewage-effluent from STW's) during storm periods in the early part of the year. A regression of the reciprocal of river discharge against TP concentration indicated that point-source inputs for the catchment were likely to be 1.2 g TP s^{-1} ($r^2 = 0.86$) (House and Denison, 1998). This value is much lower than predicted for a catchment such as this with a people equivalent (PE) of ca. 180,000. Assuming an export of 0.73 kg TP PE^{-1} the predicted value amounts to a flux of 4.2 g s^{-1}. The apparent discrepancy most likely reflects a loss of phosphorus to sediments and plants in the river during the lower flows in the spring and summer (House and Warwick, 1999; May *et al.*, 2000). The importance of sewage effluent in the river also suggests that the total phosphate composition would be dominated by the soluble reactive phosphorus (SRP) fraction. This is confirmed by the results for the spot sampling measurements in May and June (see Tab. II). The results from the spot samples all show an increase in SRP and TP concentrations between the upper and lower sites, with SRP making a greater contribution to TP further downstream. For example, in June, SRP was 77% of TP at the upstream site (U), increasing to 83% at the midstream site (M) and 92% at the downstream site (D). This reflects the increasing influence of SRP from STW effluent at the downstream sites.

TABLE II Results of the river water analysis. Conductivity is corrected to 25°C. Key: U: upstream site; M: midstream site; D: downstream site; SRP: Soluble Reactive Phosphorus; TP: total phosphorus

Site	*Temp/°C*	*pH*	*Conductivity /μS cm^{-1}*	*Alkalinity /mEq l^{-1}*	*SRP/μg l^{-1}*	*TP/μg l^{-1}*	*Discharge/m^3 s^{-1}*
29/3/99							
U	9.4	7.9	799	–	147	–	–
D	10.4	8.7	868	–	502	–	3.18
11/5/99							
U	13.2	8.1	752	2.47	266	384	–
M	15.8	8.2	818	2.27	440	523	–
D	15.5	8.2	777	2.33	706	833	1.89
2/6/99							
U	13.5	7.9	596	1.68	276	359	–
M	16.0	7.9	711	1.92	523	632	–
D	15.9	8.1	868	2.54	1208	1319	2.77

Phosphorus Contents in Plants and Sediment

A total of 38 samples of different plant tissues and 33 samples of sediment were analysed from the three sites. Combining all of the results for all plants and sediments for all sampling occasions, the mean concentration of phosphorus in the plant tissue was found to be higher than in the sediments, *i.e.*, 4.7 mg TP g^{-1} ($\pm$ 3.8 se: standard error) in plants compared to 2.7 mg TP g^{-1} ($\pm$ 1.6 se) in sediments (all sediment masses expressed on a dry weight basis). Casey and Downing (1976) found similar mean values of 5.5 mg TP g^{-1} for complete *Ranunculus penicillatus* plants, with higher concentrations in actively growing shoot apices (mean of 9.54 mg TP g^{-1}) than roots (4.36 mg TP g^{-1}). In the present work, there was no discernible trend in either the phosphorus content of the root or shoot tissue of plants during the growing season, or in the Phosphorus content of sediments from the river channel or that associated with plant roots (Fig. 3). Although there is evidence from other studies, *e.g.*, Moore *et al.* (1994), that the SRP content of porewaters of sediments containing plants is lower than that in sediments without plants, this could not be confirmed by the limited data obtained here (see Tab. VI). The porewater phosphorus is a relatively minor component of the pool stored in the sediment and the latter also acts to buffer the concentration of phosphorus in solution (see sediment TP and porewater concentrations in Tab. VI). It is also possible that phosphorus rich suspended matter accumulates in the plant beds during low-flow conditions. For example Sand-Jensen (1998) found increases in total phosphorus and organic matter in near-surface sediments (< 1 cm depth) within plant stands but these were generally an order of magnitude lower in concentration than observed in the present study. Sampling to a sediment depth of 5 cm makes it difficult to detect changes in the near-surface sediments that might be expected from the accumulation and scouring of sediments in the plant stands.

