Sustain. Water Resour. Manag.
DOI 10.1007/s40899-017-0187-3

ORIGINAL ARTICLE

Ok Tedi copper mine, Papua New Guinea, stimulates algal growth in the Fly River

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Received: 21 March 2017 / Accepted: 23 August 2017

Abstract Fish populations utilised by riparian populations along the Fly River, Papua New Guinea (PNG), downstream of the Ok Tedi gold and copper mine have markedly declined in species richness (between 21 and 90%) and biomass (between 57 and 87%) during the operation of the mine (Storey et al., The Fly River Papua New Guinea. Environmental studies in an impacted tropical river system. Developments in Earth and Environmental Sciences, vol 9. Elsevier, Amsterdam, pp 427–462, 2009). A concern was that copper in wastes from the mine were negatively impacting algae in the river, thus altering the food web supporting the fish populations. This investigation found that the mining discharge to the Fly River increased, rather than decreased algal biomass in the Fly River, and did not appear to impact algae in associated off-river water bodies. It appears that nitrogenous explosives used in the mine have a fertilizing impact on the Fly River. There was no apparent impact of mine discharges on phytoplankton in the floodplain off-river water bodies, which was often concentrated in a prominent sub-surface maximum, and was not the main source of riverine plankton.

Keywords Fly River · Papua New Guinea · Ok Tedi mine · Floodplain · Phytoplankton · Copper · Nitrogen

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Introduction

The social, economic and environmental impacts of mines in developing countries, where they are often operated by multinational companies, are controversial (Slack 2009; Vidal 2015). The Ok Tedi mine, a large copper and gold mine located in the Star Mountains in Papua New Guinea close to the border with the province of West Papua in Indonesia, has been a focus of international attention as a result of the large scale of the environmental impact, and the resulting international court cases (Barker 1995; Hettler et al. 1997; Townsend and Townsend 2004; Campbell 2011). Impacts include extensive sediment deposition in the Ok Tedi, the Fly River, and on the flood plain (Markham and Day 1994), altered inundation patterns leading to the die off of at about 350 km^2 of floodplain rainforest (Campbell 2011) and a major decline in the species richness and biomass of fish along the river, by 21–90 and 57–87% respectively (Storey et al. 2009). These environmental changes may have serious consequences for people living on the floodplain, many of whom rely on wild resources for a significant part of their diet or livelihood (Bentley 2007).

One notable component of the environmental impact of mining for metal ores is the contamination of waterways by toxic metals and/or acid mine drainage (Down and Stocks 1977; Morin and Hutt 1997). At Ok Tedi waste rock from the mine and, until relatively recently, the tailings arising from concentrating the ore have been dumped into creeks draining into the Ok Tedi, a river which in turn drains into the Fly River and thence to the Gulf of Papua (Bolton et al. 2009). The ore is rich in sulphide minerals which are potentially acid forming (Morin and Hutt 1997) and can trigger the release of toxic-dissolved metals under aerobic conditions.

Published online: 31 August 2017

A possible factor contributing to the decline in fish biomass and diversity downstream of the mine is that copper released from the waste rock is reducing algal biomass in the river, thereby altering the food web which ultimately supports the fish. Copper is a metal known to be toxic to aquatic life (Nor 1987; ANZECC 2000). A number of algal species are known to be particularly sensitive to copper toxicity (e.g. Nor 1987; Stauber 1995; ANZECC 2000) and copper sulphate has been widely used as a treatment for algal blooms in lakes and ponds (e.g. Illinois State Water Survey 1989). Consequently, it is not surprising that investigations of the impacts of effluents from copper mines have often focussed on the impacts on algae and aquatic plants (e.g. Yasuno and Fukushima 1987; Correa et al. 2000; Ferreira and Graça 2002).

Concern that algae in the river may be negatively impacted as a result of copper leaching from the tailings and waste rock deposited in the river was initially articulated by the Peer Review Group (PRG 2000) established by Ok Tedi mining. Results from toxicity testing and copper chemical speciation investigations conducted for the company were interpreted as demonstrating inhibition of algal growth in the river was likely (Stauber et al. 2009). Investigations of food webs were also undertaken (Bunn et al. 1999; Storey and Yarrao 2009).

