Hydrobiologia (2008) 610:1–11
DOI 10.1007/s10750-008-9417-x

PRIMARY RESEARCH PAPER

Benthic shear stress gradient defines three mutually exclusive modes of non-biological internal nutrient loading in shallow lakes

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Received: 29 November 2007 / Revised: 16 April 2008 / Accepted: 22 April 2008 / Published online: 10 June 2008

Abstract Assessment of the importance of internal nutrient loading is essential for managing and restoring eutrophic shallow lakes. To date, studies of internal loads have tended to focus on one of two abiotic processes, either molecular diffusion or sediment/nutrient entrainment (resuspension). This study presents a new approach to determining the non-biological fluxes of nitrogen (N) and phosphorus (P) from the sediment to the water column of shallow lakes. Three mutually exclusive flux processes: (i) molecular diffusion, (ii) turbulent diffusion (eddy diffusivity) and (iii) wind-induced resuspension of N and P, were related to a gradient of benthic shear stress. A model presented here allowed the durations and magnitudes of different non-biological fluxes to be calculated over time, based on benthic shear stress. Two site-specific critical shear stress thresholds determined which of the three flux processes dominated for any benthic shear stress value. The model was calibrated for a shallow lake and the continuous flux of nutrient from the sediment to the overlying water generated by each process during that period was calculated, enabling the estimation of the relative importance of each of the three flux processes over a one-year period. Wind-induced resuspension dominated the internal nutrient flux, operating for 38% of the time and contributing 0.9 T P year^{-1} and 10.2 T N year^{-1} to the internal nutrient load. In contrast, molecular diffusion only contributed 0.01–0.02 T P year^{-1} and 0.12–0.20 T N year^{-1} to the water column, while turbulent diffusion provided up to 0.6 T P year^{-1} and 6.2 T N year^{-1}. Our model suggests that turbulent diffusion is a neglected and potentially important process contributing to internal nutrient loading in shallow lakes, whereas molecular diffusion appears to be relatively unimportant in lakes that experience turbulence at the sediment–water interface.

Keywords Flux · Diffusion · Molecular · Turbulence · Resuspension · Eutrophication · Restoration · Internal loading · Nutrient · Nitrogen · Phosphorus · Model · Lake Waihola · Shallow lake

Introduction

An understanding of the contribution of internal nutrient loading to lakes is important for managing

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and restoring eutrophied lakes. The flux of nitrogen (N) and phosphorus (P) from the sediment of lakes and reservoirs results from the combination of many interacting biotic and abiotic factors. Calculations of the flux of nutrients from sediments to the water column (internal load or flux) is commonly based solely on the mass of nutrient transported via molecular diffusion (e.g., Nürnberg, 1988; Ignatieva, 1996; Kelderman et al., 2005). Molecular diffusion is the random movement of molecules (Brownian motion) down a concentration gradient (Cussler, 1997), and thus only occurs while a gradient is present. Differences in pore-water and lake water nutrient concentration (e.g. Schallenberg & Burns, 2004) tend to maintain this gradient, but only while turbulence at the sediment–water interface (SWI) does not obliterate the benthic boundary layer. The assumption of non-turbulence at the SWI is valid only when benthic currents are laminar, pore-water and lake water are in density equilibrium and a benthic boundary layer exists. On the other hand, nutrient concentration gradients across the SWI can vanish when the benthic boundary layer breaks down and pore-water becomes entrained in eddies. Pore-water nutrients may then be transported by eddy diffusivity (the term *diffusion* is nominal as the process is convective; Lamont & Scott, 1970), a mechanism hereby described as the eddy-mediated transport of pore-water only (Fig. 1). Molecular and turbulent diffusion are mutually exclusive processes delimited by a benthic shear stress threshold above which turbulent eddies are generated at the SWI. Studies comparing transport fluxes of molecular vs. turbulent diffusion have demonstrated that fluxes resulting from the latter tend to be several orders of magnitude greater (e.g. Portielje & Lijklema, 1999; Haugan & Alendal, 2005).

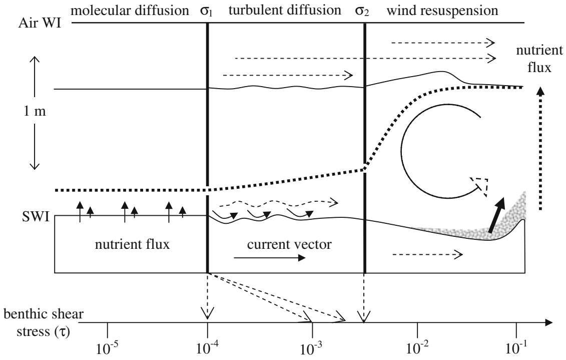

Fig. 1 The three non-biological components of internal nutrient flux in Lake Waihola. Molecular diffusion describes the process in which nutrient molecules move from a region of high concentration (sediment) to low concentration (lake water) by Brownian motion, and is only relevant in calm conditions (shear stress $<\sigma_1$). During periods of turbulence, when $\sigma_1<$ shear stress $<\sigma_2$, dissolved nutrients only are transported across the sediment–water interface by eddies, resulting in turbulent diffusion. Whole sediment is entrained by the water column under windy conditions, when shear stress $>\sigma_2$

