Quinn, J., Rutherford, K., Wilcock, B., Depree, C., Young, R., Schiff, S. (2018), Nutrient-periphyton interactions along a temperate river and response to phosphorus input reduction, pp. 10-18. In Gastescu, P., Bretcan, P. (edit, 2018), Water resources and wetlands, 4th International Conference Water resources and wetlands, 5-9 September 2018, Tulcea (Romania), p.312

Available online at http://www.limnology.ro/wrw2018/proceedings.html

4th International Conference Water resources and wetlands, 5-9 September 2018, Tulcea (Romania)

NUTRIENT-PERIPHYTON INTERACTIONS ALONG A TEMPERATE RIVER AND RESPONSE TO PHOSPHORUS INPUT REDUCTION

John QUINN[1], Kit RUTHERFORD[1], Bob WILCOCK[1], Craig DEPREE[1], Roger YOUNG[2], Sherry SCHIFF[3]

[1]NIWA, PO Box 11115, Hamilton, New Zealand ph. +64 8567026
[2]Cawthron Institute, 98 Halifax Street East, Nelson 7010, New Zealand, ph. +64 3 548 231
[3]University of Waterloo, 200 University Ave W, Waterloo, ON N2L 3G1, Canada ph. +1-519-888-4567
Email: John.Quinn@niwa.co.nz; Kit.Rutherford@niwa.co.nz; Bob.Wilcock@niwa.co.nz; Craig.Depree@niwa.co.nz; Roger.Young@Cawthron.org.nz; sschiff@waterloo.ca

Abstract

We investigated nutrient-periphyton interactions and nutrient attenuation loading along a 80 km reach of a gravel-bed temperate river during summer over 2011-2017, before and after a sewage treatment upgrade to reduce phosphorus loading, using reach-scale measurements and *in situ* chambers. Dissolved reactive phosphorus (DRP) and dissolved inorganic nitrogen (DIN) decline over the most enriched 31 km reach averaged 80% and 71%, respectively, and were least (28% and 38%, respectively) in the cool, wet, summer of 2012, when periphyton Chlorophyll a was relatively low and flow was highest (20 m^3/s). The dominant forms of dissolved P and N changed from DRP and DIN, respectively, near the nutrient inputs at the top of the study reach to dissolved organic P and dissolved organic P at the bottom (>40 km from the plains). These changes reflected periphyton uptake of DRP and DIN, while DOP and DON were more stable longitudinally. Sloughed periphyton also contributed to downstream transport of particulate organic nutrients. Sloughing was greater in the afternoon than morning, due to the lift of gas bubbles entrapped in periphyton, and during spates. Reduced sewage P input to the river did not reduce DIN uptake markedly and associated periphyton biomass reduction was modest. Evidence suggests that bed sediments provide periphyton with an ongoing source of P during summer, facilitated by high afternoon pH (9-10). Periphyton C/N and C/P indicated increasing nutrient limitation over the lower river at DIN <400 and DRP <6 mg/m^3. Regression modelling showed that reach scale areal uptake (*U*) of DIN could be largely explained by gross primary production and temperature, whereas initial DRP concentration and respiration accounted best for DRP uptake. We conclude that models of nutrient attenuation/spiralling in rivers need to consider contributions of dissolved and particulate nutrients, along with dissolved forms, and that periphyton management should consider sources of both sediment and water column nutrients.

Keywords: Periphyton, nitrogen, phosphorus, attenuation, nutrient limitation, organic nutrients, particulate, sloughing

1 INTRODUCTION

Excessive growth of aquatic plants (blooms of algae and macrophytes) due to nutrient enrichment of freshwaters by inputs from human activities is a global problem. The nutrient enrichment response in gravel-bed rivers is typically manifest in development of abundant periphyton biomass, where other controlling factors (e.g., high light, stable flow regime, warm temperatures, low grazing pressure) are favourable. Excessive periphyton can degrade aquatic biodiversity and a wide range of freshwater ecosystem services, including the provision of drinking water for people and livestock and recreational suitability for swimming and fishing. If toxin-producing cyanobacteria become abundant, the periphyton also present a known poisoning hazard to dogs and a potential risk to swimmers (MFE/MOH 2009). Managing these effects requires an understanding of the relationships between nutrients (particularly N and P) and periphyton growth rates and biomass to provide targets for reduction of nutrient loading from point and diffuse sources (e.g., sewage treatment plants and agriculture, respectively).

However, growing periphyton also remove nutrients from the water column and thereby may limit periphyton growth downstream. Periphyton also excretes organic forms of nitrogen and phosphorus (DON and DOP), and periphyton sloughing results in downstream transport of particulate organic N and P (Withers and Jarvie 2008). Thus, periphyton on riverbeds can have significant effects on the concentration, timing and form of nutrients at downstream locations, with consequent effects on eutrophication symptoms (e.g., algal blooms,

deoxygenated "dead zones", fish kills) of downstream rivers, lakes and the coast (e.g., Berezina and Golubkova 2008).

Statistical and mechanistic models have been developed that address some of these nutrient-periphyton interactions (e.g., Rutherford 2011; Chapra, Flyle et al. 2014; Snelder, Booker et al. 2014) and there have been large cross-biome experiments focusing on attenuation of single nutrients (Peterson et al. 2001). However, there are few case studies that examine periphyton and nutrient interactions, considering all major nutrient forms, or documented 'natural experiments' examining how these interactions are altered by management actions to reduce nutrient loadings.

