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On modelling the impacts of phosphorus stripping at sewage works on in-stream phosphorus and macrophyte/epiphyte dynamics: a case study for the River Kennet

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Abstract

A new model of in-stream phosphorus and macrophyte dynamics, 'The Kennet model', was applied to a reach of the River Kennet, southern England. The reach, which is 1.5 km long, is immediately downstream of Marlborough sewage treatment works, where phosphorus reduction by tertiary effluent treatment began in September 1997. The model is used to simulate the flow, water chemistry and macrophyte biomass within the reach, both before and after phosphorus removal from the effluent. Monte Carlo experiments coupled with a general sensitivity analysis indicate that the model offers a feasible explanation for the salient aspects of the system behaviour. Model simulations indicate that epiphyte smothering is an important limitation to macrophyte growth, and that higher stream and pore water soluble reactive phosphorus (SRP) concentrations allow the earlier onset of growth for the epiphytes and macrophytes, respectively. Higher flow conditions are shown to reduce the simulated peak epiphyte biomass; though at present, the effect of flow on the macrophyte biomass is unclear. Another simulation result suggests that phosphorus will not be released from the bed sediments in this reach following phosphorus removal from the effluent. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Soluble reactive phosphorus; Soluble unreactive phosphorus; Particulate phosphorus; Kennet; Thames; Macrophyte; Epiphyte; Mathematical model; General sensitivity analysis; Monte Carlo simulation; The Kennet model; River basin management

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1. Introduction

Increasing nutrient inputs to lakes and rivers are a major cause for concern because enhanced nutrient status of water bodies can result in nuisance growth of algae and macrophytes. Excessive growth and subsequent decomposition of plant biomass can result in low dissolved oxygen concentrations, which are detrimental to the invertebrate and fish populations (Fisher et al., 1995). Furthermore, changes in the nutrient status can affect the composition and diversity of aquatic plant species, by changing in the competitive balance between species. For example, higher phosphorus (P) concentrations have been linked to the excessive growth of epiphytic algae that may restrict macrophyte development. Under low flow conditions the epiphytes, and the detritus that they trap, form a thick layer that shades the macrophyte's surface, thus restricting the rate of photosynthesis (Sand-Jensen, 1977; Phillips et al., 1978).

It is now widely accepted that P is the major limiting nutrient in UK freshwater systems and therefore, it is important to understand the movement and fate of P in the aquatic environment (Mainstone et al., 2000). The P in freshwater systems is derived from external and internal sources. External inputs come from diffuse and point source inputs from the land surface. Within the UK, the major diffuse input results from the addition of fertiliser to crops and the wastes from by farm animals, whilst point source inputs include discharges from industry and sewage treatment works (STWs). Internal inputs are generated from sources within the water body, such as the sediment and decomposition of litter (Golterman, 1975; House et al., 1995). The dynamics of P in the aquatic environment are complex and include many feedbacks; Phosphorus can be sorbed and released from suspended and bed sediment or precipitated with calcite (House et al., 1995; Neal et al., 2002b). Also, P may be removed from the interstitial pore water in the bed sediment by macrophytes or from the water column by epiphytic algae. These uptake rates are further complicated by the growth patterns of the macrophytes and epiphytes. Their growth and death

depends upon the prevailing flow and climatic conditions (e.g. solar radiation and water temperature) and limiting factors such shading and P availability (Dawson, 1976; Ham et al., 1981; Wright et al., 1982).

As part of the EU Urban Waste Water Treatment Directive, phosphorus stripping is a legal requirement at STWs to reduce the phosphorus load entering lake and river systems thought sensitive to nutrient inputs (CEC, 1991). Given the costs inherent in removing P from effluent, a methodology for the quantification and prediction of the impacts of P stripping on the water quality and ecology is much needed. In particular, such a methodology is urgently required for lowland areas of the UK where the balance between sewage inputs and river flow is likely to change due to increasing urbanisation, groundwater abstraction and climate variability, which are currently predicted to cause more extreme low-flow conditions (Neal et al., 2000, 2002b; Marsh and Sandersen, 1997). As part of a methodology that will include field and laboratory work, mathematical models are needed to aid the understanding of freshwater P dynamics and to make predictions of future changes under likely scenarios (Neal et al., 2000). Thus, the aim of the work is to apply a new model to assess the impacts of P stripping at Marlborough STW which discharges into the River Kennet, southern England, and to use the model as a learning tool to investigate how the reach functions. As such, the specific objectives are:

1. to determine the key processes and factors controlling the model behaviour using a Monte Carlo technique combined with a general sensitivity analysis;
2. to test if the model can reproduce observed P and macrophyte and epiphyte dynamics both before and after effluent treatment;
3. to assess the impacts of epiphyte growth on the macrophyte biomass both before and after effluent treatment;
4. to simulate the impacts of different levels of effluent treatment on the streamwater SRP and TP concentrations and the macrophyte dynamics; and

5. to determine under what conditions P will be released from the bed sediments.

2. Study area and data resource

The River Kennet drains an area of approximately 1200 km², and is a major tributary of the River Thames, southern England (Fig. 1). Rising from a source at 190 m a.s.l., the river flows broadly eastwards for *c.* 40 km before entering the Thames at Reading at 32 m a.s.l. Cretaceous Chalk covers approximately 80% of the total catchment area. As such, the river system is of particular interest because cretaceous chalk is representative of large areas of lowland UK (Fig. 1). The relief is dominated by gently sloping valleys, with the highest point on the Marlborough Downs at 294 m.

The long-term annual precipitation over the catchment is 774 mm, though approximately only 38% becomes river flow due to high evapotranspi-

ration (NERC, 1998). The river flow is dominated by groundwater inputs since the chalk strata form an important aquifer. Consequently the flow response is highly damped except for the Enbourne tributary that is underlain by tertiary clay. The long-term annual mean flow at Theale, the lowest gauging station on the Kennet, is 9.64 m³ s⁻¹ (294 mm of runoff), and the mean annual flood is estimated as 37.3 m³ s⁻¹ and the flow exceeded 95% of the time is 3.84 m³ s⁻¹. The catchment is mainly rural, with arable agriculture being the predominant land-use. There are several large towns along the main stem and, as such, treated sewage and industrial effluent is discharged directly into the Kennet. The catchment provides water for public and industrial supply by means of direct surface and groundwater abstractions. A substantial yield of 70–90 MI/d is abstracted from the chalk aquifer by 33 boreholes arranged in seven well fields that make up the West Berkshire Groundwater Scheme.

The reach modelled lies 1.5 km downstream of Marlborough gauging station, and is itself 1.5 km