Shear stress represents a convenient way of expressing the hydrodynamic energy exerted on the SWI. The movement of lake water over sediment exerts a stress at the interface that increases with the velocity of benthic currents (benthic shear stress, τ). During low energy conditions benthic shear stresses are minimal and laminar flow typically prevails at the SWI, allowing nutrient gradients to be maintained. Eddies at the sediment–water interface are established when the velocity of benthic currents increases beyond the capacity for water viscosity to constrain unidirectional (laminar) flow (Falter et al., 2004). The increase in water velocity during turbulent conditions consequently results in elevated benthic shear stresses. To this end, the exclusivity of molecular and turbulent diffusion is theoretically maintained by the critical shear stress threshold (σ) that defines the boundary between laminar and turbulent flow.

The benthic current velocities of many shallow lakes are sometimes sufficient to entrain the surficial sedimentary matrix into the water column (Hamilton, 1990; Hamilton & Mitchell, 1996). Consequently, pore-water is entrained into the water column during wind resuspension events, overriding and negating both molecular and turbulent diffusion (Fig. 1). However, while diffusive transport processes only transport dissolved nutrients, the entrainment of sediment provides a means for transporting particulate, sediment-bound nutrients, as well as any dissolved compounds. Thus, the entrainment of pore-water from a given area over a given time results in a flux of nutrient significantly greater than a turbulent diffusive flux integrated over the same sediment area (Fig. 1).

Given that sediment entrainment is a function of benthic current velocity, the onset and cessation of entrainment must also be defined by a benthic shear stress threshold (Hamilton, 1990; Peterson, 1999). The benthic shear stress (τ) threshold separating molecular diffusion and turbulent diffusion, defined as σ_1, is smaller than the τ threshold that separates turbulent diffusive and wind resuspension processes, defined as σ_2. If both σ_1 and σ_2 are quantified, then the dominant non-biological nutrient transport processes (i.e. molecular diffusion, turbulent diffusion or wind resuspension) acting at any given time can be determined from σ_1, σ_2, and τ.

The goal of our study was to determine and predict the magnitude of three mutually exclusive non-biological nutrient flux processes operating in a shallow lake, based on benthic shear stress calculations. Together with estimates of critical shear stress values and information on sediment–water nutrient gradients, the total non-biological nutrient contribution from the sediment to the overlying water was calculated and integrated over a one year period. A composite, three process, model for assessing continuous non-biological internal nutrient loading to lakes based on instantaneous benthic shear stress estimates is thus presented, and results for a shallow lake are evaluated.

Lake description

Lake Waihola (area = 5.4 km^2) is a shallow (Z_{mean} = 1.3 m, Z_{max} = 2.2 m), eutrophic lake located in the South Island of New Zealand (46°02′S 170°05′E) (Schallenberg et al., 2003b) (Fig. 2). It is situated c. 10 km west of the Pacific Coast and is both tidal and subject to elevated salinities (up to 4.8‰) (Schallenberg & Burns, 2003; Schallenberg et al., 2003a, b). It has a number of small tributaries and a theoretical mean, non-tidal, hydraulic residence time of c. 150 days (Schallenberg et al., 2003b). Nuisance cyanobacterial blooms often occur in the austral spring and summer resulting in the restriction of recreational