This study aimed to quantify nutrient and periphyton interactions at local and river reach scales and the effect of reduction in P loading. It focused on nutrient and periphyton interactions along an 80 km of the lower Tukituki River (5-6 order, median flow 17 $m^3 s^{-1}$), New Zealand (Fig. 1). The river is affected by inputs of nutrients from upwelling of agriculturally N-enriched groundwaters and P-enriched secondary treated, oxidation pond, sewage treatment plant (STP) effluent from 2 towns (combined population c 8000). The Tukituki River is highly valued for trout fishing and swimming but both these uses are degraded by sometimes excessive abundance of periphyton, including cyanobacterial mats, during summer.

2 METHODS

2.1 Longitudinal surveys

We estimated nutrient uptake using a combination of longitudinal surveys of nutrients, periphyton and stream metabolism under a range of summer baseflow conditions (flows 4-20 m^3/s). Sampling was conducted during summers of 2001 to 2017, before and after STP upgrades in 2015 that reduced P loadings by over 90%. Seven longitudinal surveys along the lower Tukituki and its Waipawa River tributary (Fig. 1) from upstream of the STP inputs (sites T2, T3 and W1) to near the sea (T13 or T14) were undertaken in summer (usually mid-February) of 2011, 2012, 2013, 2015, 2016 and 2017). Differences in general weather conditions (e.g. cool wet in 2012 c.f. hot, dry in 2011 and 2013) resulted in different antecedent and surveys flows and periphyton. The Waipawa had very similar flow to the Tukituki at their confluence (medians 6.5 and 6.3 m^3/s, respectively) but the Waipawa had lower average concentrations of DRP (16%) and DIN (41%), resulting in dilution of these nutrients (by c. 8% and 20%, respectively) between T5 and T6, 21 km from the plains. Flow inputs were very low from tributaries along the study reach during summer, and the combined flows of gauging stations at T4 and W1 (Fig. 1) were equivalent to -4% to +10% of flow at T12 during the surveys. This enabled calculation of nutrient uptake rates by mass balance between reaches.

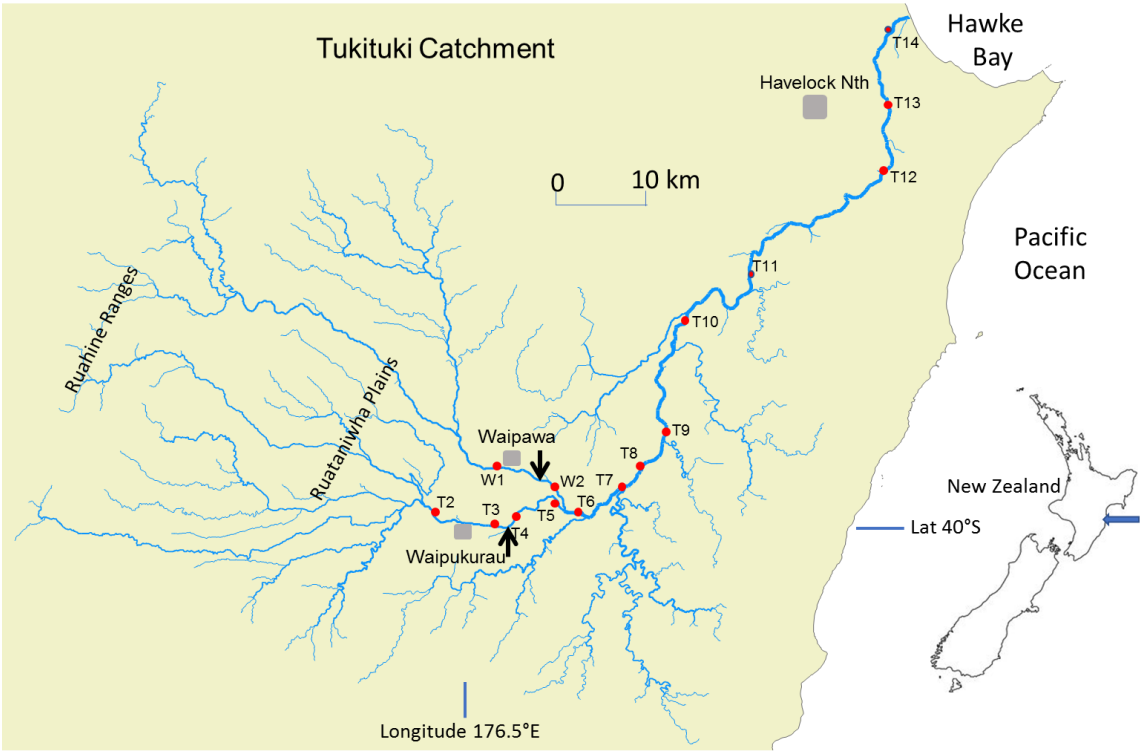

Figure 1: Location map of the Tukituki River showing the study sites and the STP discharges (black arrows). Insert shows the catchment location on the East Coast of the North Island of New Zealand

Periphyton cover was assessed, using an underwater viewer (bathyscope) at 20 points at equidistant locations across 4-5 cross-sections spaced to be representative of each sampling reach. A stream stone was collected at random at each point and the 20 stones collected were combined into a reach composite sample for periphyton assessment. All attached periphyton was scrubbed to make a periphyton sample that was transported on ice in the dark to the NIWA laboratory for analysis up to 4 days after collection. The sample was then homogenised using a "stick blender" and subsamples were assayed for chlorophyll a (Chl. a; acetone pigment extraction, spectrophotometric measurement), dry mass (DM, subsample filtered and dried 24 h at 104 °C), particulate carbon and nitrogen (PC, PN; Catalytic comb @900°C, TCD, Elementar C/N analyser) and particulate phosphorus (PP, Acid digest, DRP by FIA). Periphyton biomass/unit area was calculated by dividing the sample mass by the exposed surface area of all stones calculated from stone dimensions (Dall 1979).