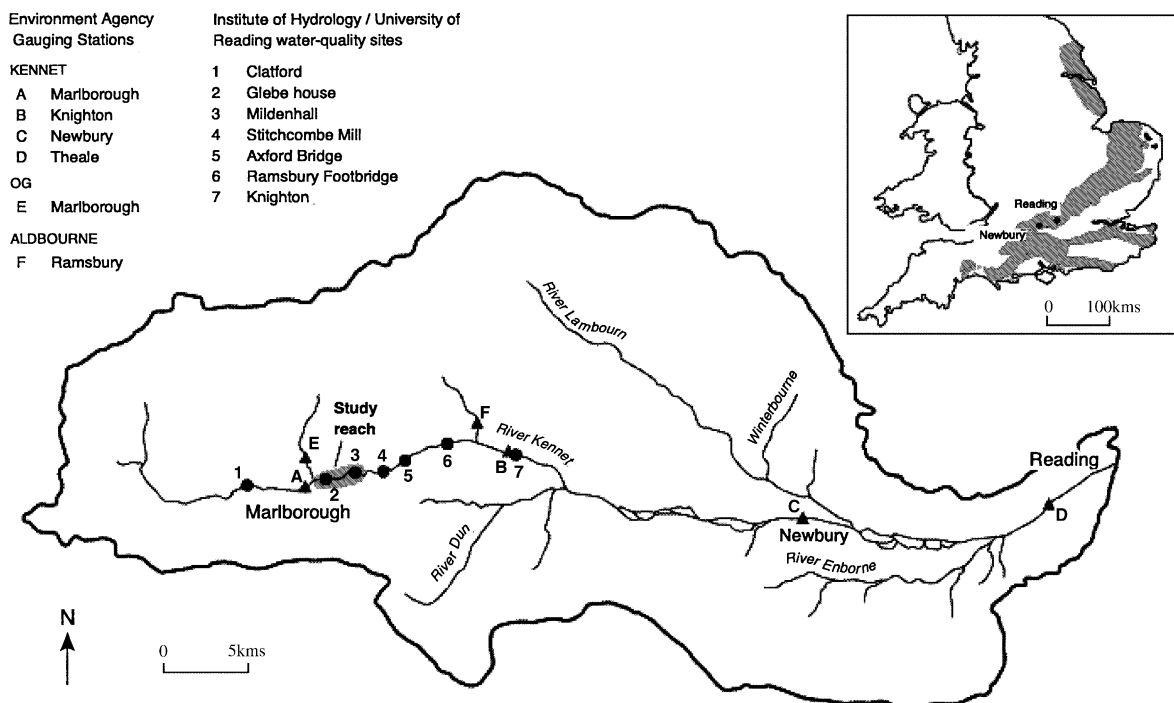


Fig. 1. Schematic of the River Kennet Catchment. The inset shows the location of Cretaceous Chalk within England.

long; Marlborough STW discharges immediately upstream of the reach. Weekly water chemistry samples were taken upstream of the reach and the STW at Clatford, and from the downstream end of reach at Mildenhall from June 1997 to December 1999. These samples were analysed for total phosphorus (TP), soluble reactive phosphorus (SRP), boron (B) and suspended sediment concentrations amongst other determinands (Neal et al., 2000). The water quality data from the Centre for Ecology and Hydrology's (CEH) weekly sampling programme for these two sites were combined with similar data gathered by the Environment Agency (EA), who sample suspended sediment and SRP concentrations at Clatford and Mildenhall on a monthly basis (Jarvie et al., 2001a). Plotting the IH and EA data together did not reveal any obvious discrepancy and therefore, both data sets were used to maximise the data span available. Thames water provided mean daily flows and TP concentrations relating to the effluent discharged from Marlborough STW. An automatic weather station (AWS) was located alongside the reach providing solar radiation data, and a Hydrolab continuous monitor was also installed, thereby providing water temperature data. A detailed analysis of the water chemistry data is presented elsewhere (Neal et al., 2000; Jarvie et al., 2002a). The macrophyte and epiphyte biomass within the reach was also been measured when practical between April 1998 and December 1999

(Flynn et al., 2002). The predominant macrophyte in the reach is water crowfoot, otherwise known as *Ranunculus penicilatus* var. *calcareous* (R.W. Butcher) C.D.K. Cook. This plant is particularly valued because of its attractive flower and the cover it offers to fish, particularly brown trout (*Salmo trutta*). Other macrophytes present include *Callitriche obtusangula* (Le Gall) and *Rorippa nasturtium-aquaticum* (L.) Hayek. The epiphyte biomass measured provides an estimate of that on the macrophytes; it does not include any phytoplankton growth in the water column or any epiphytic algae.

Presently, there are concerns that algal growth may be having an adverse impact on the macrophytes within the upper reaches of the River Kennet. In 1997, which had a particularly dry summer, anecdotal evidence suggests that algal growth was greater than in other recent years, with both the macrophytes and the river bed covered by epiphytic and epiphytic algae.

3. Methodology

3.1. Model description

The Kennet model is a mathematical representation of the major stores in the aquatic P cycle, and the in-stream processes that determine the transfer of P between those stores (Wade et al., 2002a; Fig. 2). At present, the model, which is

Table 1
Model outputs

Variable	Description	Units
x_1	Flow out of reach at time, t	$\text{m}^3 \text{s}^{-1}$
x_2	Suspended sediment at time, t	mg l^{-1}
x_3	Moveable bed load at time, t	kg m^{-2}
x_4	TP in water column at time, t	mg P l^{-1}
x_5	B in water column at time, t	g P m^{-2}
x_6	TP in pore water at time, t	mg P l^{-1}
x_7	Macrophyte biomass at time, t	g C m^{-2}
x_8	Epiphyte biomass at time, t	g C m^{-2}
x_9	Grain diameter suspended at time t	μm
x_{10}	Concentration of sediment resuspended or settled at time t	mg l^{-1}
x_{11}	SRP in water column at time, t	mg P l^{-1}
x_{12}	SRP in pore water at time, t	mg P l^{-1}
T_1	Residence time of water in reach at time, t	Day
Vel	Water velocity in reach at time, t	m s^{-1}

dynamic and operates on a daily time step, is designed to simulate a single reach. As such, it simulates the mean daily flow, the soluble reactive phosphorus (SRP), total phosphorus (TP), Boron and suspended sediment streamwater concentrations in the water column, the SRP concentrations in the pore water and the TP associated

with the bed sediments (Table 1). The model also simulates the re-suspension of bed sediment, the deposition of suspended sediment and the effects of the P concentrations on the growth of the macrophyte and epiphyte populations within the reach, and the subsequent feedback that such growth has the water column SRP and TP con-

Table 2
Input time series and constants

Input variable	Description	Units	Measured/estimated
<i>Time series</i>			
u_1	Flow into reach at time, t	$\text{m}^3 \text{s}^{-1}$	E1 ^a
u_2	Suspended sediment at time, t	mg Sed l^{-1}	M
u_3	B in water column at time, t	mg B l^{-1}	M
u_4	TP in water column at time, t	mg P l^{-1}	M
u_5	Flow into reach from STW at time, t	$\text{m}^3 \text{s}^{-1}$	M
u_6	TP concentration in sewage effluent at time, t	mg P l^{-1}	M
R	Solar radiation at time, t	Normalised 0–1 ^c	M
T	Water temperature at time, t	°C	M
u_9	Lateral flow into reach at time, t	$\text{m}^3 \text{s}^{-1}$	E ^a
u_{10}	B concentration in sewage effluent at time, t	mg B l^{-1}	E ^b
<i>Constants</i>			
L	Reach length	m	M
w	Reach width	m	M
PM	Change in potentially movable bed mass with respect to grain diameter	$\text{kg } \mu\text{m}^{-1}$	M
B_{in}	Total B concentration from all sources into reach at time, t	mg B l^{-1}	E
P_{in}	Total TP concentration from all sources into reach at time, t	mg P l^{-1}	E

Abbreviations: M = Measured data available for input, E^a = Flows estimated from measurements at nearest gauging stations, E^b = B effluent input estimated from mass-balance within reach. ^cThe original time series of net radiation values (W m^{-2}) were normalised to the range 0 to 1 by dividing by the maximum value observed.

centrations. Inputs to the model include measured and estimated time series data describing the flow, sediment and P concentrations into the reach (Table 2). Streamwater TP and SRP concentrations are simulated in this first instance because TP is a measure of the total amount of P in the system and therefore, useful for mass balance whilst SRP is a measure of the dissolved P in the streamwater, which is biologically available. Furthermore, SRP and TP concentrations are available for a site upstream of the STW

input, at the end of the Mildenhall reach and for the STW final effluent. It is assumed that TP is the sum of SRP + PP + SUP where PP is the particulate phosphorus and SUP is the soluble unreactive phosphorus. In this study, the total macrophyte biomass is defined as including all submergent and emergent species, given that all macrophytes will influence the total phosphorus available. In this study, the simulation period was January 1997 to December 1998 as for this period, all the necessary input data were readily