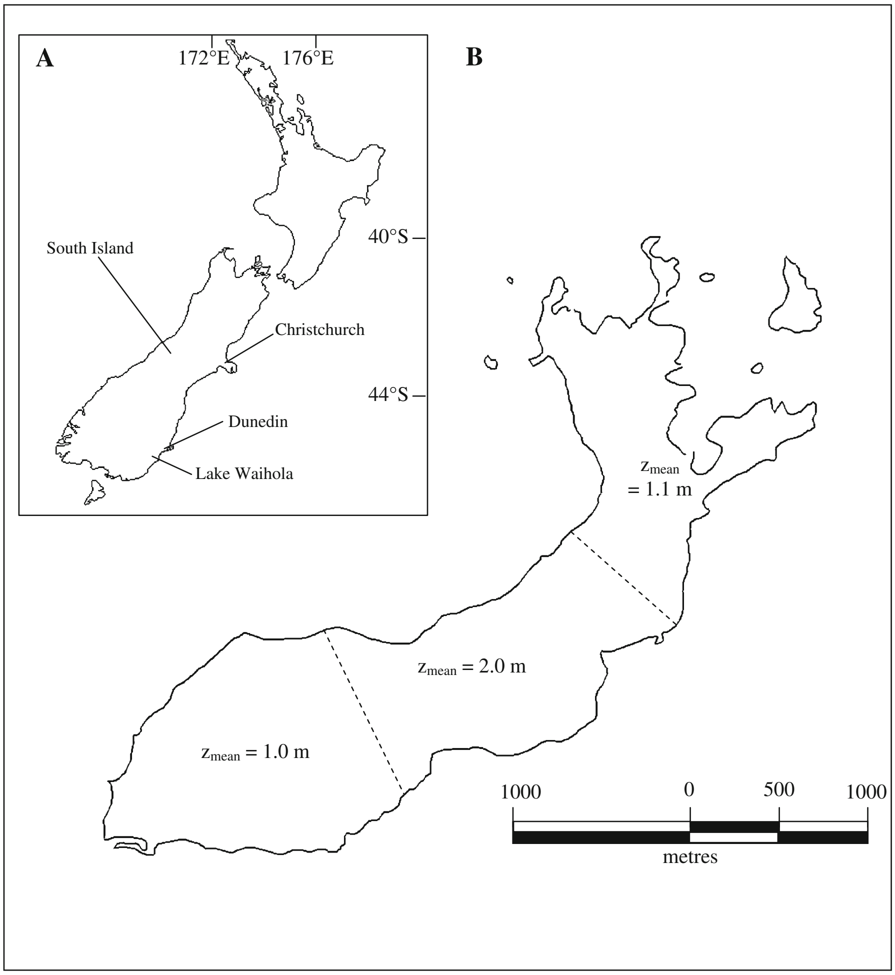

Fig. 2 (**A**) New Zealand locality map. (**B**) Lake Waihola, indicating the three modelled lake regions (depth data from Hamilton, 1990)

activities in the lake. The lake has seasonal aquatic macrophyte growth but effects of macrophytes on benthic shear stress or internal nutrient loading were not included in our non-biological flux model. The lake is polymictic but does at times exhibit horizontal salinity gradients of up to c. 2ppt in years when saline intrusions are strong (Schallenberg et al., 2003a). Effects of such density gradients were also not included in our model.

Methods

Estimating critical shear stress values

Turbulent diffusion across the SWI has been postulated by some researchers (e.g. Golosov & Ignatieva, 1999; Portielje & Lijklema, 1999) but critical benthic shear stress thresholds delimiting molecular from turbulent diffusion processes (Fig. 1) have yet to be empirically or experimentally determined for any lake sediment. As such, a potential range of σ_1 values was assumed (within the limits $0 < \sigma_1 < \sigma_2$) and the influence of variation in σ_1 on estimates of annual whole lake internal nutrient loading was examined by sensitivity analysis. Therefore, three values for σ_1 were used (0.0001, 0.001 and 0.004 N m^{-2}), ranging from just below to substantially below the estimated σ_2 value for Lake Waihola (0.04 N m^{-2}; Hamilton, 1990) (Fig. 1). Thus, the long-term, whole lake nutrient flux, as well as its relationship to different diffusive processes and to variation in σ_1, could be evaluated. Note that the critical shear stress (averaged for the wave period) for resuspension of Lake Waihola sediments (σ_2) obtained from Hamilton (1990) was based on wind velocity and a dimensionless drag coefficient assumed to be 0.02.

Model parameters

In addition to the critical shear stress values, the wind speed, direction, effective fetch and water depth were ascertained to compute continuous lake bottom shear stress. The lake was modelled as three regions of equal area, accounting for variation in fetch and sediment characteristics (Schallenberg & Burns, 2004; Schallenberg unpubl. data). Effective fetch values for the three lake regions were determined from the 16 equidistant whole lake fetch values calculated for Lake Waihola by Hamilton (1990). The percentage of each region influenced by each fetch direction was thus calculated to estimate effective fetches for each region. Hourly wind data were obtained for the period between 1 November 2000 and 31 October 2001 from the Dunedin Airport (14 km NW of Lake Waihola). This time period was selected because it coincided with continuous turbidity data available for Lake Waihola (see Model validation and calibration, below). The 1 h time step for benthic shear stress computation was based on analyses of water column equilibration with respect to current and wind velocities in Lake Waihola (Hamilton, 1990; Schallenberg and Burns, 2004).

Flux calculations: molecular diffusion

A stable and constant concentration gradient across the SWI was assumed during calm conditions, when $\tau < \sigma_1$ (Fig. 3). Although nutrient concentrations did vary over time, the sediment pore water remained c. 30 times more concentrated than the overlying water throughout a one year period in Lake Waihola (Schallenberg & Burns, 2004). Higashino and Stefan (2005) provide theoretical evidence for the rapid establishment of diffusive boundary layers after a turbulence event, supporting both the presence and stability of concentration gradients during calm periods.

The molecular diffusive flux of nutrients was modelled using Fick's first law, modified by inclusion of a porosity coefficient (Fig. 3), and applied to data collected from Lake Waihola (Table 1). Given that the diffusivity coefficients of organic-bound N and P are not known, only the fluxes of dissolved inorganic N and P were modelled. Thus, a quantity of nutrient was added to the overlying water for each square meter of calm ($\tau < \sigma_1$) lake bottom, during each hour that the lake remained calm during the modelled period.