Longitudinal water sampling along the upper half of the reach was from upstream to downstream to sample approximately the same parcel of water based on estimated travel times from a model predicting average velocity in relation to flow (Johnson 2011). During the latter surveys sampling was done from early in the morning (starting at dawn) and again in the afternoon to evaluate diel variations due to light/primary production effects. In the lower river the longer distances/flow times between reaches made this 'parcel tracking' impractical. Water samples were collected from the main river flow at mid-depth. Spot measurements of pH and dissolved oxygen (DO) and temperature were made with calibrated field instruments. Unfiltered samples for measurement of TP and TN were stored immediately on ice in the dark whilst samples for dissolved nutrient analyses (DRP, TDP, NH_4-N, NO_3-N, TDN) were filtered in the field (Whatman GFC filter) before storing on ice. Dissolved inorganic N (DIN) was calculated as NH_4-N + NO_3-N, dissolved organic N (DON) was TDN-DIN and dissolved organic P (DOP) was TDP-DRP). Particulate N (PN) and P (PP) were calculated as TN-TDN and TP-TDP. Downstream transport of periphyton "clumps" and associated particulate nutrients was measured using paired drift nets (0.5 mm mesh) set at mid-depth and at/just below the water surface for c. 1 hour and the volume filtered was calculated from the net opening area (50 cm^2) and the average of water velocity measured at the net inflow at the beginning and end of deployment. Samples were transported and analysed using the same methods as described above for periphyton.

Reach scale areal N and P uptake rates (U, mg m^{-2} h^{-1}) were calculated from the field samples as the difference in concentrations (mg m^{-3}) between paired upstream (C_{up}) and downstream (C_{down}) concentrations divided by mean reach depth (D, m) and the reach travel time (T, distance between sites (m) / mean velocity (m s^{-1})) predicted from a physical model of the river (Johnson 2011)) for the flow measured at the sites or at nearby flow stations using the equation: $U = (C_{up}\text{-}C_{down})/D/T$.

Reach scale metabolism (net and grow primary production (NPP, GPP) and ecosystem respiration (ER) were calculated from single station diurnal dissolved oxygen and temperature data (Young and Huryn 1996) collected using D-Opto loggers over 1-3 days at the time of the nutrient uptake surveys. Average reach depths were calculated from measurements across 5 cross-sections located upstream of each dissolved oxygen and temperature monitoring location.

2.2, Chamber nutrient uptake measurements: *In situ* measurements of nutrient uptake enabled manipulation of dominant periphyton community type (filamentous diatoms or greens or cyanobacteria) and biomass and light/dark comparisons. We measured the areal uptake (U) of dissolved N and P species (NH_4-N, NO_3-N, DIN, DON, DRP, TDP, DOP) by difference in concentrations between the beginning and end of ca. 2-3 h *in situ* incubations of river bed rocks and attached periphyton, under ambient light in fully enclosed, recirculating, plexiglass, respiratory chambers (Hickey 1988) and then in the dark, after refreshing the chambers with river water and covering with black PVC sheeting held down by river stones. Dissolved oxygen (DO) and temperature were measured at 1-minute intervals by RBR or D-Opto meters in the chambers and NPP and GPP and ER were calculated from the rate of change in DO, the chamber water volume and the light exposed surface area of the stones (as described above). Photosynthetically active radiation (PAR) at the water surface was measured at 15-minute intervals during the chamber measurements using a Li-Cor Li-190-R meter within 14 km of the site. The biomass of periphyton on the incubated rocks was measured at the end of the incubations as described above for reach surveys. Two identical chambers were used to make twenty-four chamber light/dark measurements on 11 dates during mid-February of 2011-2015 at Tukituki River sites T4, T4_5, T5, T6 and T9, located 2-14 km downstream of STP inputs of treated domestic wastewaters (Fig. 1). The dominant periphyton types were filamentous green algae (dominated by *Stigeoclonium* sp.), fragile filamentous algae (dominated by *Melosira varians*) and cyanobacteria (mainly *Phormidium* sp.).

Patch scale areal N and P uptake rates (U, mg m^{-2} h^{-1}) within the chambers were calculated using the equation: $U = (C_{initial}\text{-}\ C_{final})$ x V/A/T. Where $C_{initial}$ and C_{final} were initial and final nutrient concentrations in

each incubation, V was the volume enclosed in the chamber apparatus (V, allowing for the measured volume of the stones and sensors), A was the exposed surface area of the stones (as described above) and T was the incubation time.

3 RESULTS AND DISCUSSION

3.1 Longitudinal patterns in river dissolved inorganic nutrients and river periphyton

The summer surveys covered a range of weather conditions, from wet, overcast and cool, in 2012, to hot and sunny, during the 2013 drought, that were reflected in patterns of nutrients and periphyton along the lower Tukituki River (Figs 2 & 3). Water column concentrations of DRP and DIN declined rapidly with distance downstream of the inputs from agricultural land and STPs in the upper part of the study area (Fig, 2A, D). The increase in DRP downstream of the Waipukurau STP discharge (between T3 and T4, Fig. 1) was greatest (4-fold) during 2013 before the STP upgrade when the flow of 3 m^3 s^{-1}, equivalent to the 1 in 5-year 7-day low-flow level. The STP upgrades achieved >90% P-input reduction from mid-2015 and DRP only increased by on average 2 mg /m^3 (18%) between T3 and T4 in 2016-17, compared with by 18 mg /m^3 (190%) during 2011-2014 (Fig 2A). DRP and DIN declined on average 80% and 71%, respectively, over the 31 km from T4 to T10 and 86% and 90% over 60 km from T4 to T12. DRP and DIN attenuation below T4 were least (28% and 38% to T10 and 78% and 60% to T12, respectively) in the cool, wet, summer of 2012 (Fig. 2D) when periphyton Chl. a was relatively low (Fig. 3B) and flow was highest (20 m^3/s), resulting in a 3-fold lower travel time (43 h) from T2 to T14 than in 2013 (120 h).