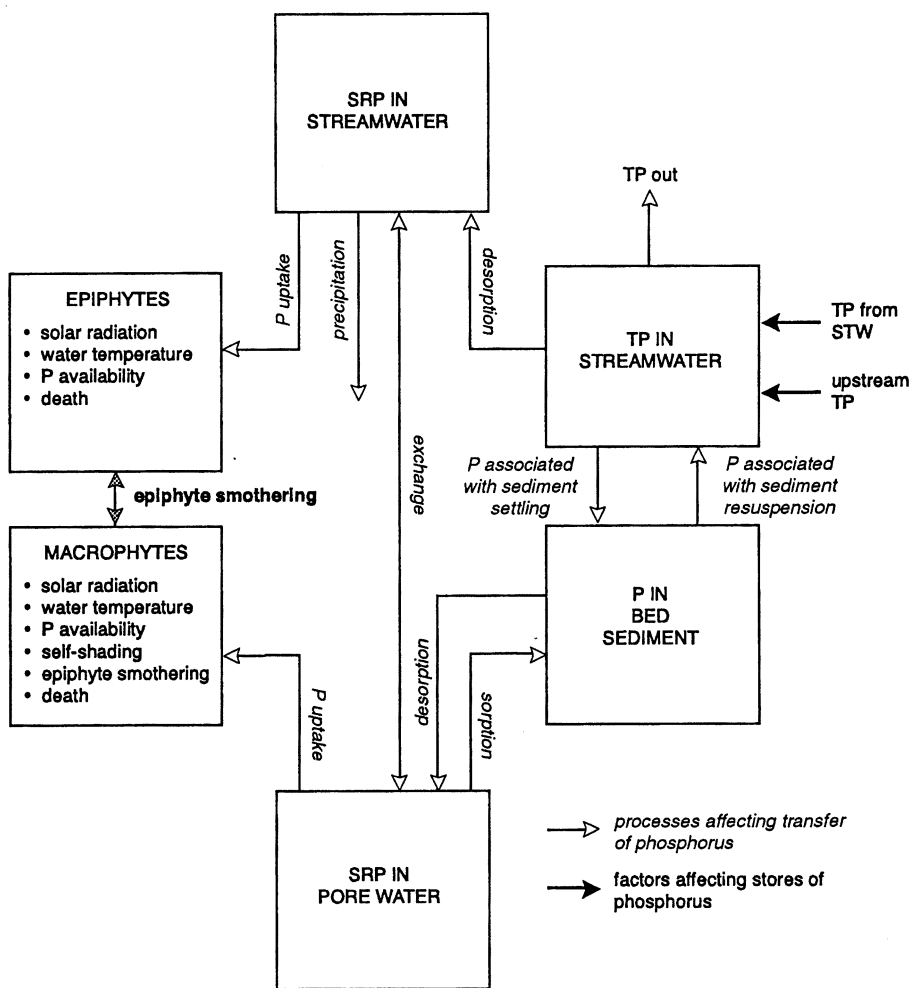


Fig. 2. Schematic of the model of in-stream phosphorus dynamics showing the main stores and transfer processes. The model is described in detail in Wade et al. (2002a).

Table 3
The model equations

Determinand	Equation
Flow	$\frac{dx_1}{dt} = \frac{(u_1 + u_5 + u_9 - x_1)}{T_1}$
Suspended sediment	$\frac{dx_2}{dt} = \frac{(u_2 - x_2)}{T_1} + \frac{1000}{V} \left(\frac{dPM}{dx_9} \right) \left(\frac{dx_9}{dt} \right) = \frac{(u_2 - x_2)}{T_1} + \frac{dx_{10}}{dt}$
Bed mass moved	$\frac{dx_3}{dt} = \frac{1}{Lw} \left(\frac{dPM}{dx_9} \right) \frac{dx_9}{dt}$
Water column TP	$\frac{dx_4}{dt} = \frac{(P_{in} - x_4)}{T_1} - \frac{c_3 c_4 x_8 x_7 R x_{11} \theta_E^{(T-20)} wa}{(u_1 + u_5 + u_9)^{1-b} (c_5 + x_{11})} + c_7 (x_{12} - x_{11}) - c_8 x_{11} + \left\{ \begin{array}{l} \text{gain} \\ \text{loss} \end{array} \right\}$ $P_{in} = \frac{(u_4 u_1 + u_6 u_5 + 0.016 u_9)}{(u_1 + u_5 + u_9)}$ $+ \frac{1}{\rho_s (1-n)} x_6 \frac{dx_{10}}{dt} 10^{-3} \quad \text{gain}$ $+ K_D^{sus} x_{11} \frac{dx_{10}}{dt} 10^{-6} \quad \text{loss}$
Boron	$\frac{dx_5}{dt} = \frac{B_{in} - x_5}{T_1}$ $B_{in} = \frac{(u_1 u_3 + u_5 u_{10})}{u_1 + u_5 + u_9}$
TP associated with the bed sediment	$\frac{dx_6}{dt} = - \left\{ \begin{array}{l} \text{gain} \\ \text{loss} \end{array} \right\} - c_7 (x_{12} - x_{11}) n - \frac{c_{15} c_{10} \theta_M^{(T-20)} x_7 x_{12} R c_{12}}{p (c_{11} + x_{12}) (c_{12} + x_7)} n$ $+ 10^{-6} x_{11} K_D^{sus} \frac{dx_{10}}{dt} \frac{(u_1 + u_5 + u_9)^{1-b}}{wa} \frac{1}{c_{13}} \quad \text{gain}$ $+ 10^{-3} x_6 \frac{1}{\rho_s (1-n)} \frac{dx_{10}}{dt} \frac{(u_1 + u_5 + u_9)^{1-b}}{wa} \frac{1}{c_{13}} \quad \text{loss}$
Macrophyte biomass	$\frac{dx_7}{dt} = \frac{c_{10} \theta_M^{(T-20)} x_7 x_{12} R c_{12}}{(c_{11} + x_{12}) (c_{12} + x_7)} - c_{14} x_7 x_8 x_1$
Epiphyte biomass	$\frac{dx_8}{dt} = \frac{c_4 \theta_E^{(T-20)} x_8 x_7 R x_{11}}{(c_5 + x_{11})} - c_{16} x_8 x_1$
Mean grain diameter	$\frac{dx_9}{dt} = c_1 \left(\frac{u_1 + u_5 + u_9 - x_1}{T_1} \right)$
Sediment resuspended or deposited	$\frac{dx_{10}}{dt} = \frac{1000}{V} \frac{dPM}{dx_9} \frac{dx_9}{dt}$
Water column SRP	$x_{11} = \frac{0.75 x_4}{1 + (10^{-6} K_D^{sus} x_2)}$
Pore water SRP	$x_{12} = \frac{0.75 \cdot x_6}{1 + \frac{K_D^{Bed}}{p} 10^{-3} x_3}$

Table 4
Model parameters^a

Parameter	Description	Units	Value or range given in or derived from the literature	Range used in Monte Carlo simulations	Reference
c_1	Sediment resuspension/ settling	$\mu\text{m s m}^{-3}$	1–10	5–50	Estimated
c_2	Pore water depth (multiplier)	[\emptyset]	0.25–0.45	0.25–0.45	Estimated
c_3	Proportion of P in epiphytes	$\text{g P g}^{-1} \text{C}$	0.0054	0.0054 ^a	Dawson, 1976
c_4	Epiphyte growth rate	$\text{m}^2 \text{g C}^{-1} \text{day}^{-1}$	0.004–0.04	0.004–0.04	Chapra, 1997
c_5	Half-saturation of P for epiphyte growth	mg P l^{-1}	0.0002 – 0.496	0.002–0.2	Bowie et al., 1985
K_d^{sus}	K_d for suspended sediment	$\text{dm}^3 \text{kg}^{-1}$	200	100–300	Jarvie et al., 2002a
c_7	P exchange (water column/ pore water)	day^{-1}	0.4–86.4	0.3–3.0	Wagner and Harvey, 1997
c_8	Precipitation of P in water column	day^{-1}	0.68	0.35–1.05	House et al., 1995
c_9	K for bed sediment, K_d^{Bed} (as a fraction of K_d^{sus})	[\emptyset]	0.1–1.0	0.1–1.0	Jarvie et al., 2002a
c_{10}	Macrophyte growth rate	day^{-1}	0.1–0.8	0.2–0.6	Dawson, 1976 Wright et al., 1982
c_{11}	Half-saturation of P for macrophyte growth	mg P l^{-1}	0.0002–0.496	0.002–0.2	Bowie et al., 1985
c_{12}	Self-shading	gC m^{-2}	74	10–50	Dawson, 1976
c_{13}	Bed (bulk) sediment depth	m	0.1–1.0	0.1–1.0	Estimated
c_{14}	Macrophyte death rate	$\text{s g C}^{-1} \text{day}^{-1} \text{m}^{-1}$	0.01–0.3	0.01–1.0	Chapra, 1997