Flux calculations: turbulent diffusion

The turbulent flux of dissolved nutrient across the SWI is inherently complex to model. A complete understanding of the behaviour of eddies, and the interaction with sediment and pore water, does not yet exist. Instead, a more general approach to modelling turbulent diffusion was employed. The small eddy model of Lamont and Scott (1970) was used to

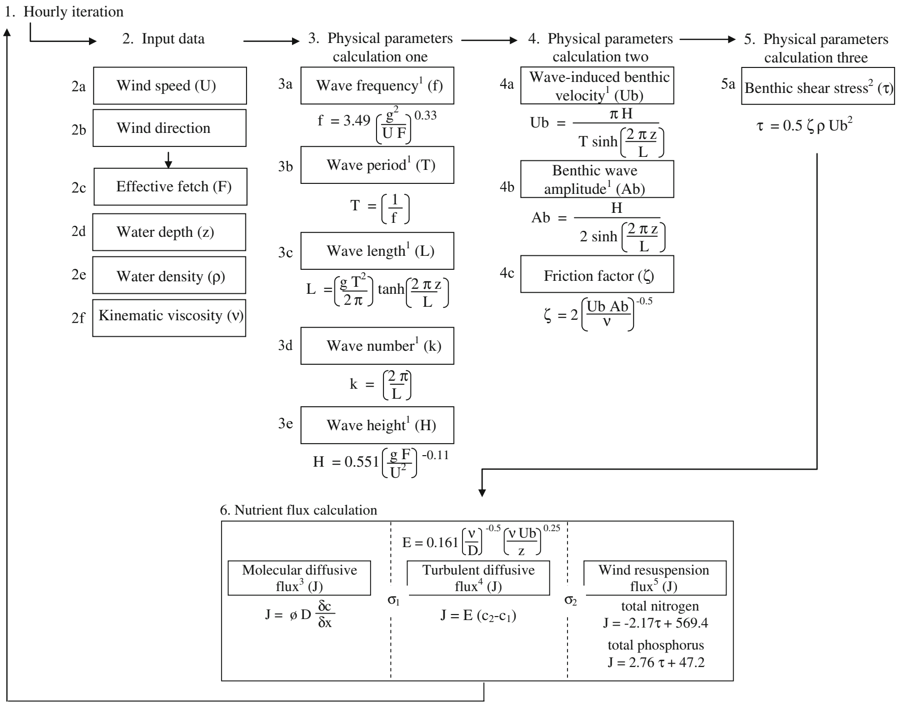

Fig. 3 The Lake Waihola model. For each hour of the modelled period a single iteration was processed and recorded, establishing the dominant non-biological flux process and the magnitude of its upward flux. Equations adapted from [1]Hamilton (1990); US Army Corps of Engineers (1984), [2]Hamilton and Mitchell (1996; [5]1997), [4]Lamont and Scott (1970) and [3]Maerki et al. (2004). c = concentration, x = diffusion pathlength. The wind resuspension flux equations of Hamilton and Mitchell (1997) for total nitrogen and total phosphorus have $R^2 = 0.004$ (P-value unspecified) and $R^2 = 0.324$ ($P < 0.001$), respectively. Furthermore, the wavelength equation features wavelength as both the response and as a predictor, requiring solution by iteration. To allow the model to calculate wavelength automatically, Hamilton developed a regression equation with $\tanh(2\pi z/L)$ as the response and $2\pi z/gT^2$ as the predictor. Hamilton reported $R^2 = 1$ for this relationship, though our attempts to recreate this correlation were unsuccessful. Instead, a regression equation specific to a single value of z was used, with T as the predictor and L as the response (e.g. $L = -0.0183T^5 + 0.2912T^4 - 1.7565T^3 + 4.8754T^2 - 2.366T + 0.5511$ for $z = 1.1$, with $R^2 = 1$)

Table 1 Parameters used in the calculation of molecular diffusion within the Lake Waihola model

Parameter	Value	Reference
Averaged relative resistivity	0.7	This Study
Average porosity (% water content)	90	This Study
Diffusivity coefficient ($m^2\ s^{-1}$) NO_3^-	1×10^{-9}	Li & Gregory (1974)
Diffusivity coefficient ($m^2\ s^{-1}$) PO_4^{3-}	9×10^{-10}	Li & Gregory (1974)
Diffusion pathlength (m)	0.002	This Study
Lake Water DN concentration (ppb)	305	Schallenberg & Burns (2004)
Lake Water DP concentration (ppb)	24	Schallenberg & Burns (2004)
Pore Water DN concentration (ppb)	9300	Schallenberg & Burns (2004)
Pore Water DP concentration (ppb)	940	Schallenberg & Burns (2004)

DN = dissolved nitrogen, DIP = dissolved phosphorus. Average relative resistivity was established over a 1 cm path length through freshly exposed surface sediment using the electrodes of a standard digital multimeter. Average porosity was calculated from the pore water obtained after centrifugation of the sediments. Diffusion pathlength was the presumed depth of oxidized sediment immediately beneath the sediment–water interface, as determined from a sharp lighter to dark brown colour change provide the rate of nutrient release given various parameters (including benthic current velocity), which was then applied to the known concentration of nutrients within the pore water from Schallenberg & Burns (2004) (Fig. 3). The small eddy model was utilized for time periods when $\sigma_1 < \tau < \sigma_2$, and added a velocity-dependent quantity of nutrient to the water column per square metre, per hour. Therefore, the main difference between molecular and turbulent nutrient diffusion estimates was the inclusion of benthic current velocity in the calculation of the latter (Fig. 3). The small eddy model also utilizes a Schmidt number (calculated using a molecular diffusivity coefficient), and thus again limited the model to estimating only turbulent fluxes of dissolved inorganic nutrients.