The dominant forms of dissolved P and N changed from DRP and DIN, respectively, near the nutrient inputs at the top of the study reach to DON and DOP at the bottom (>40-50 km from the plains), except in 2012 when flows were highest and periphyton biomass lowest (Figs. 2 & 3B). This reflected removal of DRP and DIN while DOP and DON were more stable longitudinally. The chamber studies showed that release of DON and DOP resulted in uptake of TDN and TDP being lower than DIN and DRP, respectively (Fig. 5). Furthermore, DON *U* in light chambers was significantly negatively correlated with Chl. a and GPP and, in dark, was negatively correlated with respiration rate (ER). Together these results indicate that there some of the DRP and DIN, taken up by periphyton is released for downstream transport as DON and DOP ("nutrient spiralling" (Newbold 1981)). PP and PN concentrations were variable at sites, with higher values in the afternoon than morning, but generally lower than for respective dissolved forms and did not show consistent longitudinal patterns (Figs 2C and 2F).

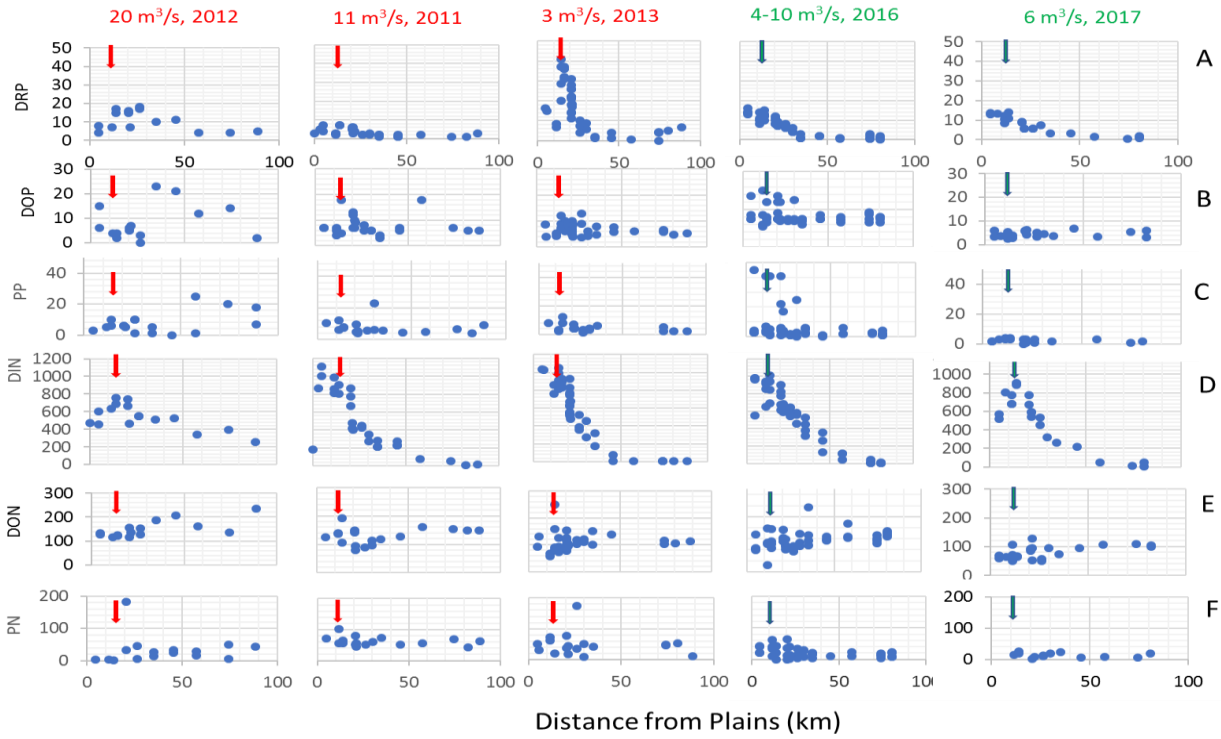

Figure 2: Longitudinal patterns in dissolved nutrients (mg/m^3) during summer (February) surveys 2001-2017 before and after sewage phosphorus load reduction in mid-2015. Arrows indicate STP input, with red and green arrows and labels indicating before and after STP upgrade for P removal