Table 4 (Continued)

Parameter	Description	Units	Value or range given in or derived from the literature	Range used in Monte Carlo simulations	Reference
c_{15}	Proportion of P in macrophytes	$\text{g P g}^{-1} \text{ C}$	0.0054	0.0054 ^a	Dawson, 1976
c_{16}	Epiphyte death rate	$\text{s day}^{-1} \text{ m}^{-3}$	0.01–0.05	0.01–0.05	Bowie et al., 1985
θ_M	Macrophyte temperature dependency	[\emptyset]	1.01–1.066	1.066 ^a	Bowie et al., 1985
θ_E	Epiphyte temperature dependency	[\emptyset]	1.01–1.066	1.066 ^a	Bowie et al., 1985
n	Porosity	[\emptyset]	0.3	0.3 ^a	Chow et al., 1988
ρ_s	Bulk sediment density	kg m^{-3}	2.65	2.65*	Chow et al., 1988
a	Velocity–flow parameter	m^{-2}	0.18	0.18	Estimated
b	Velocity–flow parameter	[\emptyset]	0.68	0.68	Estimated

^a Model parameters fixed with a single value for model simulations since literature suggested these were the most appropriate values. Estimated = parameter values estimated through calibration and expert knowledge.

available. Moreover, the period represents times before, during and after effluent treatment at Marlborough STW.

Mass-balance equations are used to quantify the amount of P (and carbon in the case of the macrophytes and epiphytes) associated with the different stores in the aquatic P cycle (Table 3). The rates of mass transfer between stores are modelled as temperature-dependent first-order (linear) exchanges and these rates are represented as parameters in the equations (Table 4). Whilst the equations are comprised of linear exchanges, the combined response is non-linear. The linked differential equations are solved using a 4th order Runge–Kutta numerical integration algorithm with a variable step Merson integration routine. This ensures that the equations are solved

accurately. The technique has also proved fairly stable with few numerical problems.

3.2. General sensitivity analysis

A General sensitivity analysis (GSA) was undertaken to identify the key model parameters controlling the P dynamics and macrophyte growth pattern both prior to and post P stripping. The macrophyte pattern is of particular interest because of the concern over the conservation of *Ranunculus* within the reach, and also the macrophyte growth represents the integrated effect of the model equations given it depends on the flow, in-stream P concentrations and epiphyte dynamics. The GSA was based on the utilisation of the model together with a classification algorithm.

The general system behaviour was defined by the five criteria derived from studies of water quality and macrophyte growth in southern England and observations made by river keepers and users. In the definition of the criteria, year 1 relates to 1997 when P stripping started, and year 2 relates to 1998. The criteria that relate to year 1 are derived mainly from anecdotal evidence from river keepers and users of the river who observed the macrophyte peak to be earlier in the year, with less biomass than in recent years. Whilst this evidence is tentative and not scientifically based, it does allow broad criteria to be set as to the possible behaviour of macrophytes subject to P loading given the paucity of macrophyte data. These criteria were coded into the mathematical model as a classification algorithm to allow the model output to be identified as either representative or not representative of the observed behaviour. The behaviour criteria were defined according to as follows:

1. The peak macrophyte biomass must be less than 100 g C m^{-2} in year 1 and greater than 50 g C m^{-2} and less than 150 g C m^{-2} in year 2 (Dawson, 1976; Wright et al., 1982; Flynn et al., 2002);
2. The peak macrophyte biomass must occur between the 1st May and 1st August in year 1, and between the 1st August and 1st October in year 2 (Dawson, 1976; Wright et al., 1982; Flynn et al., 2002);
3. The peak in the epiphyte biomass must occur between the 1st May and 1st September in year 1 and between the 1st August and 1st December in year 2.
4. The daily suspended sediment concentrations must be greater than 0.2 mg l^{-1} and less than 250 mg l^{-1} in both years (Jarvie et al., 2002a);
5. The mean annual pore water SRP concentrations must be greater than 0.1 mg P l^{-1} and less than 10 mg P l^{-1} in both years; and
6. The mean annual water column SRP concentrations must be less than 0.2 mg P l^{-1} in both years (Jarvie et al., 2002a).

The idea of the GSA was to inject uncertainty into the model by randomly selecting the model

parameters from uniform probability distributions rather than experimentally derived values. This was achieved by using a Monte Carlo technique: The model was run and a set of parameters was drawn randomly from the distributions, the simulation done, the result stored and the process repeated 10 000 times (Spear, 1970). Uniform probability distributions were chosen so that each parameter value had an equal chance of being chosen. The range of the parameter distributions was determined from values derived from the available literature, though six parameters were held constant as their values were well defined in the literature (Table 4).

Each simulation result consisted of the parameter vector itself and the behavioural outcome; whether the particular parameter vector gave rise to the behaviour, B or not (i.e. non-behaviour NB). Namely, the final result of the 10 000 simulations is m parameter vectors that led to behaviour and $n = (10\,000 - m)$, which did not. The final results were analysed statistically to identify the key parameters causing the model to reproduce the observed behaviour. The theory behind this statistical analysis is based on the separation between the cumulative probability distributions. A Kolmogorov–Smirnov two-sample test is utilised to assess the separation (Hornberger and Spear, 1980; Spear and Hornberger, 1980). The statistic $d_{m,n}$ is determined as the maximum vertical distance between the cumulative probability distribution curves for m behaviours and n non-behaviours (e.g. Fig. 3). Thus, large values of $d_{m,n}$ indicate that the parameter is important for simulating behaviour. Successive runs of 10 000 simulations were done with the parameter ranges adjusted between runs so as to increase the number of behaviours to a level sufficient for the statistical analysis (Spear and Hornberger, 1980; Whitehead and Hornberger, 1984).

For each model run, a two-year period was simulated with a daily time step. The input data used to drive the model were derived from water quantity and quality datasets collected by the Environment Agency and Institute of Hydrology/Reading University, respectively. No observed flow data were available for the reach.

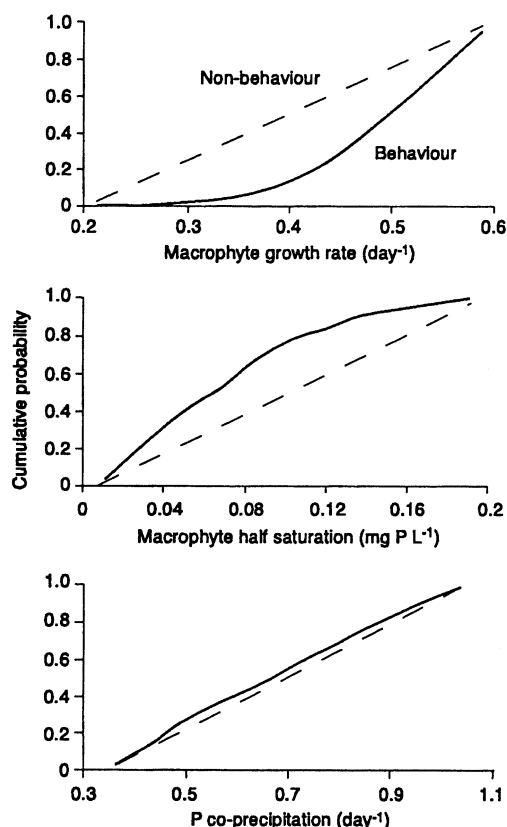


Fig. 3. Cumulative distribution functions under the behavioural mapping for parameters: (a) macrophyte growth rate; (b) macrophyte half saturation, which exhibit a distinct separation; and (c) co-precipitation of P with calcite, which exhibits no separation.