Flux calculations: wind-induced resuspension

Hamilton and Mitchell (1997) presented relationships between benthic shear stress and resuspended total nutrients for Lake Waihola. The relationships provided by Hamilton and Mitchell (1997) were utilized in the model presented here (Fig. 3). The wind-induced resuspension equations provided the velocity-dependent nutrient contribution per square meter for each hour when $\tau > \sigma_2$. The regression equations of Hamilton & Mitchell (1997) were statistically significant for TP but not for TN (see Fig. 3).

Model validation and calibration

The validity of the modelled shear stress values between 1 November 2000 and 30 June 2001 was assessed by comparing them to turbidity data collected at hourly or 15 min intervals recorded during that time using a YSI 6920 data logger with YSI 6026 self-wiping turbidity probe (Schallenberg & Burns, 2004) (Fig. 4). Turbidity, a measure of light scattering by particles, was used as a proxy for the concentration of particles suspended in water (Schallenberg & Burns, 2004). Turbidity data were resolved into either a calm state where resuspension did not affect lake turbidity (turbidity ≤ 20 NTU, Schallenberg & Burns, 2004), or

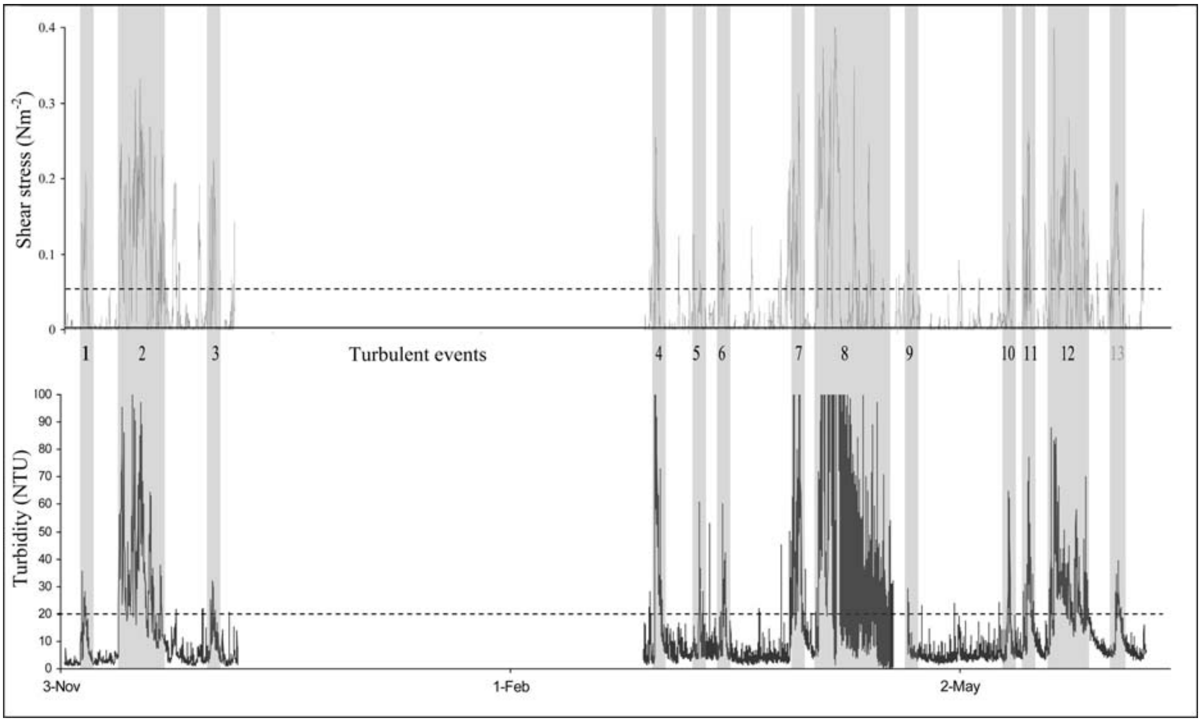

Fig. 4 Calibration of the model by comparing calculated shear stress values with turbidity data collected in the field. Although shear stress predicts the onset of turbidity, it is not proportional to the magnitude. Turbidity thresholds are indicated by dashed lines. Shaded boxes indicate resuspension events

a state when sediment resuspension occurred (turbidity > 20 NTU). Predicted ($\tau > \sigma_2$) and actual resuspension (turbidity > 20 NTU) were determined for the time series to confirm that the shear stress model and σ_2 gave accurate predictions predictions of sediment resuspension events.

No validation or calibration was possible for σ_1 and, therefore, the potential importance of σ_1 to the annual nutrient flux was examined by sensitivity analysis.

Results

Calibration

Wind events were used to calibrate the model, and were visually identified on the turbidity trace as an increase in NTU above 20, followed by a relatively slow reduction of NTU over time (Fig. 4). Thirteen such events were identified, and the calculated benthic shear stress values at the onset of these turbidity events all exceeded σ_2 (Fig. 4: grey boxes). Furthermore, the calculated benthic shear stresses did not predict any turbidity events. Thus, the independent turbidity data confirmed that σ_2, as determined by Hamilton & Mitchell (1997), is an accurate predictor of the onset of wind-induced resuspension events in Lake Waihola. However, attempts to statistically correlate the magnitude of turbidity with benthic shear stress resulted only in a weak but significant correlation ($R^2 = 0.19$, $P < 0.001$). Thus, benthic shear stress reliably predicted turbidity events, but not the resultant turbidities in Lake Waihola.