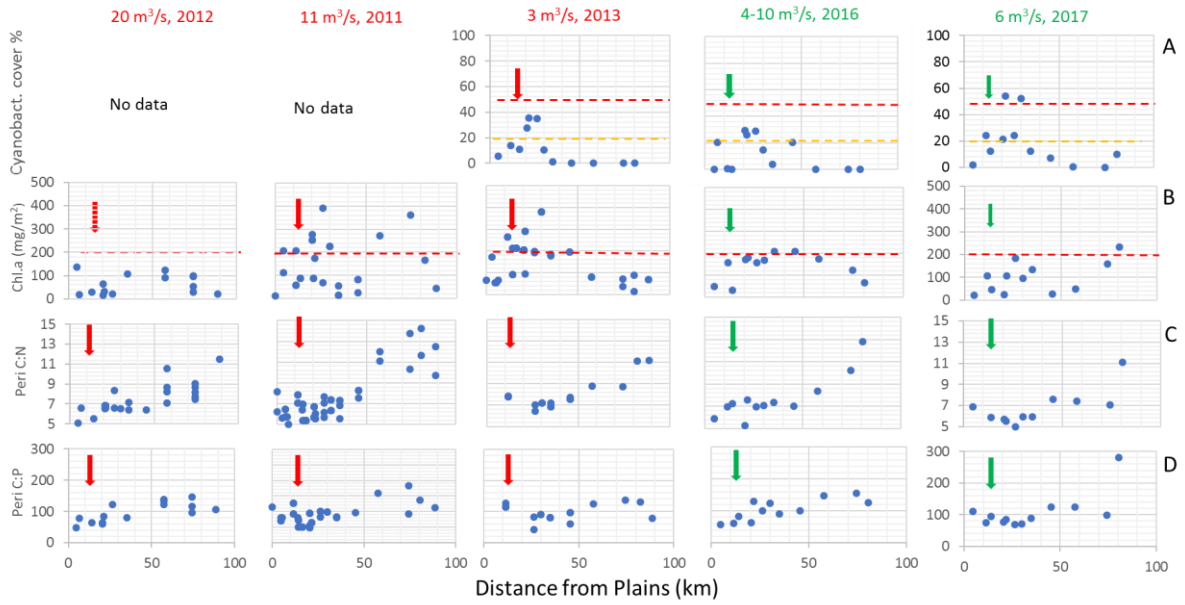

Figure 3: Longitudinal patterns in cyanobacterial mat cover and periphyton biomass, C:N and C:P mass ratio during summer along the Tukituki River before (red headers) and after (green) reduction in STP P load (arrows). MFE/MOH (2009) provisional amber and red alert levels for cyanobacterial mat cover and MFE (2014) maximum acceptable periphyton biomass are indicated by dashed lines

Cyanobacterial mat cover (Fig 3A) often exceeded the MFE/MOH (2009) interim Amber Alert Level (20%), and at 2 sites exceeded the Red Alert Level (50%) above which public notification of the potential risk to health is mandatory. DIN was greater than 300 mg m^{-3} (Fig. 2C) at the sites where cyanobacterial mat cover exceeded the amber alert (20% cover) level (Fig. 3A), indicating this may be an effective target to prevent development of "amber alert" cyanobacteria cover in this river. However, cyanobacteria mat cover and downstream extent were similar before and after the P input reduction, likely due to P scavenging and desorption from sediments entrapped within the mats (Dodds 2003; Wood et al. 2015). Abundant periphyton and high GPP were associated with afternoon pH values commonly between 9 and 10 from T3 to T14, at which P bound to sediment Calcium, Magnesium, Iron and Aluminium can be released under oxic conditions (Jensen and Andersen 1992), providing a sediment P source in addition to the STP and upstream surface water input sources.

Periphyton biomass (Chl. a; mean = 125 mg/m^2) was high relative to other New Zealand rivers during summer (mean 57 mg/m^2, data in Matheson et al. (2016)). Chl. a was least overall (mean 57 mg/m^2) during the cool, wet, summer of 2012, when flow was highest (Fig. 3B). In contrast, Chl. a was highest, during hot dry summers of 2011 and 2013 (means 171 and 159 mg/m^2) before the STP upgrade, when periphyton biomass sometimes exceeded the MFE (2014) maximum acceptable level (200 mg/m^2) near the STP input. Chl. a generally declined at downstream sites where DIN and DRP were depleted, particularly under very lowflow conditions in 2013 (Fig. 2A, D). Many previous studies have shown controlling effects of high flow and low nutrients on periphyton biomass (e.g., Biggs and Close 1989; Uehlinger et al. 1996). There was also some evidence of lower Chl. a near the STP discharge after the P control in 2016 and 2017 (Fig 3B). The increasing periphyton C:N and C:P with distance downstream also indicated nutrient deficiency (C:N >7.5 and C:P>119, respectively, (Hillebrand and Sommer 1999)) at the lower river sites (Fig. 3C, D) where dissolved nutrients were low relative to the upper river (i.e., DIN <400 and DRP <6 mg/m^3, Fig. 2D, A, respectively).

Sloughed periphyton also contributed to nutrient spiralling as downstream transport of particulate nutrients under both steady flow and increasing flow conditions. Under steady flows, there was 5-fold more periphyton caught in the afternoon in drift nets at the surface (mean 1.8 mg Chl. a/m^3) than mid-water column (Paired t-test, $P < 0.05$, 2016 and 2017 data when mean (95%CI) benthic chl. a was 120(42) mg/m^2), whereas surface and water column catches were similar during the morning. During the afternoon we observed the surface floating periphyton was buoyed up by gas bubbles indicating that photosynthesis within the periphyton mats contributed to periphyton sloughing. Endogenic periphyton sloughing, under steady flow conditions, has previously been attributed to self-shading in "mature" growths (Higgins et al. 2008). Nutrient/resource deficiency within mature mats has been associated with increased propensity to slough in response to increased current (Biggs et al. 1999). It is plausible that self-shading and resource limitation within periphyton facilitated

endogenic sloughing in the Tukituki, but our results indicate the lift force generated by gas bubble formation within periphyton mats and filaments during photosynthesis enhances endogenous sloughing markedly.