The investigation reported here was undertaken to test the hypothesis that mine effluents were reducing algal biomass in the river and associated off-river flood plain water bodies. It was proposed to assess algal biomass through fluorimetric measurements of chlorophyll at a number of sites upstream and downstream of the junction of the Ok Tedi and the Fly Rivers in the expectation that chlorophyll concentrations would be lower below the junction.

Methods

On four occasions, between June 2007 and February 2008, we measured chlorophyll at multiple sites in the Fly River system in Papua New Guinea to assess directly whether algal standing crop was being negatively impacted by the mine discharges. On three of those occasions we sampled both the Fly and Strickland Rivers, as well as a number of off river water bodies (ORWBs) located on the Fly River flood plain because these form an important component of the Fly River aquatic ecosystem.

The climate in the area is classified as tropical rainforest (Af) under the Köppen–Geiger climate classification system (Peel et al. 2007). This means that, over the course of a year, there is little seasonal variation in climate. Day length varies little, with Tabubil, the largest town, only 5° south of the equator. Temperature is also stable, the coldest month is July with a mean monthly temperature of 23.6, and the hottest is November with 25.0 °C. The highest average monthly rainfall occurs in June (572 mm) and the lowest in November (371 mm) (climate.org 2017). Consequently, there is little necessity for a sampling program to encompass a full year, and the four sampling periods encompassed the climatic extremes, such as they are.

Four sites on the Fly River and one on the Strickland (Fig. 1) were sampled in June/July and October/November 2007 and again in January 2008. Two sites on the Fly River were sampled again in February 2008. The sites on the Fly were located upstream and downstream of the junction with the Ok Tedi and upstream and downstream of the junction with the Strickland (Everill Junction). Sites were selected to assess the possible impacts of the inflows of the Ok Tedi and Strickland on algal assemblages, as indicated by chlorophyll concentrations measured fluorometrically, in the Fly River.

Field measurements of chlorophyll were taken with a BBE Fluoroprobe (2007 model). At each site, measurements were taken at five sites across the river on each of three transects located about 100 m apart giving a total of 15 measurement locations at each site. Across each transect the sites were located with one about 10 m from each bank of the river, one at the midpoint and one each between the midpoint and the bank sample. At each site the probe was lowered to the river bottom and then raised slowly, with a measurement being taken approximately each 10 s. The number of measurements collected at any sampling point on any occasion varied with the depth of the river, but was generally between 10 and 20, giving about 300 measurements per site on each sampling occasion (Table 1). In addition to the three complete sampling exercises, a further set of river samples was collected above and below the Ok Tedi junction in February 2008. On that occasion only one transect with 71 measurements were collected at the Kiunga site but a full three transects with 223 measurements were collected at Nukumba.

The fluoroprobe uses 6 LED light sources to stimulate fluorescence of chlorophyll pigments in the algal cells. As each measurement is taken the probe records water temperature, the depth of the measurement (via a pressure transducer) and the fluorescence resulting from pulses at six wavelengths. The software in the instrument uses the fluorescence data to calculate the contribution of various pigments and this is processed to provide an estimate of the amounts of four algal groups: brown algae (diatoms), green algae, cyanobacteria and Cryptophyta. In addition, an estimate of total chlorophyll is calculated by summing the results for the four algal groups.

The fluoroprobe was checked against "calibration" samples on three sampling exercises. A water sample was collected, placed in a pvc pipe and the chlorophyll