Flux estimates

The calibrated parameters and required environmental data were put into the model to hindcast the magnitudes and durations of the three non-biological flux processes during a one-year period in Lake Waihola, based on three assumed values of σ_1 and the confirmed σ_2 value from Hamilton & Mitchell (1997) (Fig. 5). Molecular diffusion accounted for the smallest contribution to non-biological nutrient flux (0.01–0.02 T PO_4-P year^{-1}; 0.12–0.20 T NO_3-N year^{-1}), regardless of the assumed σ_1 value. The percentage of time that molecular diffusion was active in Lake Waihola increased 13% between $\sigma_1 = 0.0001$ N m^{-2} (39%) and $\sigma_1 = 0.001$ N m^{-2} (52%), and increased a further 8% between the $\sigma_1 = 0.001$ N m^{-2} and $\sigma_1 = 0.004$ N m^{-2} (60%) states.

The nutrient contribution from turbulent diffusive fluxes were 0.62 T PO_4-P year^{-1} and 6.19 T NO_3-N year^{-1} when $\sigma_1 = 0.0001$ N m^{-2} and were 0.08 T PO_4-P year^{-1}and 0.83 T NO_3-N year^{-1} when $\sigma_1 = 0.004$ N m^{-2}. Regardless of the σ_1 value assumed, the bulk of the non-biological nutrient flux in Lake Waihola was from wind-induced resuspension (0.85 T P year^{-1}; 10.22 T N year^{-1}), which was the dominant flux process in the lake for 38% of the modelled time period.

Discussion

Relative importance of the three flux processes

The model presented here calculated the hourly τ at the SWI of Lake Waihola, and assigned one of three non-biological internal nutrient flux processes, as defined by two critical shear stress thresholds (Fig. 5). Integration over a one-year period allowed the relative importance of molecular diffusion, turbulent diffusion and wind-induced resuspension to be determined on an annual basis. The calculated nutrient fluxes ranged between 2.1 and 3.0 g m^{-2} year^{-1} total N, and 0.17 and 0.27 g m^{-2} year^{-1} total P, depending on the σ_1 value used (Table 2). Between 0.02 and 0.04 g m^{-2} year^{-1} DIN (dissolved inorganic nitrogen), and 0.002 to 0.003 g m^{-2} year^{-1} DIP (dissolved inorganic phosphorus), were contributed via molecular diffusion. While molecular diffusion occurred for a substantial proportion of time ($\sigma_1 = 0.0001$ N m^{-2}, 39%; $\sigma_1 = 0.001$ N m^{-2}, 52%; $\sigma_1 = 0.004$ N m^{-2}, 60%), it contributed to less than 1% of the non-biological internal load of nutrients to the water column. In contrast, when σ_1 was assumed to be close to σ_2 ($\sigma_1 = 0.004$ N m^{-2}), turbulent diffusion occurred only 2% of the time but contributed 7% and 8% of the total N and P flux, respectively. Although the actual value of σ_1 has not been determined for Lake Waihola, the small eddy model indicates that turbulent diffusivity is likely to be more important than molecular diffusion to the internal nutrient load. Therefore, turbulent diffusion may be an important but neglected

Fig. 5 The magnitude and relative time allocations for the modelled non-biological, internal nutrient fluxes of Lake Waihola (1 Nov. 2000 to 31 Oct. 2001). These fluxes were calculated using three different critical shear stress (σ_1) values: 0.0001, 0.001, and 0.004 N m^{-2}. (TN = total nitrogen, TP = total phosphorus)