Therefore, input flows were estimated from the four nearest gauging stations at Marlborough (on the Kennet and Og), Ramsbury and Knighton. All these gauging stations are maintained by the Environment Agency. The flow in the reach was estimated from a mass-balance calculation using the mean daily flow observed at each gauging station. This estimate was also adjusted for the influence of lateral inflow, the input from Marlborough STW and groundwater abstraction from Axford. The latter two influences are monitored by Thames Water plc. Streamwater and STW chemistry were only available with a resolution of 1 week. Thus, to generate a daily time series, one data value was copied forward in time until the next observation was made. Whilst this obviously

limits the resolution of the model for assessing the weekly dynamics of the system, it represents a pragmatic modelling response to data scarcity. Furthermore, the basic structure of the model remains unchanged so that if daily data is available then the model can use it.

In this instance, as the output boron (B) concentration and the flow time series are known, the B input from the STW was back calculated. This provides a time series of B concentrations from the STW with which to test the assumption made by Neal et al. (2002a) that the input of B from the sewage treatment works is fairly constant and can be used as a tracer to test for the effectiveness of the reduction of P during P stripping.

To run the model it was also necessary to specify the initial conditions for each of the differential equations. In the case of flow, suspended sediment, TP and B for the stream water, macrophytes and epiphytes, the initial values could be estimated from observed data in December 1996. The bed load and the grain size were estimated from studies of the River Lambourn by Evans and the pore water TP concentrations from initial measurements made by House (all unpublished results). The first 30 days of simulated output were not used in the calculation of statistics later compared to the behaviour criteria; as such, the effects of the initial conditions on the results were minimised. Given 2 years were simulated, the behaviour criteria had to be met in each year for the result to be counted as a behaviour.

After identifying the model parameters controlling the macrophyte behaviour, the Monte Carlo simulations were run again. In this case, the behaviour criteria were changed so that the model could be used to determine the parameter values required to simulate a sustained release of P from the bed sediment to the overlying water column. As such, the following behaviour criteria were used in addition to criteria 1–4:

7. The mean annual pore water SRP concentrations must be between 0.05 and 10 (inclusive) in year 1 greater than 0.11 in year 2;
8. The mean annual water column SRP concentrations must greater than 0.12 and 0.2

- In years 1 and 2 respectively;
9. The mean annual water column TP concentrations must be greater than 0.16 in year 2; and
 10. The mean annual TP concentrations associated with the stream bed must be less than 0.54 in year 2.

The simulations were run twice. Firstly, the criteria 1–4 and 7–10 were used and secondly, only criteria 7–10 were used to remove any constraints related to macrophyte growth.

3.3. Manual calibration

The model was also calibrated manually; the model was run over the simulation period and the model parameters adjusted until the output matched or closely matched that observed. This was done to check that the model could reproduce the behaviour observed in the reach of the River Kennet as well as the generalised behaviours defined for the purposes of the generalised sensitivity analysis. The model parameters were kept within the ranges specified within the literature.

3.4. Model scenarios

The model parameters obtained during the manual calibration were used to investigate the impact of epiphyte growth on macrophyte biomass. To achieve this, the model was run 10 times, and on each run the epiphyte growth rate was increased to assess the impact on the macrophyte growth.

A second set of scenarios was applied to investigate the effect of adjusting the P input from the STW on macrophyte growth. For the first scenario the input TP concentration in the final effluent was kept at pre-stripping concentration for the entire simulation period. In the next four scenarios, the pre-stripping TP concentration was reduced by 25, 50, 75 and 100%, respectively. For each scenario, the model was run using each parameter set that produced an output that met the phosphorus and macrophyte growth criteria (1–6).

Table 5

Model parameters significant to 95% level (0.083) or greater

Parameter	Description	$d_{m,n}$
C_{10}	Macrophyte growth rate	0.373
C_{11}	Macrophyte half saturation	0.295
C_{16}	Epiphyte death rate	0.290
C_4	Epiphyte growth rate	0.235
C_{12}	Macrophyte self shading	0.194
C_5	Epiphyte half saturation	0.130
C_{14}	Macrophyte death rate	0.093

4. Results

The 10 000 simulations produced 277 outputs in the behaviour and 9723 in the non-behaviour categories, respectively.

4.1. Kolmogorov–Smirnov (K–S) test

The parameters and the corresponding $d_{m,n}$ statistics that are significant above the 95% level are mainly those directly controlling the biomass of macrophytes, such as the macrophyte and epiphyte growth rates (Table 5). The epiphyte growth is important as it determines the biomass of the epiphytes and therefore, the extent to which macrophyte growth is impacted. Other important parameters include the macrophyte self-shading, half-saturation and death rate constants that also define the limits to growth.

Some examples of the differences between behaviour and non-behaviour cumulative frequency curves are shown in Fig. 3a–c. The cumulative frequency curve for the macrophyte growth rate parameter shows that the most behaviours occur at the higher values in the range (Fig. 3a). Conversely values at the lower end of the range give the most behaviours for the macrophyte half saturation (Fig. 3b). When the behavioural outcome is insensitive to the parameter value then the behaviour and non-behaviour cumulative frequency curves are broadly similar, with no statistically significant separation between them (Fig. 3c). An example of such a parameter in this application is the one describing the P precipitation with calcite.

The most significant correlations are shown in

Table 6
Correlations between model parameter values that give rise to behaviours^a

Parameter	Description	Parameter	Description	Correlation coefficient
c_{10}	Macrophyte growth rate	c_{11}	Macrophyte half saturation	0.58
c_4	Epiphyte growth rate	c_5	Epiphyte half saturation	0.36
c_{16}	Epiphyte death rate	c_{11}	Macrophyte half saturation	0.33
c_{16}	Epiphyte death rate	c_{12}	Macrophyte self shading	-0.29
c_{16}	Epiphyte death rate	c_{10}	Macrophyte growth rate	-0.22
c_4	Epiphyte growth rate	c_{12}	Macrophyte self shading	-0.21

^a -0.15 < All other correlations < 0.17.

Table 6, with the largest correlation ($r = 0.58$) between macrophyte growth rate and half saturation. This result suggests that more behaviours are generated when the macrophyte growth rate and half saturation are together low or high. In general, the correlations between parameters are low and therefore, the majority of the model parameters are independent, and little further information can be discovered about the parameter controls on the model behaviour that cannot be derived from the $d_{m,n}$ statistic.

4.2. P release from sediment — Monte Carlo simulations

From the model runs, no behaviours were obtained using criteria 1–4 and 7–10, nor when using only 7–10. Thus, it was not possible using the specified parameter ranges to simulate a significant transfer of phosphorus from the bed sediment to the water column. This suggests that following P removal from the effluent, P will not be released from the streambed.

4.3. Model parameters: manual calibration

The model parameters determined through manual calibration are listed in Table 4. The model parameters all lie within the ranges derived from the literature. In the following sec-

tions, the coefficient of determination is used to compare the observed data to the simulated output (Table 7; Nash and Sutcliffe, 1970).

4.4. Flow

The simulated flow displays the same patterns as the flows observed upstream of the reach at Marlborough and downstream of the reach at Knighton (Fig. 4). In all cases, the hydrographs show a seasonal pattern typical of a river dominated by groundwater inputs. During winter and spring, the highest flows occur during the periods of high groundwater discharge into the river. The flows in 1997 are approximately four times lower than the corresponding flows in 1998. The shape of the hydrograph for 1997 is a generalised ‘whale-back’, though the influence of individual storm events on the river flow can be seen as a series of super-imposed spikes. In 1998, the flows rose significantly in January, May and November. From May 1998 to early October 1998, the falling limb of the hydrograph decays slowly, until mid-October when the flow rises significantly.