There was no significant difference (*t*-test, 95% CL: confidence limit) between the phosphorus content of shoot or root material at any of the sampling times, partly as a result of the relatively large variability in their TP contents. This contrasts with the results obtained for *Ranunculus penicillatus* by Spink *et al.* (1993) who found that increasing SRP concentrations from 40 to 200 $\mu g\, l^{-1}$ in experimental channels led to plants acquiring increasing amounts of phosphorus in their tissue. This may be the result of the lower

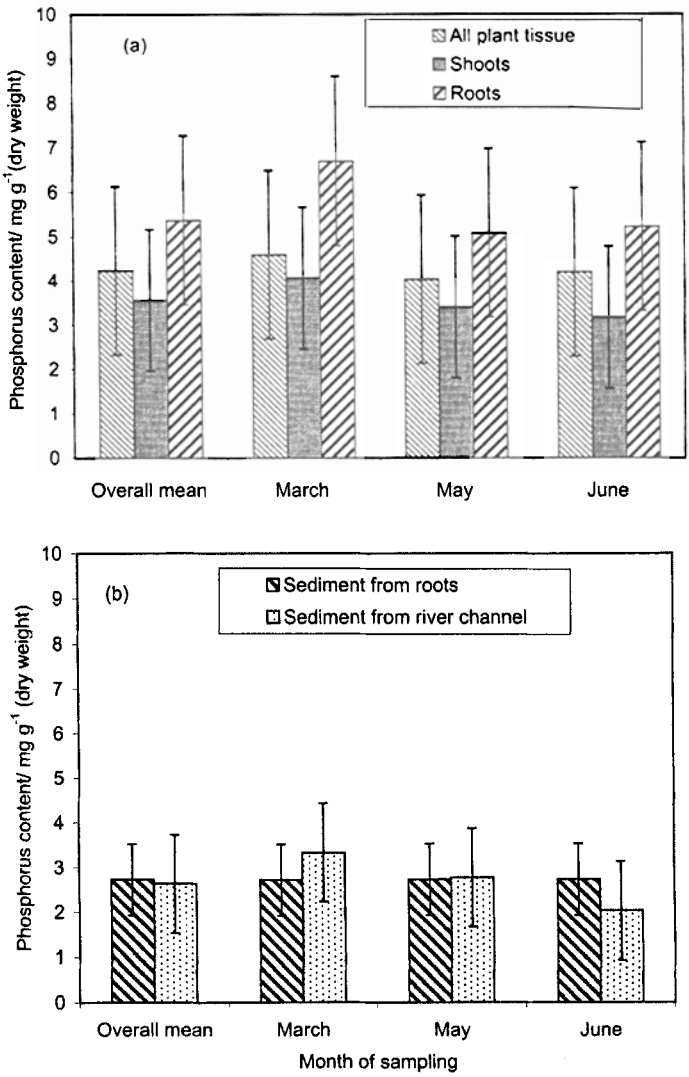

FIGURE 3 Total concentrations of phosphorus measured after acid oxidation of plant tissue and bed-sediments. Standard deviations in the determinations are shown as bars for (a) 38 samples of plant tissue (24 shoots and 14 roots), and (b) 17 sediments collected attached to roots and 16 sediments from various parts of the river channel free from macrophytes.

concentrations of dissolved phosphorus that were used in the experiments by Spink *et al.* (1993) compared with the values measured in the River Thame (Tab. II).

Differences were observed in the phosphorus content of the sediments from the less impacted site (U), compared to the downstream site. Sediments associated with all type of roots contained 3.0 mg TP g^{-1} ($\pm$ 1.4 se) at site D compared with 2.3 mg TP g^{-1} ($\pm$ 0.6 se) at site U. Similarly, bed-sediments in areas free from macrophytes contained 3.2 mg TP g^{-1} ($\pm$ 2.4 se) at the downstream site and 2.2 mg TP g^{-1} ($\pm$ 1.8 se) at site U. Larger differences in EPCo and porewater concentrations of SRP were observed between sites (Tab. VI). At site D, porewater concentrations from the river channel and collected from plant roots were much higher than the EPC_o of the sediment. At the less impacted site (U) the EPC_o and porewater concentrations were much closer, indicating an approach to equilibrium between the porewater and the sediment particularly in sediments associated with roots. Although the sites were generally subject to different SRP concentrations in the water (Tab. II), this was not reflected in the results of the analysis of plant tissue with values of 4.2 mg TP g^{-1} ($\pm$ 3.8 se) for site D and 3.9 mg TP g^{-1} ($\pm$ 2.8 se) at site U.