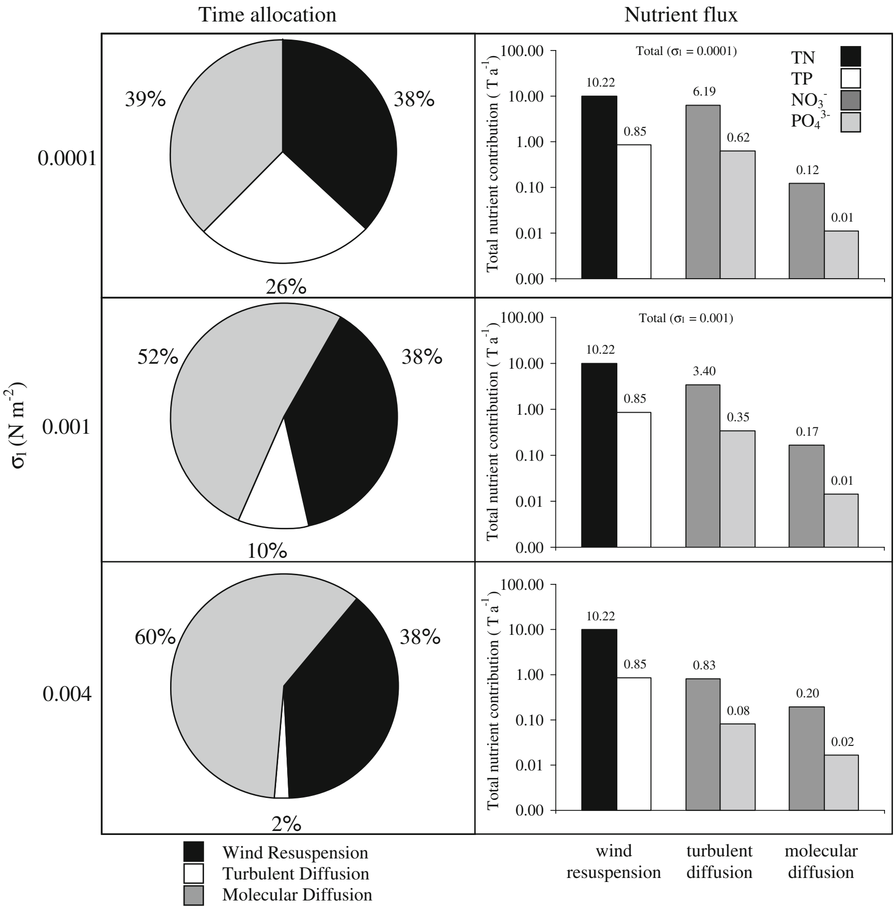

Table 2 Nutrient budget of Lake Waihola

Parameter	Nitrogen	Phosphorus	Reference
External loading (T year^{-1})	43	2.5	Schallenberg & Burns (2001)
Internal loading (T year^{-1})	11.3–16.5	1.0–1.5	This study
% of external load	26–41	40–60	This study
Retention (T year^{-1})	5.4	1.1	Schallenberg & Burns (2001)
% of external load	13	44	This study
Loss (outflow, denitrification) (T year^{-1})	48.9–55.1	2.4–2.9	Schallenberg & Burns (2001)

factor that is highly relevant to internal nutrient loading in shallow lakes.

Wind-induced resuspension was the most important non-biological process for transporting nutrients across the SWI in Lake Waihola, with $\tau > \sigma_2$ for 38% of the time. As such, the surficial pore water nutrient reservoir was often entrained into the overlying water column.

Implications for lake nutrient budgets and restoration

Schallenberg & Burns (2001) calculated the approximate non-tidal external nutrient inputs into Lake Waihola from tributaries and rainfall as 43 T year^{-1} and 2.5 T year^{-1} for N and P, respectively (Table 2). Our model estimated a non-biological internal nutrient load to the water column of 11.3–16.5 T year^{-1} N, and 1.0–1.5 T year^{-1} P (Table 2). Therefore, according to our estimates, 40–60% of the P entering the water column was recycled from the sediment. Schallenberg and Burns (2001) used sediment core data to calculate a net retention into lake sediment of 5.4 T N year^{-1} and 1.1 T P year^{-1} (Table 2), equivalent to 13% and 44% of the external N and P loads. Our model consequently indicates that the annual internal nutrient load (derived from non-biological processes) is greater than the annual net nutrient retention and represents a substantial component of the total nutrient load contributed to the Lake Waihola ecosystem while a proportion of resuspended sediment settles again to the lake bed on the time scale of days (Hamilton & Mitchell, 1996), we did not have accurate estimates of interactions between nutrient fractions once entrained in the water column and subsequent nutrient adsorption, desorption and re-sedimentation. Such information would contribute to the modelling of the net, longer-term, effects of sediment resuspension on internal nutrient loading and bioavailability.

The minor importance of molecular diffusion

The composite shear stress-gradient model calibrated with Lake Waihola data showed that, of the three internal nutrient fluxes modelled, molecular diffusion provided the smallest contribution to the nutrient load of the water column. Molecular diffusion alone is probably insufficient to describe the magnitude of internal nutrient supplied to any shallow lake. Wind energy routinely instigates turbulence at the SWI of shallow lakes (e.g. Carper & Bachman, 1984; Luettich et al., 1990; Dillon & Evans, 1993). The nutrients entrained into the water column during short wind events can exceed the molecular diffusive flux integrated over much longer periods (e.g. Sondergaard et al., 1992), at the same time disrupting vertical sediment nutrient profiles which are often used to calculate the latter flux (i.e. Jorgensen & Revsbech, 1985). Thus, molecular diffusion alone cannot adequately describe the magnitude of internal nutrient transport in windy shallow lakes.

Critique of previous approaches

Several different methods have previously been used to estimate the internal nutrient budgets of shallow lakes. As described above, nutrient budgets calculated from molecular diffusion alone are likely to be underestimates, and are generally established using either pore water profiles determined from sediment cores or benthic chambers. Both these approaches give estimates specific to small areal units (ie. fractions of a m^2) and are, therefore, not very useful for whole-lake estimates of internal nutrient loading. Furthermore, by creating a closed system for measurement purposes, these methods may alter in situ sediment and water column nutrient concentrations and redox conditions.

Thus, a more reliable approach for modelling internal loading is a whole-lake approach requiring lake-specific flux data for each transport mechanism that influences the nutrient budget. An example of this approach is SWITCH (Sediment Water Interaction by Transport and Chemistry), a model that tracks nutrient through the physical, biological and chemical sources and sinks in Lake Veluwe (Smits & van der Molen, 1993). SWITCH and other dynamic models (e.g. Cózar et al., 2005) may be more accurate tools for predicting whole lake internal nutrient loading, but they require substantial input data (or assumptions).

