Can a Simple Model Quantify Stream Nutrient Dynamics?

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ABSTRACT

Management of point and diffuse sources of nutrient requires quantification of permanent loss and transformations that affect periphyton biomass in streams and nutrient loads to downstream lakes and estuaries. The "nutrient addition method" is commonly used to quantify nutrient loss in streams in terms of the uptake length S_w (Stream Solute Workshop 1990). A simplified computer model is used to conduct numerical experiments and determine whether S_w values enable managers to quantify the impact of nutrient spiralling on periphyton and/or permanent nutrient removal. Uptake lengths are estimated in two different ways. Method 1 examines the rate of change of inorganic nutrient concentration without subtracting "background" concentration. It yields estimates of "net" uptake (gross uptake minus mineralisation) that are fairly easy to interpret and which indicate whether or not the system is in "equilibrium". Method 2 is advocated by the Stream Solute Workshop and examines the increase in nutrient concentration above "background". It yields S_w values that vary with distance in a manner which is hard to interpret. Neither method furnishes an estimate of permanent nutrient removal and structured growth models that incorporate intracellular storage and time lags between uptake and growth are probably required for this. The study illustrates the potential for numerical experiments used in conjunction with experimental studies to help understand the behaviour of complex biological systems.

INTRODUCTION

Catchment-scale mass balance studies invariably show that the nutrient flux measured at the catchment outlet is smaller than the sum of all the nutrient inputs to that catchment (Alexander et al. 2002). The difference represents transformation, storage and/or permanent loss (collectively termed "attenuation"). Attenuation occurs at the land-water interface, in streams and in groundwater, but in this paper we focus on streams. When managers impose controls on point (e.g., sewage treatment plants) and diffuse (e.g., landuse) sources of nutrient they need to quantify: (1) permanent losses that affect the load of "bioavailable" nutrient to receiving lakes and estuaries; and (2) "transformations" that affect periphyton biomass and water quality within the stream.

NUTRIENT SPIRALLING IN STREAMS

Aquatic plants and microbial biofilms attached to the bed (collectively termed "periphyton") remove soluble nutrients from the overlying water when in their growth phase. They release soluble nutrients (by respiration and lysis) and particulate nutrients (by sloughing, scour and dislodgement) back into the water column. A fraction of the detritus (dead particulate organic matter) is mineralised (either within the periphyton mat or in the water column) to release soluble nutrients and the remainder is "lost" (either because it is refractory or becomes buried). Nutrients in the water column are subjected to downstream transport while those in the periphyton mat are not. The term "nutrient spiralling" has been used to describe the processes that occur in streams (Newbold et al. 1981).

Two aspects of nutrient spiralling are important to managers. First, spiralling affects the rate of permanent nutrient removal which in turn affects the flux of "bioavailable" nutrient entering a downstream lake or estuary. Bioavailable nutrient includes: (1) readily available nutrients (e.g., nitrate, ammonium and dissolved reactive phosphorus); (2) less readily available nutrients (e.g., labile organics that are readily broken down by microbial activity to inorganics); but excludes (3) refractory nutrients (e.g., organics that are not readily broken down by microbial activity or sunlight). Second, spiralling affects the distance

below a point source (e.g., a STP) over which elevated nutrient concentrations result in high periphyton biomass and its associated water quality problems.

The Stream Solute Workshop (1990) formalised an experimental protocol for investigating the dynamics of nutrient spiralling in streams termed the "nutrient addition method"[1]. A stock solution of nutrient and a conservative tracer is injected at a steady rate, and samples are collected at known distances downstream after the conservative tracer has reached steady state. The aim is to increase stream nutrient concentration above ambient by enough to detect the increase (typically 20%), but not enough to affect uptake rates. The rate at which the nutrient concentration returns to ambient is used to estimate the nutrient uptake rate assuming first-order kinetics

$$C(x) - C_b = A\exp(-k_c x / U) \qquad 1$$

$C(x)$ = nutrient concentration a distance x downstream from the injection point measured when the conservative tracer has reached a plateau (mg/m3); C_b = "background" nutrient concentration (mg/m3); A = the value of C - C_b at x = 0; U = mean velocity (m/day); and k_c = nutrient uptake rate coefficient (/day). Results are commonly expressed in terms of the uptake length S_w (m)