The biomass of macrophytes in the river at the downstream site increased during the growing season. At sites U and M it was difficult to quantify the biomass because of the changing water levels in the river and difficulties in sampling deeper areas (Tabs. III to V). Biomasses were in the normal range for such species (Westlake, 1973). Difficulties were experienced at all other sites in placing the quadrat properly in the river with high macrophyte shoots and also in sampling deep roots and rhizomes in the sediments. Also root material from the previous seasons, growth was indistinguishable from fresh growth, leading to much variability in estimating biomass.

The results were used to estimate the total mass of phosphorus associated with the main macrophyte species at each site using the TP and water contents of the tissue, and areal coverage of the plants in a 100 m section (Tabs. III to V). If samples of a particular species were not obtainable because of access or river conditions, *e.g.*, *Nuphar lutea* at site D in March and June, the biomass was estimated from the nearest sampling time and assumed to be unchanged. At site U, *Glyceria maxima* and *Sparganium erectum* dominated the river with only a relatively small amount of *Carex riparia* that was only sampled once, in the May survey. The results indicate a decrease in phosphorus in macrophyte tissue in the 100 m section mainly as a result of a

TABLE III Amount of phosphorus in the macrophytes in the upstream site, U. Total area of the site was 500 m^2. Values in brackets estimated from nearest survey data. Key: se, standard error

		29 *March*, 1999				11 *May*, 1999				2 *June*, 1999			
Plants	*Tissue*	*Bed area* (m^2)	*Fresh weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)	*Bed area* (m^2)	*Fresh weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)	*Bed area* (m^2)	*Fresh weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)
Carex riparia	Shoot	(2)	–	–	(6.0)	2	8.7 (se 5.0)	2.1	6.0	2	–	–	(6.0)
	Roots and rhizomes		–	–	(2.3)		5.3 (se 5.7)	2.0	2.3		–	–	(2.3)
Glyceria maxima	Shoot	30	5.9	4.4	94.5	15	4.4 (se 2.3)	2.9	18.9	15	7.3 (se 3.2)	2.9	34.6
	Roots and rhizomes		9.7	5.9	187.4		9.6 (se 7.9)	4.8	45.1		4.1 (se 1.6)	5.8	34.8
Sparganium erectum	Shoot		0.3	6.1	5.6		12.8 (se 5.9)	4.4	101.2		5.1 (se 3.0)	3.5	41.4
	Moribund shoot	40	2.0	3.5	26.3	38	–	–	–	35	–	–	–
	Roots and rhizomes		3.0	4.4	150.5		7.6 (se 7.5)	2.5	110.9		6.4 (se 2.8)	3.9	99.6
	Total mass of *P* (g)				473				284				219

TABLE IV Amount of phosphorus in the macrophytes in the middle site, M. Total area of the site was 600 m^2. Values in brackets estimated from nearest survey data. Key: se, standard error

		29 *March*, 1999				11 *May*, 1999				2 *June*, 1999			
Plants	*Tissue*	*Bed area* (m^2)	*Fresh weight* ($kg\ m^{-2}$)	*TP* ($mg\ Pg^{-1}$) *dry*	*Mass of P in* 100 *m* (*g*)	*Bed area* (m^2)	*Fresh weight* ($kg\ m^{-2}$)	*TP* ($mg\ Pg^{-1}$) *dry*	*Mass of P in* 100 *m* (*g*)	*Bed area* (m^2)	*Fresh weight* ($kg\ m^{-2}$)	*TP* ($mg\ Pg^{-1}$) *dry*	*Mass of P in* 100 *m* (*g*)
Schoenoplectus lacustris	Shoot	(16)	–	–	(38.0)	16	13.6 (se 4.1)	3.5	44.3	16	8.5 (se 4.0)	2.5	31.6
	Roots and rhizomes		–	–	(80.9)		7.2 (se 1.1)	8.4	108.0		5.1 (se 4.3)	6.9	53.8
Sparganium erectum	Shoot	(17)	–	–	(66.9)	17	10.8 (se 4.0)	4.3	47.3	15	15.1 (se 4.2)	4.3	76.4
	Roots and rhizomes		–	–	(98.8)		9.6 (se 7.3)	4.0	115.4		6.9 (se 4.3)	5.7	77.4
	Total mass of *P* (g)				285				315				239