A relatively small increase in flow, from 5 to 10 m^3/s, increased the suspended periphyton caught in nets by 100-fold (to 15 mg Chl. a/m^3) between consecutive days at site T12 during the 2017 survey. The water column data were used to make conservative estimates of downstream transport of particulate N and P as 3.6 mg N/m^3 & 0.27 mg P/m^3 under normal flows and 180 mg N/m^3 & 13 mg P/m^3 during the small flow increase at T12 in 2017. Larger spates that scour the attached periphyton (e.g., Chl. a at T9 dropped from 135 mg/m^2 on 15/2/17 to 2 mg/m^2 on 1/3/17 following an 85 m^3/s spate on 20/2/17) also transport substantial quantities of particulate periphyton N and P downstream. Using the average (+ 95% CI) periphyton N and P densities for all surveys of 1.55 (0.45) g N/m^2 and 0.095 (0.014) g P/m^2, respectively, and the mean river width of 41 (2.5) m, depth of 0.49 (0.03) m over the 80 km study reach, we estimated that 5075 kg N and 313 kg P are stored in periphyton within the reach. If this periphyton was scoured and exported to the coast over a day, the N and P loads would be 20- and 28-fold higher than the daily average TN and TP loads under our survey conditions at T12 of 247 kg N and 11 kg P, calculated using the average flow during the surveys (9 m^3/s) and T12 average TN of 305 (135) mg/m^3 and TP of 14.9 (4.3) mg/m^3 for all surveys. This indicates a scouring spate would deliver a substantial pulse of N and P to the coast. The effects of spates on periphyton scour are well-known (e.g., Biggs and Close 1989; Peterson 1996; Uehlinger 1996; Biggs et al. 1999), but few studies have considered the effects on downstream nutrient transport.

3.2 Reach scale uptake of dissolved inorganic nutrients

Uptake rates of DIN and DRP declined downstream as nutrients were depleted (Fig. 4). Stepwise multiple regression modelling, using data from reaches within the upper 25 km where nutrients were relatively abundant, showed that reach scale areal uptake (*U*) of DIN could be largely explained by gross primary production (GPP, r^2 = 48%) and temperature (combined r^2 = 91%) whereas *U* DRP was best explained initial DRP concentration (r^2 = 50%) and respiration rate (combined r^2 = 65%). These findings indicate that periphyton metabolic activity is the main driver of nutrient attenuation in the Tukituki mainstem. *U* DIN (mainly NO_3-N) rates were in the upper range of *U* NO_3-N values at 72 North American rivers (most between 0.3 and 30 mg NO_3-N /m^2/h, (Hall et al. 2009)) and were high relative to 140 rivers reviewed by Ensign and Doyle (2006) (inter quartile range 0.3-4 mg NO_3-N /m^2/h). Our reach scale *U* DRP rates (Fig. 4) were intermediate relative to inter quartile range (0.3-2.1 mg DRP/m^2/h) of 172 rivers reviewed by Ensign and Doyle (2006). These medium-high rates support Wollheim et al.'s (2006) contention that high order rivers (though under-represented in nutrient uptake research) have considerable influence on dissolved nutrient export. The strong links we found between *U* DIN with DIN concentration and GPP are also consistent with findings of Hall et al. (2009) at sites across North America and Pueto Rico.

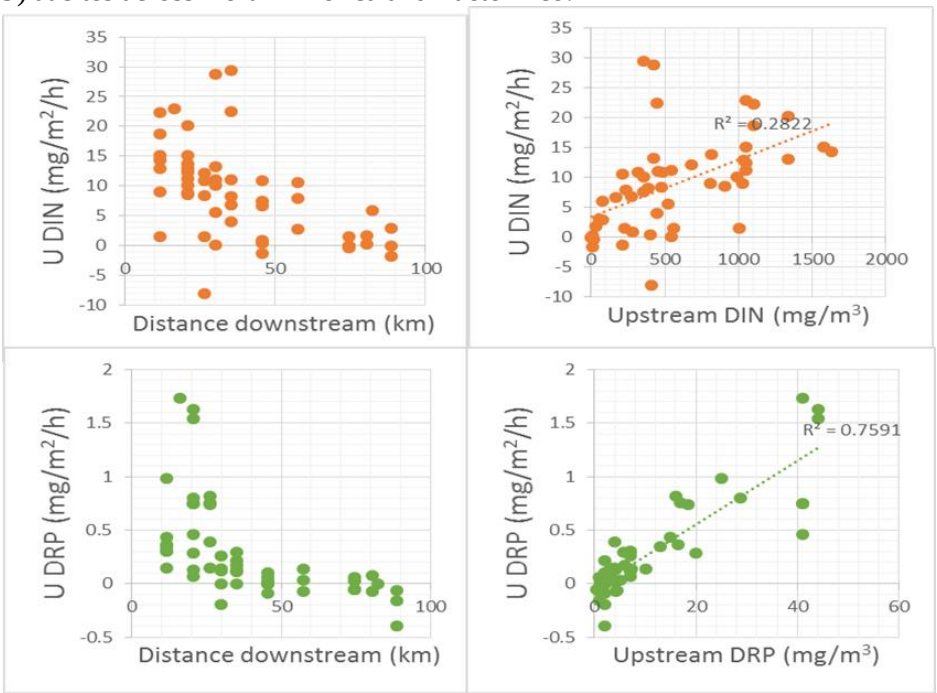

Figure 4 Reach scale areal uptake rates for DIN and DRP versus distance downstream and reach upstream nutrient concentration (2011-2013 data)

3.3 Chamber scale uptake of dissolved nutrients

Chamber experiments found that light influenced N uptake more than P uptake, consistent with the strong link between *U* DIN and GPP at reach scale (see above). N areal uptake rates (*U*) were significantly higher in light than dark for TDN and its components (NH_4-N, NO_3-N, DIN), except for DON (Fig. 5).
In contrast, uptake of TDP and DRP did not differ between paired light and dark chambers (Fig. 5). Release of DON and DOP made uptake of TDN and TDP lower than DIN and DRP, respectively. Drivers most strongly correlated with *U* DIN in the light were Net Production (r^2 = 0.59) > Gross Production > DRP (r^2 = 0.40) > Chl. a (r^2 = 0.30> light (r^2 = 0.22). A regression model for *U* DIN (r^2 = 60%) included initial DRP and Chl. a.
Together the reach scale and chamber uptake results confirm the importance of biological uptake by periphyton in riverine dissolved N and P dynamics (Dodds 2003; Ensign and Doyle 2006; Withers and Jarvie 2008; Tank et al. 2018). Our findings also emphasise the need to consider dissolved and organic nutrients in a holistic view of dissolved nutrient dynamics (Withers and Jarvie 2008) in rivers, including the role of sloughed periphyton.