$$S_w = U / k_c \qquad 2$$

By making different assumptions about the background nutrient concentration C_b (Fig. 1) different estimates were made of S_w. Method 1 assumes C_b = 0 and fits Eq. 1 to the background concentration profile. Method 2 assumes C_b = $C_2(x)$ = variable and fits Eq. 1 to the increase in concentration. This is the protocol recommended by the Stream Solute Workshop. Method 3 assumes C_b = C_3 = constant and also fits Eq. 1 to the increase in concentration. The Stream Solute Workshop recommends Method 3 because concentrations often change slowly with distance (viz., C_2(x) ~ constant). This paper asks whether the uptake lengths S_w estimated in this manner enable managers to quantify permanent nutrient removal and/or the impact on periphyton.

[1] The Stream Solute Workshop also formalised a protocol using isotopically or radioactively labelled nutrients termed the "tracer addition method" but this is not discussed.

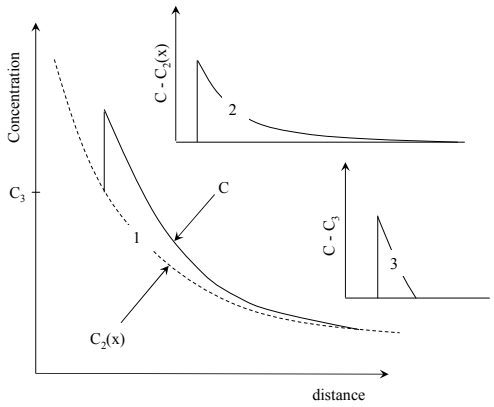

Fig. 1. Alternative estimation methods for S_w.

STREAM NUTRIENT MODELS

A simplified stream nutrient-periphyton model is used to explore aspects of nutrient and periphyton dynamics in streams. The model assumes: (1) there is a single limiting nutrient; (2) channel geometry is constant; (3) flow is uniform and steady; (4) nutrient in the water exists in either the available (inorganic) or the temporarily unavailable (organic) form; (5) periphyton remove inorganic nutrient from the water; (6) periphyton generate inorganic nutrient via first-order respiration/excretion; (7) periphyton generate organic nutrient via first-order death/sloughing; (8) organic nutrient hydrolyzes at a first-order rate to inorganic nutrient; (9) a fraction of the organic nutrient generated by periphyton death/sloughing is lost (e.g., denitrified, trapped in the bed or converted to refractory forms); (10) the periphyton growth rate varies with inorganic nutrient concentration in the water following Monod kinetics; and (11) the periphyton have a fixed carbon to nutrient ratio. The model equations are:

$$\frac{dP}{dt} = \mu_{max}\left(\frac{N_i}{k_s + N_i}\right) - (k_r + k_d)P \qquad 3$$

$$\frac{dN_i}{dt} = -U\frac{dN_i}{dx} + k_h N_o + \frac{k_r \Theta P}{H} - \frac{\mu_{max}\Theta}{H}\left(\frac{N_i}{k_s + N_i}\right) \qquad 4$$

$$\frac{dN_o}{dt} = -U\frac{dN_o}{dx} + \frac{(1-\beta)k_d \Theta P}{H} - k_h N_o \qquad 5$$

where P = periphyton biomass (gC/m2); μ_{max} = maximum periphyton growth rate (gC/m2/d); N_i = inorganic nutrient concentration in the water (g/m3); N_o = organic nutrient concentration in the water (g/m3); U = mean velocity (m/d); H = mean water depth (m); k_r = respiration rate (/d); k_d = death rate (/d); k_h = mineralisation rate (/d); k_s =

half-saturation concentration for periphyton growth (g/m3); Θ = nutrient/carbon ratio (assumed constant) (-) and β = proportion of dead biomass not mineralised (-). Equations are solved using a 4th-order Runge-Kutta scheme implemented using VBA in Excel.