TABLE V Amount of phosphorus in the macrophytes at the downstream site, D. Total area of the site 1200 m^2. Values in brackets estimated from nearest survey data. Key: se, standard error

		29 *March*, 1999				11 *May*, 1999				2 *June*, 1999			
Plants	*Tissue*	*Bed area* (m^2)	*Fresh weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)	*Bed area* (m^2)	*Fresh Weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)	*Bed area* (m^2)	*Fresh weight* ($kg\,m^{-2}$)	*TP* ($mg\,Pg^{-1}$) *dry*	*Mass of P in 100 m* (*g*)
Nuphar lutea	Shoot		–	–	(4.6)		4.0 (se 1.4)	4.1	4.6		–	–	(15.3)
	Roots	(6)	–	–	(1.7)	6	0.8 (se 0.2)	6.1	1.7	20	–	–	(5.7)
	Rhizomes		–	–	(3.2)		1.6 (se 0.4)	2.1	3.2		–	–	(10.7)
Phalaris arundinacea	Shoot		1.3	5.9	19.5		–	–	(57.6)		6.7 (se 2.0)	3.0	64.2
	Stems and moribund	30	1.9	2.5	17.1	30	–	–	–	20	–	–	–
	Roots		0.4	7.5	8.8		–	–	(70.0)		7.2 (se 5.7)	4.0	87.4
Schoenoplectus lacustris	Shoot	3	–	–	(4.5)	8	8.1 (se 3.7)	2.8	12.8	7	5.2 (se 4.1)	2.8	9.6
	Roots and rhizomes		–	–	(4.4)		2.4 (se)	4.0	11.6		–	5.0	(10.2)
Sparganium erectum	Shoot	18	–	–	(31.6)	41	6.5 (se 2.7)	5.2	72.0	50	–	–	(87.8)
	Roots and rhizomes		–	–	(40.8)		2.7 (se 1.4)	3.2	93.0		–	–	(113.4)
	Total mass of *P* (g)				136				327				404

decrease in coverage of *Glyceria maxima*. At the middle site, M, there was no survey in March but later surveys indicated little change in the bed-coverage of *Sparganium erectum* or *Schoenoplectus lacustris*, the main species at the site. The total mass of phosphorus associated with macrophytes in the section was similar to site U. The downstream site did show a systematic increase in biomass of *Sparganium erectum* and an increase in *Nuphar lutea* between May and June. These contributed to the increase from ca. 140 g to 400 g of phosphorus in macrophyte tissues in the 100 m section (Tab. V).

Comparison of Macrophyte Phosphorus and River Flux

The relative importance of the two main sources of phosphorus for plants, *i.e.*, from sediment porewaters and from the main body of the water, is uncertain although empirical relationships have been postulated for lakes (Carignan, 1982). There is some evidence in the literature (Pelton *et al.*, 1998) that phosphate uptake from the water column in streams is more important than in lakes. Applying the equation expressing the relative importance of root uptake given by Carignan (1982) to the data from the March survey (Tabs. II and VI), leads to root uptakes of 5–19% for the upstream site and 8–36% for the downstream site. Even in this relatively nutrient rich river, uptake by sediments may be appreciable but is difficult to account for in a mass balance. Therefore only the flux of phosphorus in the river water will be compared to phosphorus contained in the standing crop, but it is acknowledged that the plants will obtain some of their phosphorus requirements from the bed-sediments.

The riverine flux of total phosphorus was estimated from the weekly TP concentration data and mean daily river discharge at Wheatley (Littlewood *et al.*, 1998). Fluxes were also estimated for the upstream site by assuming that the total phosphorus concentrations were $\approx 20\%$ (Tab. II) and river discharge $\approx 30\%$ of those at site D. The results in Table VII show a high flux in January to March because of the high river discharge (Fig. 2), decreasing to a minimum of $142\,\mathrm{kg\,TP\,d^{-1}}$ in May. For the downstream site, these fluxes are large compared with the phosphorus contents of the standing crop of macrophytes (Tabs. III to V) and even in May, the total phosphorus