4.5. Suspended sediment

The observed suspended sediment concentrations range from approximately 0.2 to 120 mg l⁻¹ (Fig. 4). The higher flow conditions in 1998 do not

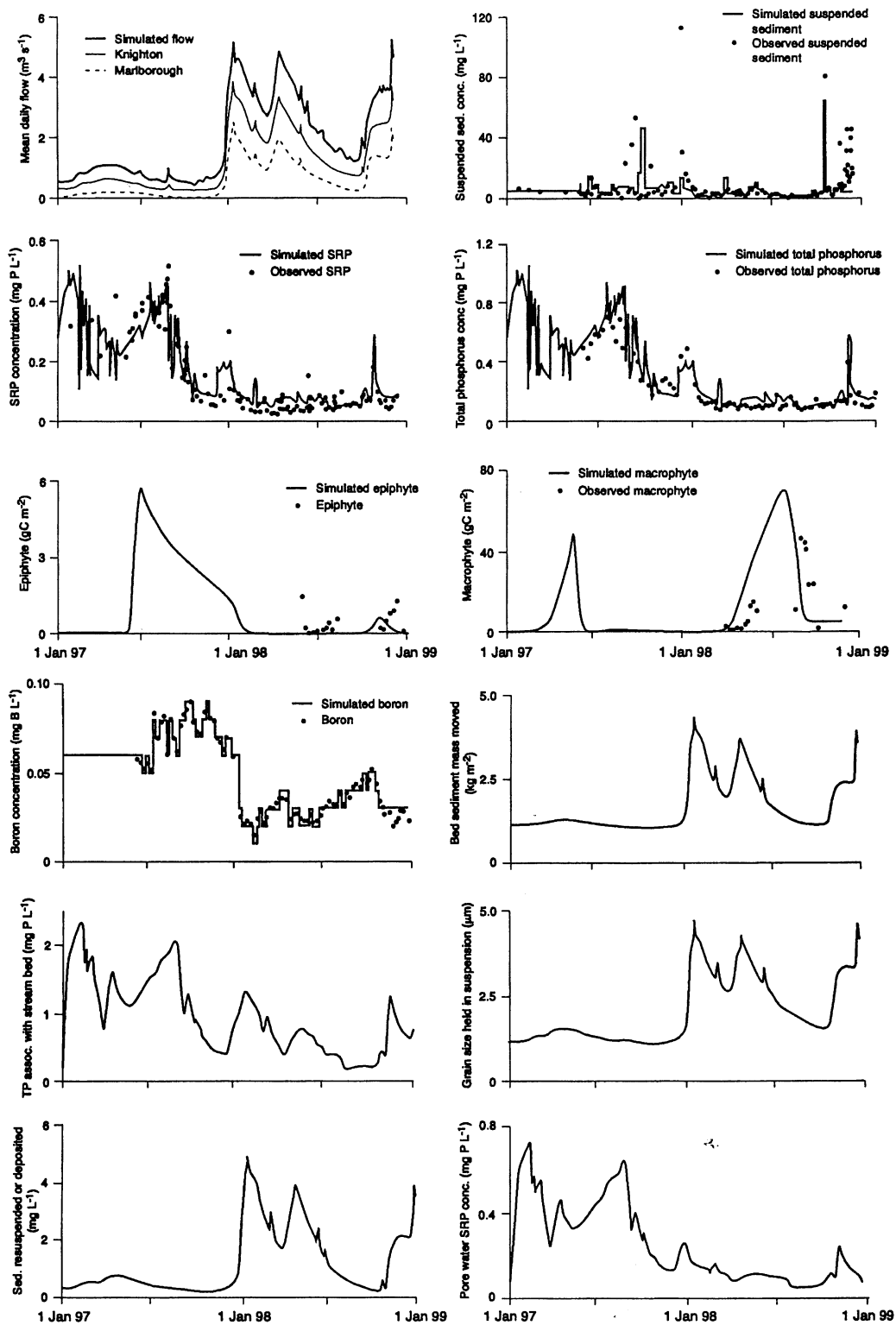


Fig. 4. Observed data and simulated model output before and after P removal from the Marlborough STW effluent, January 1997 to December 1998.

Table 7

Coefficient of determination: a test of the model output in comparison with the observed data

Description	CD
Suspended sediment	0.10
Total phosphorus in water column	0.81
Boron	0.98
SRP in water column	0.87
Macrophyte biomass	< 0
Epiphyte biomass	< 0

produce higher sediment concentrations than 1997 and high sediment concentrations are recorded when the flows are relatively low. During the summer months, the suspended sediment concentrations are fairly constant at approximately 0.2 mg l^{-1} . The increase in suspended sediment with flow indicates that the main source within the catchment is diffuse, as more sediment is washed into the river during periods of high flow.

The simulated suspended sediment concentrations display a similar dynamic pattern to the observed concentrations, though the simulated peak sediment concentrations tend to underestimate those observed, which results in a low value of the coefficient of determination (Table 7).

4.6. Total phosphorus in the water column

The observed total phosphorus concentrations decrease from a maximum of approximately 1 mg P l^{-1} in 1997 to approximately 0.1 mg P l^{-1} in 1998 following the introduction of P stripping in

September 1997 (Fig. 4). However, the lower TP concentrations observed in 1998 also coincide with the period of higher flows. In 1998, the observed concentrations exhibit peaks in January and November that correspond to periods of increasing flow. This suggests inputs of P from diffuse sources within the upper Kennet catchment are important controls in the streamwater P concentrations in the reach. During the summer months, the observed TP concentrations fall to an annual minimum, probably due to biological uptake of SRP (Jarvie, 2002b). The simulated TP concentrations match with a reasonable degree of accuracy, the dynamics of those observed (Table 7). However, some of the peak concentrations either over-estimate or under-estimate the observed TP concentrations.

4.7. Soluble reactive phosphorus in the water column

The observed SRP concentrations follow the same general pattern as the TP concentrations declining from approximately 0.6 mg P l^{-1} in 1997 prior to P stripping, to approximately 0.07 mg P l^{-1} in 1998 following P stripping. Higher SRP concentrations are observed during the periods characterised by increasing flow, indicating a greater diffuse source contribution from agricultural land (Fig. 4). The simulated concentrations are similar to those observed with the dynamics being reproduced (Table 7).

4.8. Boron in the water column

The observed Boron concentrations exhibit a

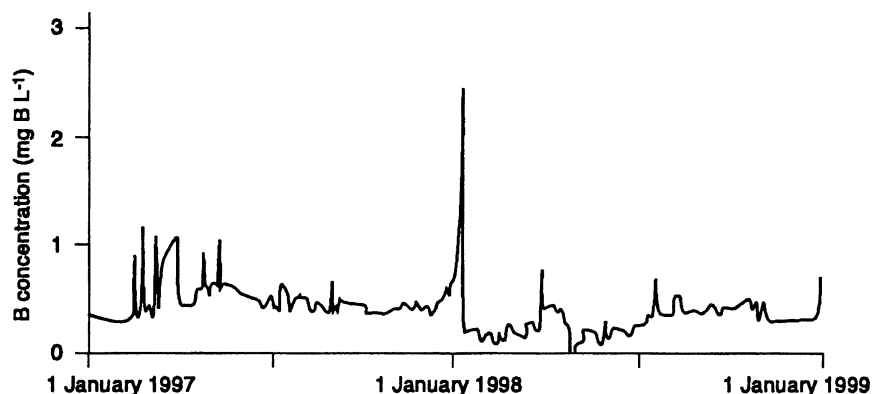


Fig. 5. The derived B concentration in the final effluent from Marlborough STW.

decrease with flow, indicating that the major source of Boron within the reach is from the STW (Fig. 4). Given the STW boron time series was back calculated from the reach B load and the upstream B load by mass-balance, then the simulated output B concentration matches that observed. The derived B time series for the STW shows that the output is fairly constant over time (Fig. 5).