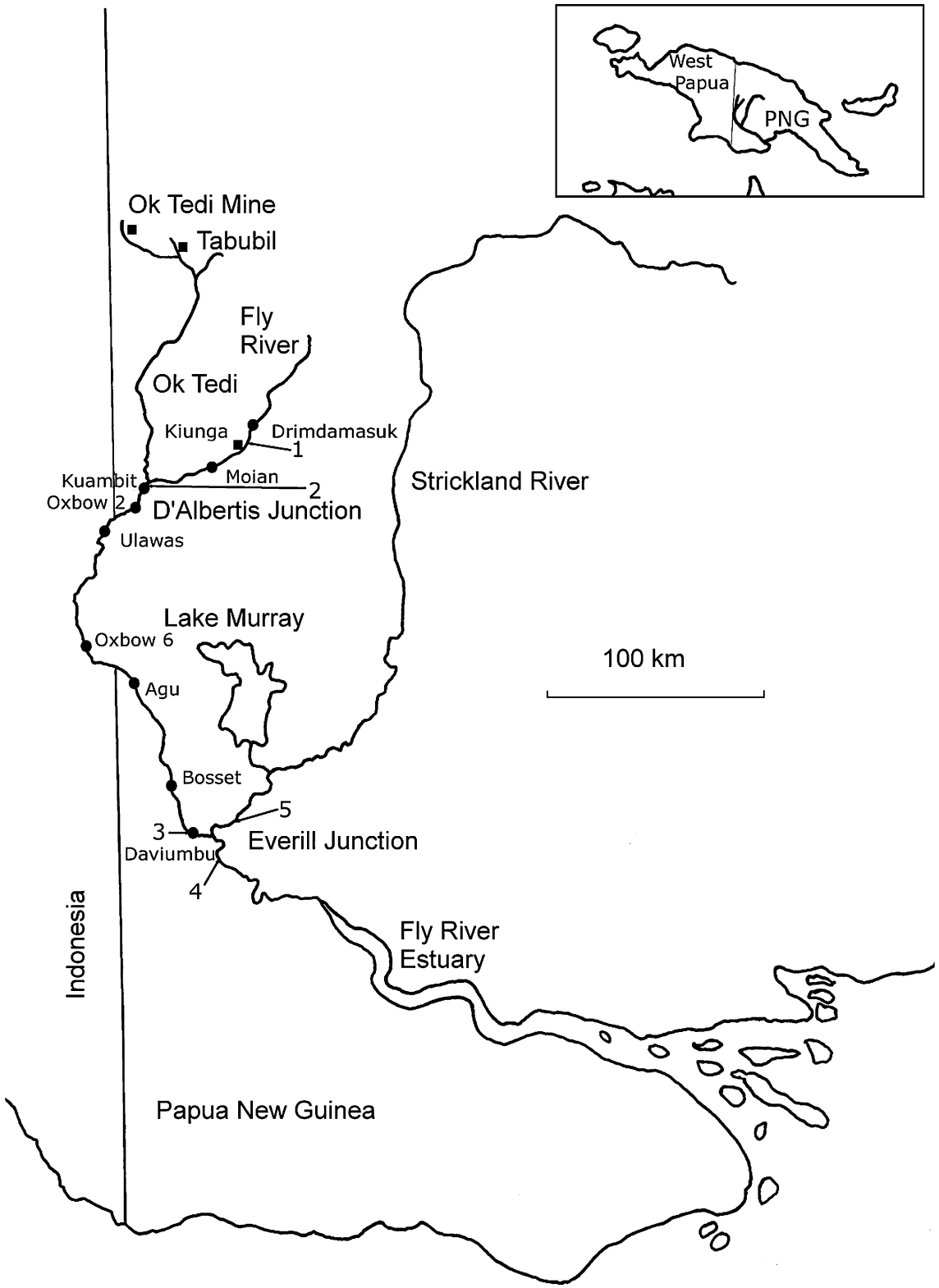

Fig. 1 Map indicating riverine sampling locations (*1* Kiunga, *2* Nukumba, *3* Obo, *4* D/S Everill, *5* Strickland) and locations of the sampled ORWBs

Table 1 Average pigment concentrations for four algal groups and yellow substance, and percentage light transmission at various river sites on the four sampling occasions

Site	*n*	Chlorophyta (μg/L)	Cyanobacteria (μg/L)	Diatoms (μg/L)	Cryptophyta (μg/L)	Gelbstoff (μg/L)	Transmission (%)
June							
Kiunga	248	0.053	0.262	0.202	0.039	0.444	83
Nukumba	359	0.435	0.918	0.170	0.004	0.378	58
Obo	350	0.406	0.891	0.193	0.031	0.542	64
Lower Fly	438	0.482	1.866	0.471	0.011	0.361	40
Strickland	671	0.504	3.297	0.739	0.053	0.327	27
October							
Kiunga	480	0.110	1.167	0.632	0.043	0.512	48
Nukumba	362	0.286	1.355	0.199	0.008	0.348	43
Obo	311	0.517	1.881	0.050	0.014	0.274	34
Lower Fly	336	0.621	4.909	0.002	0	0.003	3.4
Strickland	313	0.162	5.703	0	0	5.866	0.3
January							
Kiunga	344	0.186	0.432	0.172	0.030	0.467	80
Nukumba	279	0.195	4.100	0	0	0.021	6.0
Obo	283	0.792	0.945	1.080	0.034	1.952	67
Lower Fly	287	0.702	1.456	0.336	0.002	0.463	48
Strickland	238	0.751	2.327	0.377	0.009	0.284	27
February							
Kiunga	71	0.062	1.327	0.895	0.009	0.641	50
Nukumba	224	0.418	2.293	0.193	0	0.208	26
Agu	111	0.467	3.526	0.022	0	0.062	12
Obo	241	0.340	1.719	0.004	0.002	0.224	38