Table 1. Summary of model coefficients

Mean velocity	U	8640	m/d
Mean depth	H	0.1	m
Flow	Q	10	L/s
Max algal growth rate	μ_{max}	25	mg/m2/d
Half saturation	k_s	5	mg/m3
Respiration rate	k_r	0.10	per day
Death/sloughing rate	k_d	0.10	per day
Mineralisation rate	k_h	0.10	per day
Nutrient/carbon ratio	Θ	1	(-)
Recycling fraction	$1-\beta$	1	(-)
Initial inorganic conc	$N_i(0)$	100	mg/m3
Initial organic conc	$N_o(0)$	100	mg/m3
Initial periphyton	$P(0)$	120	mg/m2

MODEL PREDICTIONS

Fig. 2 (top) shows steady-state predictions for a stream with no lateral inflows and 100% nutrient recycling ("base" case). Model coefficients are shown in Table 1. Nutrient concentrations are maintained at $N_i = N_o = 100$ mg/m3 at $x = 0$ and $P(0)$ is the equilibrium biomass for those concentrations.

Inorganic nutrient concentration decreases and stabilises at $N_i \sim 1$ g/m3 at x ~10 km. Organic nutrient concentration increases and stabilises at $N_o \sim 190$ g/m3. The sum $N_i + N_o = 200$ mg/m3 everywhere because there is no net removal ($\beta = 0$).

Fig. 2 (bottom) shows predictions for a steady inorganic nutrient addition at $x = 2$ km ("addition" case). Nutrient addition increases inorganic nutrient concentration by 20% as recommended by Stream Solute Workshop (1990). Results are shown after 10 day of steady injection but simulations were also run for 1 day and until steady state was achieved, and for a steady nutrient addition at 1 km intervals from 1 to 15 km.

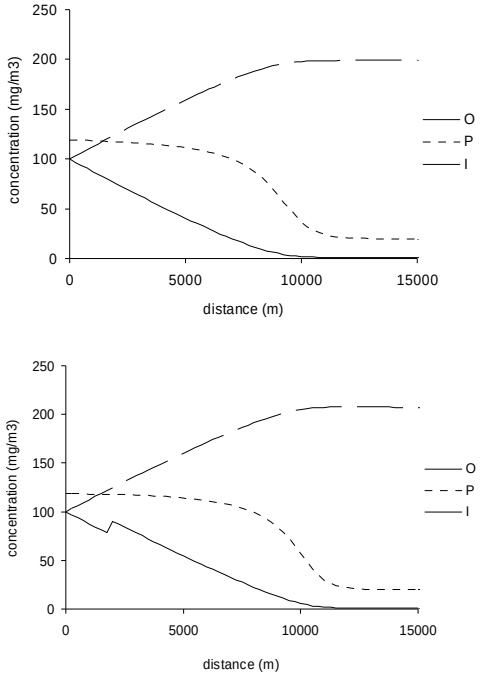

Fig. 2. Predicted inorganic (I), organic (O) and periphyton (P) profiles for the "base" (top) and "addition" (bottom) cases.

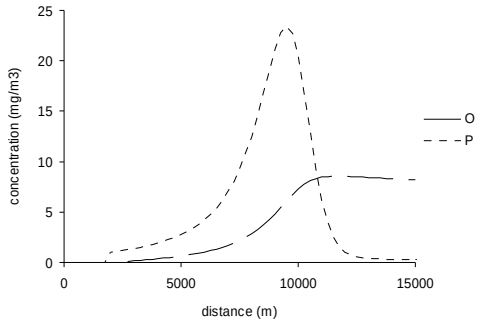

Fig. 3. Predicted differences in organic nutrient (O) and periphyton (P) between the "addition" and "base" cases.

Fig. 3 shows predicted changes to organic nutrient and periphyton profiles after 10 days nutrient addition at $x = 2$ km. Near $x = 10$ km periphyton biomass is significantly higher. Nutrient addition causes the point at which inorganic nutrient reaches the half-saturation concentration to move downstream. As a result the point at which periphyton drops (see Fig. 2) also moves downstream. At the injection point there is a small increase in periphyton (the result of higher inorganic nutrient concentrations) but organic nutrient is hardly affected.