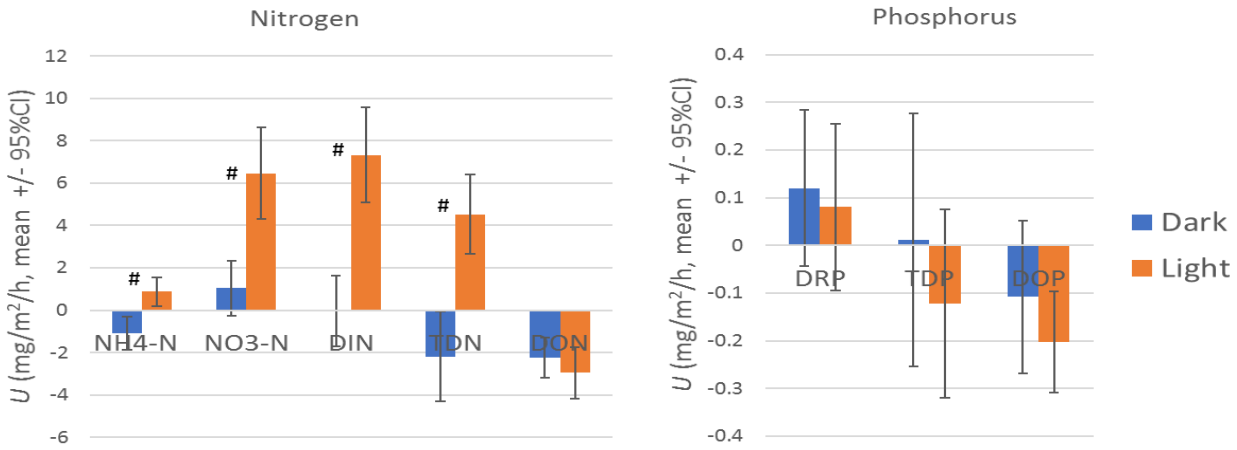

Figure 5: Comparison of dissolved N and P areal uptake rates in light and dark. # = paired t-test of light vs dark was statistically significant (P < 0.05, n = 19 light/dark paired observations)

4 CONCLUSIONS

Periphyton interacts strongly with nutrients along the Tukituki River, altering the quantity, form and timing of nutrient transport to downstream reaches and the coast, and causing N and P deficiency in periphyton at the lower half of our 80 km study reach. Some of the dissolved inorganic N and P taken up by periphyton is released and transported (spiralled) downstream as dissolved organic forms, that are less amenable to uptake by downstream periphyton than inorganic forms. Some is also spiralled as particulate nutrients in periphyton sloughed by "gas bubble lift" under steady flows, by current shear dislodging periphyton in small spates, and combinations of current shear, fine particle abrasion and bed movement during large spates/flood flows.
While nutrient attenuation is generally considered desirable, the periphyton growth that drives the nutrient attenuation in the Tukituki River also results in eutrophication symptoms when produces nuisance periphyton densities/types. During our summer surveys, periphyton nuisances sometimes occurred in the upper part of the Tukituki study reach, as amber or red "alert" levels of cyanobacterial cover where DIN was > ca.300 mg/m^3 and/or as nuisance levels of Chl. a. There was some evidence that >90% reduction in STP P input at the upper end of our study reach reduced the occurrence of nuisance Chl. a levels. However, cyanobacteria mat cover and downstream extent were similar before and after the P input reduction, likely due to P scavenging from sediments entrapped within the mats and release of P bound to riverbed sediments induced by high afternoon pH levels. This suggests periphyton management should consider control of sources of both sediment and water column nutrients.
Most studies of nutrient attenuation focus on the dissolved nutrients (NH, NO_3, DIN and DRP), but we showed that dissolved organic and particulate forms of N and P contribute significantly to downstream nutrient transport in the Tukituki River during summer. We conclude that there is a need for more focus in riverine nutrient attenuation studies/modelling on the dissolved and particulate organic forms, and the role of periphyton transport downstream during high flow events, to provide a holistic view of river nutrient attenuation and transformations.

ACKNOWLEDGEMENTS

This research was funded by MBIE Programme CO1X1005 and NIWA Strategic Science Investment Fund Eutrophication Risk Project. Thanks to Karl Safi and Helen Brider (NIWA) for periphyton identifications, NIWA Chemistry Laboratory for analyses and Mike English, Aslan Wright-Stow, Brian Smith, Elizabeth Graham, Geoff Holland and Peter Arnold for field assistance. The paper was improved by comments of an anonymous reviewer.

REFERENCES

Berezina N.A., Golubkova S.M. (2008). Effect of drifting macroalgae Cladophora glomerata on benthic community dynamics in the easternmost Baltic Sea. *Journal of Marine Systems* **74**: S80-S85.

Biggs, B.J.F. and Close, M.E. (1989). Periphyton biomass dynamics in gravel bed rivers: the relative effects of flows and nutrients. *Freshwater Biology*, 22: 209-223.

Biggs, B.J.F., Tuchman, N.C., Lowe, R.L. and Stevenson, R.J. (1999). Resource stress alters hydrological disturbance effects in a stream periphyton community. *Oikos*, **85**(1): 95-108.