4.9. Epiphyte biomass

There is no clear pattern in the observed epiphyte biomass, perhaps indicating that the epiphytes are susceptible to the prevailing flow conditions. The simulated epiphyte biomass is greater in the first year than the second, with the simulated biomass in 1998 within the range observed. Prior to effluent treatment, the simulated epiphyte peak is 6 times higher than that observed

post treatment in 1998. Furthermore, the epiphytes persist in the reach for 8 and 2 months in 1997 and 1998, respectively. The reduction in epiphyte biomass corresponds to lower TP and SRP concentrations in the reach and to higher flow conditions.

4.10. Macrophyte biomass

The observed macrophyte growth pattern begins in March/April and peaks in August, before declining to zero by the end of November (Flynn et al., 2002; Fig. 4). The simulated macrophyte biomass reaches a higher peak and occurs later in 1998 compared to 1997.

4.11. Bed load, grain diameter and sediment resuspended / deposited

The simulated bed load, grain diameter, and concentration of sediment resuspended and de-

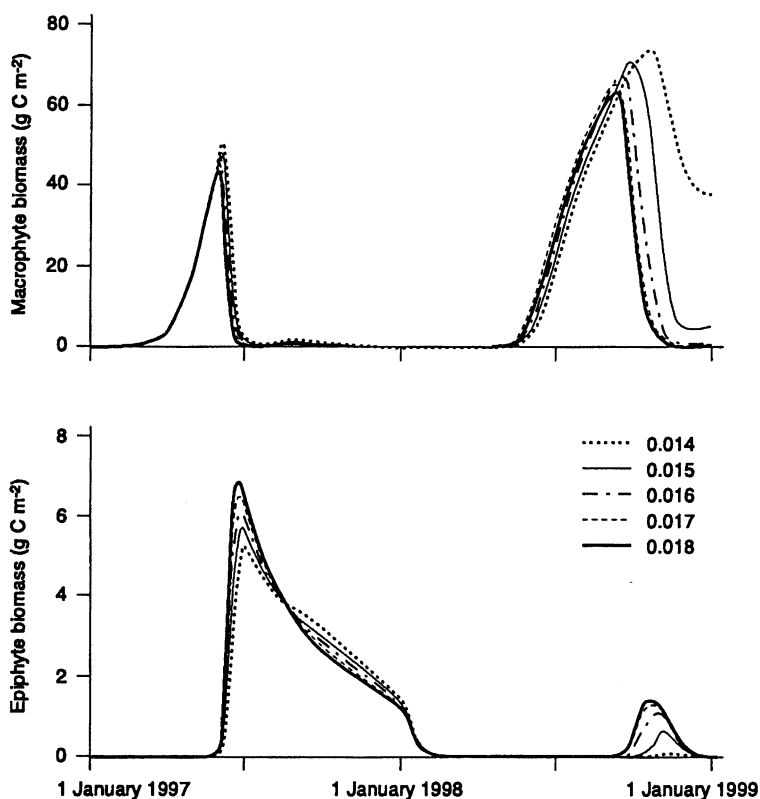


Fig. 6. Simulated (a) macrophyte and (b) epiphyte biomass as a function of epiphyte growth rate.

posited are all strongly related to the river flow. The bed load available is strongly related to the initial value chosen. The grain diameter resuspended and deposited is in the range of values observed (unpublished results). The sediment values are both positive (resuspension) and negative (deposition). As the flow increases, then the larger the grain size that is lifted from the streambed and therefore, the more sediment is moved from the bed and the more of the bed is available for resuspension. Conversely, as the flow drops, the smaller is the grain size that is held in suspension and less of the bed is available for resuspension, and the mass of material resuspended from the bed also drops.

4.12. Pore water TP and SRP concentrations

The simulated pore water TP and SRP concen-

trations exhibit the same patterns as the water column TP and SRP concentrations. The TP associated with the streambed is higher than that associated with the water column, except during the summer months when the simulated biological uptake is more important as the macrophytes remove SRP from the pore water. Following this decrease in SRP, the TP in the stream bed also decreases to re-establish the equilibrium between the pore water and P attached to the sediment. The SRP concentrations in the pore water and the water column are almost equal, suggesting that the two are in equilibrium.

4.13. Epiphyte growth scenario

The model was run 10 times, and on each successive run the epiphyte growth rate was increased from 0.011 to 0.02 in steps of 0.001. The

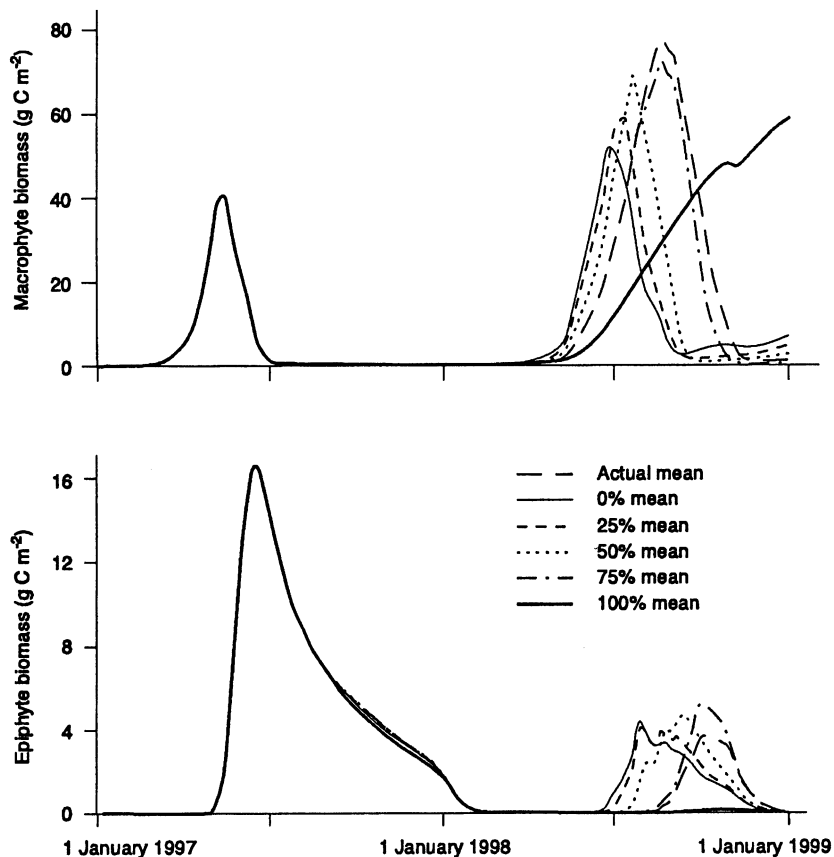


Fig. 7. Ensemble mean simulated (a) macrophyte and (b) epiphyte biomass under a range of effluent scenarios.

simulated epiphyte and macrophyte biomasses that resulted are shown in Fig. 6a and b, respectively. Increasing the epiphyte growth rate, in general, increases the simulated epiphyte peak biomass and made the peak occur earlier in the year for 1997 and 1998. However, when set to 0.02, the epiphyte biomass peak occurs later than when the parameter was set at 0.018 and 0.019, possibly indicating a feedback with the macrophyte biomass.

As the epiphyte biomass increases, the simulated macrophyte peak biomass decreases and occurs earlier in the year. At low values of the epiphyte growth rate (< 0.014), the macrophytes growth is unchecked in year 2. This indicates that the epiphyte growth patterns are having an impact on the macrophyte growth.