Fig. 4 shows profiles of $C(x)$ - C_b for inorganic nutrient. The three methods of estimating "background" concentration are defined in Fig. 1.

Note the log scale for concentration. There are two important features of Fig. 4. First, concentration differences do not plot as straight lines which indicates that Eq. 1 does not apply over the whole study reach. Over short sub-reaches, however, Eq. 1 holds approximately. After 1 day of injection predicted concentrations of conservative tracer were found to be "steady" for ~7.5 km downstream from the injection point. Eq. 1 was fitted to inorganic nutrient concentrations in the first 3 km below the injection point Eq. 2 used to estimate the uptake length S_w (see Table 2). Second, near the injection point the slope varies significantly between Methods 1, 2 and 3. As a result estimated S_w values differ significantly between methods (see Table 2).

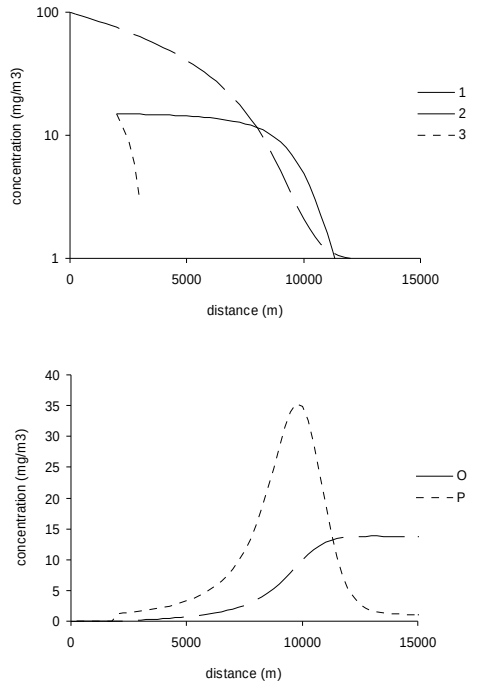

Fig. 4. Predicted differences in inorganic nutrient between the "base" case and "addition" at 2 km (top) and 25 km (bottom) . Fig. 1 defines "background" inorganic nutrient profiles used in Methods 1, 2 and 3.

RESULTS AND DISCUSSION

Method 1 yields a small S_w (implying rapid uptake) for the 2 km addition but a very large S_w (implying negligible uptake) for the 25 km addition. Method 1 does not subtract the pre-addition "background" concentration and hence quantifies "net" uptake (gross uptake by periphyton minus mineralisation from organic to inorganic nutrient). In the reach $2 < x < 5$ km gross uptake exceeds mineralisation giving a rapid decrease in N_i (Fig. 2) a large k_c (Eq. 1) and a small S_w (Table 2). In the reach $25 < x < 28$ km uptake and mineralisation are in balance giving a very small "net" uptake and hence a very large S_w.

Table 2. Uptake lengths for injection at 2 km.

Method	Source	1 day	10 days	steady-state
1	2 km	5.2	5.2	5.2
2	2 km	36	60	69
3	2 km	0.78	0.80	0.81
1	25 km	∞	∞	∞
2	25 km	0.38	0.52	0.62
3	25 km	0.38	0.52	0.62

values are S_w (km)

In these simulations nutrient recycling is 100%. Once "equilibrium" has been established between uptake and mineralisation (as is the case in the reach $25 < x < 28$ km) no further change in nutrient concentration or periphyton biomass would be expected unless there is a nutrient inflow or a change in habitat (e.g., shade or substrate). Managers may need to know how far below a point source of nutrient (e.g., a STP) elevated nutrient concentrations cause high periphyton biomass. Fig. 2 indicates that even though there is 100% nutrient recycling, inorganic nutrients and periphyton biomass decrease in the reach $0 < x <$ ~10 km before reaching a steady-state.