Thus, the methodologies generally used to estimate internal nutrient loading fall on a continuum, with simplicity and realism as reciprocals, and with pore water profiling and complex dynamic modelling as end members.

The shear stress gradient model presented here is a simple modelling approach which defines three mutually exclusive flux processes along a shear stress gradient. By conceptually simplifying the modelling approach in this way, the amount of input data required to use the model is greatly reduced compared to complex dynamic models. We, therefore, present this model as a compromise approach which appears to yield realistic estimates of non-biological internal nutrient loading while acknowledging three flux processes, which are important in shallow lakes as well as in the shallow zones of deeper lakes.

Critique of the shear stress gradient model

Although we were unable to establish a reliable value of σ_1, our model nevertheless illustrates the importance of integrating three non-biological fluxes into estimates of internal nutrient loading to shallow lakes. Our use of shear stress thresholds to define three mutually exclusive flux processes is derived from the well-established diffusive boundary layer concept. Large diffusive boundary layers occur in the low energy systems characterized by no, or laminar, flow (Jorgensen & Revsbech, 1985). The diffusive boundary layer is reduced in thickness by an increase in energy in the system or physical perturbations within the boundary layer, both of which induce turbulence and lead to eddy diffusivity (e.g. Jorgensen & Revsbech, 1985; Higashino & Stefan, 2005). We therefore postulate the existence of σ_1 which occurs in the absence of a diffusive boundary layer, but where τ is insufficient to entrain bulk sediment. If the relevant data are available, an alternative approach to defining σ_1 uses a Reynolds Roughness number specific to the turbulent/laminar boundary and to the kinematic viscosity, as well as measures of roughness length, and the water density at the onset of turbulence.

A process consistent with turbulent diffusion, as proposed in our model, has been identified in Lake Krasnoye (Golosov & Ignatieva, 1999). The process was identified from increases of lake water nutrient concentrations above what is possible by molecular diffusion, but without an increase in suspended sediment. Based on the nutrient and sediment concentrations of the lake water, Golosov & Ignatieva (1999) concluded that turbulent processes due to density currents at the SWI must be accountable, thus providing empirical evidence of the turbulent diffusive process we modelled here. We suggest that this process must be accounted for in lakes where $\tau > \sigma_1$.

Enhancements to the model

The flux of wind-resuspended nutrients calculated within the Lake Waihola model represent a necessary oversimplification, owing to the complex biological, chemical and physical forces that control nutrient partitioning in lake water. The wind resuspension fluxes are consequently presented for total nutrients, consisting of the sum of dissolved inorganic, dissolved organic and particulate forms. Each of these three nutrient fractions have different implications for the internal nutrient load, the effects of which are generalized in the Lake Waihola model by the use of Hamilton's model (1990), adapted from US Army Corps of Engineers (1984). While dissolved organic nutrients may constitute a significant nutrient flux from the sediment to the water column, the absence of published molecular diffusion coefficients precluded estimation of the diffusive fluxes of dissolved organic nitrogen and dissolved organic phosphorus by our shear stress gradient model at present.

Although Lake Waihola is tidal, the shear stress gradient model assumes wind to be the only source of benthic energy and does not consider tide-induced benthic currents and current modifiers (i.e. macrophytes). Owing to the complexity of tidal interactions within Lake Waihola, incorporating a tidal component was outside the scope of this model. However, a tidal benthic shear stress component could be added to the model in future.

In this attempt to consolidate three non-biological flux processes related to shear stress, we have purposely omitted the effects of biological factors on internal nutrient loading. For example, the seasonal presence of macrophytes in Lake Waihola would attenuate the propagation of wind energy translated down the water column, increasing the minimum wind speed required to induce σ_1 and σ_2 (this would be fetch dependent). Conversely, fish may cause benthic currents, reducing the amount of wind energy required to attain the critical shear stress values in Lake Waihola. More importantly, however, all aquatic plants and animals represent potential biological fluxes of internal nutrients, through uptake/ingestion, excretion/secretion and senescence/decay. As with tidal influences, incorporating macrophyte and fish effects into the Lake Waihola framework was outside the scope of our non-biological flux model. Thus, the model, in its present form, is best suited to systems in which wind is the primary control on macro-scale benthic currents (i.e. shallow, exposed lakes), and which are not dominated by benthic macrophytes.

Despite some limitations, our non-biological nutrient flux estimates for Lake Waihola were consistent with results from previous studies (e.g. Hamilton, 1990; Hamilton & Mitchell, 1996, 1997) and reasonable in relation to independent estimates of nutrient retention (Schallenberg & Burns, 2001). This suggests that the model can provide first order estimates of the relative importance of three non-biological nutrient flux processes which have rarely been compared or studied in concert.

Acknowledgements Thanks to P. Bartels, C.W. Burns, C. Tyrrell and I. Dickson for valuable assistance. K. McGill from the National Institute of Water and Atmospheric Research kindly provided the meteorological data. We also wish to thank the two anonymous reviewers of this manuscript. This research was funded by the University of Otago and the New Zealand Foundation for Research Science and Technology.

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