Chapra, S.C., Flyle, K.F. and Rutherford, J.C. (2014). Parsimonious model for assessing periphyton dominated streams. *Journal of Environmental Engineering*, **140**(6): 04014014.

Dall, P.C. (1979). A sampling technique for littoral stone-dwelling organisms. *Oikos*, **33**: 106-112.

Dodds, W.K. (2003). The role pf periphyton in phosphorus retention in shallow freshwater aquatic systems. *Journal of Phycology*, **39**: 840-849.

Ensign, S.H. and Doyle, M.W. (2006). Nutrient spiraling in streams and river networks. *Journal of Geophysical Research-Biogeosciences*, **111**(G4): 4009-4009.

Hall, R.O., Tank, J., Sobota, D., Mulholland, P.J., O'Brien, J., Dodds, W., … Arango, C.P. (2009). Nitrate removal in stream ecosystems measured by 15N addition experiments: Total uptake. *Limnology and Oceanography*, **54**: 653-665.

Hickey, C.W. (1988). Benthic chamber for use in rivers: testing against oxygen mass balances. *Journal of Environmental Engineering ASCE*, **114**:: 828-845.

Higgins, S.N., Hecky, R.E. and Guildford, S.J. (2008). The collapse of benthic macroalgal blooms in response to self-shading. *Freshwater Biology*, **53**: 2557-2572.

Hillebrand, H. and Sommer, U. (1999). The nutrient stoichiometry of benthic microalgal growth: Redfield proportions are optimal. *Limnology and Oceanography*, **44** (2): 440-446.

Jensen, H.J. and Andersen, F.O. (1992). Importance of temperature, nitrate, and pH for phosphate release from aerobic sediments of four shallow, eutrophic lakes. *Limnology and Oceanography*, **32**: 577-589.

Johnson, K. (2011). *Tukituki catchment instream flow assessments*, HBRC Plan Number 4248: 59.

Matheson, F., Quinn, J. and Unwin, M. (2016). *Instream plant and nutrient guidelines: Review and development of an extended decision-making framework - Phase 3*. NIWA Client Report HAM2015-064 117. http://www.envirolink.govt.nz/assets/Envirolink/R9-3-Instream-plant-and-nutrient-guidelines-Phase-3-report.pdf

MFE (2014). *National Policy Statement for Freshwater Management 2014*: 34 p. http://www.mfe.govt.nz/publications/rma/nps-freshwater-management-2014/index.html

MFE/MOH (2009). *New Zealand guidelines for cyanobacteria in recreational fresh waters - Interim guidelines*, Prepared for the Ministry for the Environment and the Ministry of Health, http://www.mfe.govt.nz/publications/water/guidelines-for-cyanobacteria/nz-guidelines-cyanobacteria-recreational-fresh-waters.pdf

Newbold J.D., O'Neill R.V., Elwood J.W. and Van Winkle W. (1982). Nutrient spiralling in streams: Implications for nutrient limitation and invertebrate activity. *The American Naturalist.* **120:** 628-652.

Peterson, B.J., Wollheim, W.M., Mulholland, P.J., Webster, J.R., Meyer, J.L., Tank, J.L., … Morrall, D.D. (2001). Control of nitrogen export from watersheds by headwater streams. *Science*, **292**(5514): 86-90.

Peterson, C.G. (1996). Response of benthic algal communities to natural physical disturbance. In: R.J. Stevenson, M.L. Bothwell & R.L. Lowe (Eds). *Algal ecology: freshwater benthic ecosystems* (pp. 229-252). Academic Press,San Diego, California.

Rutherford, J.C. (2011). *Computer modelling of nutrient dynamics and periphyton biomass – model development, calibration and testing in the Tukituki River*, Hawkes Bay, NIWA Client Report HAM2011-134: 46.

Snelder, T.H., Booker, D.J., Quinn, J.M. and Kilroy, C. (2014). Predicting periphyton cover frequency across New Zealand's rivers. *Journal of the American Water Resources Association*, **50**(1): 111-127. DOI: 10.1111/jawr.12120

Tank, J.L., Marti, E., Riis, T., Von Schiller, D., Reisinger, A.J., Dodds, …Webster, J.R. (2018). Partitioning assimilatory nitrogen uptake in streams: an analysis of stable isotope tracer additions across continents. *Ecological Monographs*, **88**: 120-138.

Uehlinger, U., Buhrer, H. and Reichert, P. (1996). Periphyton dynamics in a floodprone prealpine river: Evaluation of significant processes by modelling. *Freshwater Biology*, **36**(2): 249-263.

Withers, P.J.A., Jarvie, H.P. (2008). Delivery and cycling of phosphorus in rivers: A review. *Science for the Total Environment*, **400**: 379 - 395. doi:10.1016/j.scitotenv.2008.08.002

Wollheim, W.M., Voosmarty, C.J., Peterson, B.J., Seitzinger, S.P., Hopkinson, C.S. (2006). Relationship between river size and nutrient removal - art. no. L06410. *Geophysical Research Letters*, **33**(6): 6410-6410.

Wood, S., Depree, C., Brown, L., McAllister, T., Hawes, I. (2015). Entrapped sediments as a source of phosphorus in epilithic cyanobacterial proliferations in low nutrient rivers. *PLoS ONE*, **10**(10): e0141063. doi:10.1371/journal.pone.0141063

Young, R.G., Huryn, A.D. (1996). Interannual variation in discharge controls ecosystem metabolism along a grassland river continuum. *Canadian Journal of Fisheries and Aquatic Sciences*, **53**(10): 2199-2211.