4.14. P removal scenarios

In each case, the simulated macrophyte and epiphyte biomasses remain unchanged in 1997 for each P removal scenario (Fig. 7a,b). This occurs because the simulated reduction in P in the effluent occurs after September 1997. After September 1997, there is a slight spread in the epiphyte biomass values, with the greater biomass linked to higher TP inputs from the STW (i.e. a lower level of reduction). There is no commensurate response in the macrophyte biomass as, in all cases, the mass has declined to zero. In 1998, the larger the TP reduction in the effluent, the later are the peaks in both the epiphyte and macrophyte biomass. This suggests that the greater the TP available in the system, the more rapidly both the epiphytes and macrophytes grow. Progressing from a zero TP reduction in the final effluent to a 75% reduction, the peak epiphyte biomass increases and this is related to the simulated flow conditions. The greater the simulated reduction in effluent TP, then the more the onset of epiphyte growth is delayed. The simulated (and observed) river flow declines between June and mid-October 1998 and therefore, the greater the delay in epiphyte growth then the lower are the corresponding flows. Consequently, even though the amount of TP available decreases, the simulated epiphyte biomass increases due to the lower

flow conditions. Considering the actual and 100% reduction scenarios, the peak epiphyte biomass reaches its lowest levels across all simulations, given the peaks coincide with high flow conditions and therefore, the epiphytes are washed from the reach. The peak macrophyte biomass remains relatively unchanged irrespective of the amount of P reduction. This indicates that the epiphyte biomass in 1998 is insufficiently large to control the macrophyte biomass. Furthermore, the macrophytes are less sensitive to the prevailing flow conditions than the epiphytes.

5. Discussion

Given the simulation of the system's dynamics match those observed, then the model structure seems reasonable in the sense that the appropriate processes are included. The GSA suggests there are two groups of parameters controlling the model behaviour. The first of these are the parameters that directly control the macrophyte growth: the macrophyte growth rate; self-shading; and half-saturation parameters. The second group of parameters relate to the growth of epiphytic algae: the epiphyte growth; death; and half saturation parameters. These parameters are important as the epiphytic growth and death influences the macrophyte growth. Compared to another study of simulating macrophyte dynamics in a system not impacted by sewage effluent, then the parameters that limit the availability of P to the macrophytes, such as the bed sediment depth, are relatively unimportant as more P is available in the system. The results of the GSA suggest that the co-precipitation of P with calcium carbonate is an unimportant mechanism of P removal within the reach, which agrees with the findings of Neal et al. (2002b).

The calibration of the model to time-series of observed data, also suggest that the model structure is reasonable though discrepancies between the observed and simulated data do occur. The differences between the simulated and observed suspended sediment and TP concentrations, which include particulate phosphorus may occur because (i) the model is underestimating the amount

of sediment that is remobilised within the reach either due to increased flow or to river management such as weed cutting, and/or (ii) the sediment inputs from minor tributaries, such as the River Og, are significant under high flow conditions. The change in simulated streamwater SRP and TP concentrations was determined mainly by the changes in effluent input and flow. Perturbations in the concentrations caused by the interactions of P with sediment and the uptake by macrophytes and epiphytes were relatively minor except for the summer of 1997 when there was a significant retention of P by biological uptake (cf. Jarvie, 2002b). This biological uptake may result from the excessive growth of epiphytes, which may in turn have had a detrimental impact on the macrophyte growth.

The relationship between macrophytes and epiphytes is particularly important in the River Kennet, as it is perceived that epiphytic algae can have a detrimental effect of *Ranunculus* growth by shading the macrophyte's leaves and thereby, reducing photosynthesis. The results of the model simulations suggest that epiphyte smothering can reduce the macrophyte biomass. However, both the epiphyte and macrophyte biomass is controlled by the in-stream SRP concentration and the prevailing flow conditions. The simulation results suggest that the higher the SRP concentrations then earlier in the year the epiphytes and macrophytes can begin to grow. However, the peak biomass achieved appears dependent on the flow, with higher biomasses achieved in periods of lower flow. The system is highly complex and, at present, the model simulates the macrophytes as a lumped biomass; no differentiation among species is made. Further work is needed to assess the reaction and interaction of different macrophyte species to changing flow and P conditions given P uptake rates are likely to vary between species. As flow decreases, marginal species may increase to the detriment of *Ranunculus* sp., which favours higher flows. However, modelling individual species is a complex task, and it may be more realistic to differentiate species according to habitat and model lumped groups of species such as emergent or submergent plants. In addition, further observations are needed to see if epiphytes

persist in the stream during low flow periods and what water velocities are needed to remove them. Also, observations of algal growth in the reach suggest the peak biomass occurs in spring, which is earlier than the model predicts (Jarvie, 2002b). The equation describing epiphyte growth is based on a Lotka–Volterra predator–prey relationship (Table 3). As such, the simulated epiphyte biomass will always peak after the onset of macrophyte growth because the epiphytes can only grow in the presence of macrophytes. In its present form the model does not simulate phytoplankton and/or epilimnic algae and further equations will need to be added to the model to simulate such growth. Such equations are likely to be dependent upon flow, SRP availability, solar radiation, water temperature and zooplankton grazing and therefore may take the form of those used to model algal growth in the River Thames by Whitehead and Hornberger (1984). Such an assessment of phytoplankton and epilimnic growth is important given concerns over nuisance algal blooms and the hypothesis that epilimnic algae may prevent the growth of macrophyte seeds in the stream bed.

The model simulations confirm the importance of flow controls on the macrophyte–epiphyte system and therefore, further investigation of the impacts of flows is required both in a clean river system and considering simultaneous changes in P stripping and flow changes in a single reach (Wade et al., 2002b). Such considerations are vital for management decisions, particularly since the climate within the south-east of England which is likely to become drier and warmer, thereby reducing the dilution of P from STWs (Marsh and Sandersen, 1997).

The results of the model simulations suggest that P will not be released from the bed sediments in this reach. If plant growth is included in the simulations, then it is likely that the P in the pore water is being taken up by the macrophytes and the P in the water column by the epiphytes (House and Denison, 1997). Other studies of the interactions of P with riverine sediments also indicate that there is a net uptake of P by sediments (Taylor and Kunishi, 1971; House and Warwick, 1998, 1999). Having removed the

macrophyte and epiphyte growth from the simulations, no behaviours where porewater P concentrations increased were observed. There may be two reasons for this. Firstly, the bed sediments are able to sorb all the available P. Secondly, the P in the pore water and the overlying water column is equilibrium and therefore, any P released from the bed sediment moves into the pore water and then into the water column where it is removed from the reach by the water flow. Recent results from the sediment analysis indicates that there is a potential for release of P from bed sediments into the overlying water column at Mildenhall during the summer of 1998. But during the winter then the reverse is true, namely there is a net uptake of P by the bed sediments (Jarvie et al., 2002a). Thus, these results perhaps indicate that whilst there is a potential for the release of P from sediment, the dynamic nature of river reach is likely to result in the released P being removed from the system either through biological uptake or by river flow.

All of the simulations relate to a single reach that is relatively short (1.5 km). As such, some of the conclusions may change as the model is up-scaled to include multiple reaches, given the greater time available for P and macrophyte change to occur, the greater distance from the point source, the morphology of the channel, and the effects this may have on the flow and zones of sediment deposition and resuspension. However, a catchment-scale delivery and in-stream model of phosphorus developed for the River Thames suggests that in-stream processes are of secondary importance, to the point and diffuse source inputs in determining the in-stream phosphorus concentrations (Cooper et al., 2002).

6. Conclusions

The Kennet model attempts to simulate all the key processes controlling the P and macrophyte/epiphyte dynamics in river and lake systems. Given the model reproduces the observed P concentrations in the River Kennet both before and after P stripping at the Marlborough sewage works, and both the observed and generalised

macrophyte and epiphyte growth patterns then model structure seems appropriate for the River Kennet. To test the generality of the model structure, further data are needed to re-calibrate and test the model when applied to other systems, both in the UK and abroad.

The uncertainties associated with model predictions due to parameter and structural uncertainty mean that the adequacy of such 'process-based' models to represent the relative importance of the different internal in-stream processes and the rate at which they operate remains uncertain. This is especially important when considering the response of such processes to environmental change, when such models are applied outside of the data against which they were calibrated and tested. To some extent, the problem of parameter uncertainty has been addressed by the use of Monte Carlo and general sensitivity analysis techniques and it is believed that the iterative procedure of data gathering, model creation and hypothesis testing, with the same or further data, is likely to increase process understanding, thereby leading to more structurally sound models (Neal et al., 2002b). Despite the problems, The Kennet model has proved a useful tool for assessing the first order changes within river systems resulting from reduced P inputs due to P-stripping at sewage works.

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