The values of S_w estimated change with source location (Fig. 5). For Method 1 S_w decreases as source location moves from 1 to 8 km. Inorganic nutrient concentration decreases almost linearly from $1 < x < 8$ km (Fig. 2). However, following the Stream Solute Workshop protocol, injection increases concentration by 20% rather than by a fixed concentration increment, and this affects estimated S_w values. For Method 1 a large S_w indicates that uptake and mineralisation are in equilibrium ($x > 12.5$ km) and a low S_w indicates that further changes with distance can be expected ($0 < x < 7.5$ km). Thus if Method 1 is used to analyse measured nutrient profiles and it yields a large S_w value then this informs the manager that periphyton biomass is unlikely to change with distance. Conversely a very small value for S_w value informs the manager that "equilibrium" has not been reached and periphyton biomass may change with distance. There are two practical difficulties. First, if flow increases along the study reach it is necessary to estimate inflow rates and concentrations and "correct" for inflows. Second, following the standard protocol S_w varies with source location.

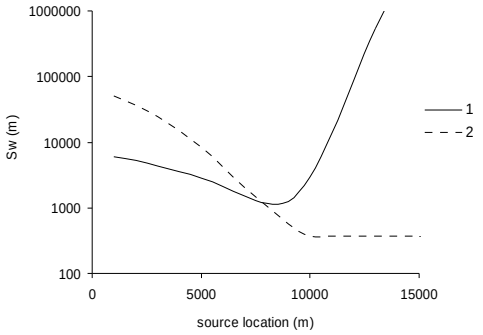

Fig. 5. Variation with source location of uptake length S_w estimated using Methods 1 and 2.

For the 2 km addition Method 2 gives larger S_w (viz., lower uptake rate) than Method 3. The reasons are obvious from Fig. 1 and 4. In the reach $2 < x < 5$ km "background" concentration decreases with distance and the Method 3 assumption that $C_b = C_3$ = constant is invalid. In the reach $25 < x < 28$ km "background" concentration is constant and Methods 2 and 3 give identical estimates of S_w. Method 3 yields biased estimates of S_w where "background" nutrient concentrations vary with distance – as is likely to be the case close to a point source.

For the 2 km addition Method 2 gives a larger S_w than Method 1 but for the 25 km addition the converse occurs (Fig. 5). Methods 1 and 2 quantify different aspects of nutrient uptake. As discussed in the previous paragraph Method 1 quantifies the "net" nutrient uptake rate (viz., the difference between uptake and mineralisation). Method 2 quantifies the rate at which inorganic nutrient concentration returns to "background" levels following the addition of nutrient. This depends on the relative rates of nutrient uptake and mineralisation. The latter is by periphyton biomass and the rate of generation of organic nutrient. These interactions are complex. For $x > 12.5$ km periphyton and nutrient concentration do not change with distance (viz., uptake and mineralisation are in equilibrium). This means that following the standard protocol, the same quantify of inorganic nutrient is injected for all sources $x >$ 12.5 km and because uptake and mineralisation are in equilibrium, S_w is independent of source location. Whereas it is fairly straightforward to interpret values of S_w estimated using Method 1, there does not seem to be a simple interpretation of the values estimated using Method 2.

Neither Method 1 nor Method 2 furnishes a direct estimate of permanent nutrient removal. The simulations presented in this paper are for 100% recycling (viz., zero permanent removal). Simulations have also been made (not reported) with 50-90% recycling and using the Droop model of nutrient uptake (Brezonik 1994) which indicate qualitatively similar findings to those presented here. It appears that a method for estimating permanent nutrient removal rates from the results of short-term nutrient additions is not available. Indeed there is some doubt whether a method can be developed. Brezonik (1994) points out the unstructured growth models (like Eq. 3-5) do not adequately describe the transient behaviour of cultures. Intracellular storage and excretion of metabolites produce changes in cell composition over time in response to changing external substrate concentrations. Unstructured models assume that growth is an instantaneous function of external or internal nutrient concentration. In reality the processes may be separated – growth may follow uptake only after some time lag. Multi-stage models have been developed for phytoplankton (Canale 1976) but have not yet been successfully applied to stream systems.

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