TABLE VI Comparison of sediment porewaters from the 29 March, 1999 survey

Site	*Type of sediment*	$EPC_0/\mu g\ l^{-1}$	*TP* /mg g^{-1}(*dry wt.*)	*Pore water SRP*/$\mu g\ l^{-1}$
U	*Glyceria* roots	17.7	2.1	13.9
U	*Glyceria* roots	26.5	2.7	28.9
U	Channel–sand/gravel	40.7	3.9	28.4
U	Channel–sand/clay	25.0	2.3	82.3
D	*Phalaris* roots	112	3.4	829
D	Channel–sand/gravel	142	4.6	474
D	Channel–sand/clay	274	2.5	97.9

TABLE VII Estimated mean daily fluxes of total phosphorus in kg d^{-1}

Month	*Upstream site, U*	*Downstream site, D*
January	24.6	369
February	20.4	306
March	21.5	322
April	12.7	184
May	9.1	142
June	14.0	216

in macrophytes amounts to $\approx 0.2\%$ of the daily flux of phosphorus in this nutrient enriched river. At the upstream site, with a much lower flux of phosphorus, the standing crop content is about 3% of the mean daily TP flux (see Tabs. III and VII). Although these figures are likely to be under-estimates because not all of the total phosphorus in the water is bioavailable, they indicate that the growth of macrophytes in the spring and early summer is not an important storage reservoir in this enriched system compared with the total throughput of phosphorus in the river. These figures relate to the standing crop and not to the seasonal growth. For the downstream site, this is ≈ 270 g in 100 m section between the end of March and early June. Extrapolating this for the entire river reach between sites U and D, the total phosphorus in macrophytes is $\approx 0.95\%$ of the total load carried downstream in April and May. This is in broad agreement with the results of Ladle and Casey (1971) for *Ranunculus penicillatus* growth in a chalk stream during April and May. In this study, they found that for a sampling reach of 27,000 m^2, the phosphorus uptake by *Ranunculus* was 1.1% of the SRP throughout in the same period.

TABLE VIII Mean tropic rank scores for the River Thame during the sampling season

Site	*River community type**	*March*	*May*	*June*
U	IIa	30	34.3	35.2
M	IIa	–	34.3	34.6
D	IIb	32	33.9	33.2

* Homes *et al.*, 1999.

Comparison of Soluble Reactive Phosphate with Plant Based Assessments of Eutrophication

The plant based assessment of eutrophication, Mean Trophic Ranking (MTR), resulted in values from 30 to 35 for these three sections of river. It is normal for the MTR to be assessed four times over a 3 year period, however an insignificant difference in the results was found between the sites (Tab. VIII); a significant difference of 3 units is needed to show a clear difference in eutrophic state (Dawson *et al.*, 1999). The range of values of MTR of 30–35 are average for this type of river (II) but significantly lower than the mean of 42 of the top 10% for this river type, indicating that within broad limits a phosphate level as measured (Tab. II) (Dawson *et al.*, 1999). This range of MTR values is interpreted in the lower range of 25–65 in which indicates that the river is eutrophic or "at risk of becoming eutrophic" (Dawson *et al.*, 1999).

CONCLUSIONS

The approach used here of applying a mass-balance to a river section with different phosphorus loading, yields information about the relative pools of phosphorus in the water column and incorporated in macrophyte tissue, and provides data on the consequences of growth for the bottom sediments. The results indicate that:

- Phosphorus incorporated in macrophytes at the most impacted site during April and May, the main part of the growing season, was relatively small compared with the flux of total phosphorus estimated for the water column over the same period, *i.e.*, $< 1\%$.

- No decrease in phosphorus in macrophytes was measured at the other sites with lower phosphorus concentrations in the water. This is partly because of the difficulties in sampling at the two sites and associated variability in the results. However, the phosphorus in the standing crop measured at the upstream site was approximately 3% of the daily mean TP flux.
- The mean concentration of phosphorus in plant tissue was greater than in the bed-sediments, when both are expressed on a dry weight basis.
- No trends were detected in the TP contents of the root or shoot tissue during the growing season or in the contents of the sediments in the river channel in the absence of roots or in sediments associated with plant roots.
- Differences were found in the phosphorus contents of sediments from the upstream, less impacted site and the downstream site where the TP concentrations in the water column were highest. Differences were more distinct for porewaters and EPC_0 values for these sites.

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