measured with the fluoroprobe. The water sample was then subsampled with the subsample stored chilled in the dark until it could be returned to the laboratory for standard spectrophotometric analysis by the trichromatic method following extraction (Eaton et al. 1995).

Field fluorimetric methods have been used several times previously to assess both the "spectral groups" of microalgae (Beutler et al. 2002) and phytoplankton biomass in both rivers (e.g. Twiss et al. 2010) and lakes (Leboulanger et al. 2002). Submersible fluorometric probes have been found to be a sensitive tool with results correlating well with standard ISO methods for assessing chlorophyll concentrations (Gregor and Marsalek 2004). They have the advantage of allowing large numbers of measurements to be taken more rapidly than water samples could be collected, and allowing field measurement regimes to be adapted when interesting results become apparent.

No fluoroprobe data were collected from the Ok Tedi upstream of the junction with the Fly River, because there was insufficient light transmission through the instrument at that location to obtain a reading, presumably because of the high levels of suspended particulate material. Samples were collected on several occasions for conventional chlorophyll extraction, but no chlorophyll was detected on any occasion.

Univariate data was analysed using the SYSTAT version 11 statistical package. The total chlorophyll data from the site upstream (Kiunga) and the site immediately downstream of the Ok Tedi junction (Nukumba) were compared using the non-parametric two sample Kruskal–Wallis test because the data were not normally distributed, even after square root or log transformations. Multivariate data was analysed using the Primer 6 package. Data on the chlorophyll levels attributable to four algal groups and gelbstoff were treated as estimates of biomass and log $(x + 1)$ transformed. Resemblance was calculated based on Euclidean distance and plotted using non-metric multi-dimensional scaling (NMDS). Difference between the algal assemblages in the ORWBs and the riverine samples, and between upstream and downstream assemblages were tested statistically using analysis of similarity (ANOSIM).

Results

River

On two of the three whole river sampling occasions, and on the February sampling, the chlorophyll concentrations downstream of the Ok Tedi–Fly River junction were between 2.5 and 5.5 times the concentration upstream, and statistically significantly different in each case (Kruskal–Wallis test, $p < 1 \times 10^{-5}$) (Fig. 2a–d), whilst on the other occasion the concentration downstream was about 5% lower than upstream, and also statistically significant ($p < 1 \times 10^{-5}$). So we conclude that on three of the four sampling occasions the discharge from the Ok Tedi stimulated algal growth. The stimulation occurred even though the turbidity of the river, as indicated by the drop in light transmission, increased substantially between Kiunga and Nukumba (Table 1). Light transmission was significantly higher at the upstream than the downstream site on each of the four occasions (Kruskal–Wallis test, $p < 10^{-5}$).

Between Nukumba and Obo the chlorophyll concentrations remained constant in June and increased in October and January (Fig. 2a–d). The concentrations of chlorophyll in the Strickland River always exceeded those in the Fly, and the concentrations in the Fly below Everill Junction always exceeded those upstream at Obo. In all cases, the differences were significant ($p < 0.001$).

Based on pigment concentrations, cyanobacteria algae (Cyanobacteria) were the most abundant photosynthetic plankton group in all riverine transects (Table 1). Diatoms were the next most abundant in all transects at Kiunga in June, October and February (but not January) and in the Strickland in June. In all other transects, except for one of three at Kiunga in January, the green algae (Chlorophyta) were next most abundant after the cyanobacteria. Cryptophyta were usually only present in relatively low abundance.

Between Kiunga and Nukumba, upstream and downstream of the Ok Tedi junction, the abundance of diatoms and cryptophytes declined on every occasion (Table 2)

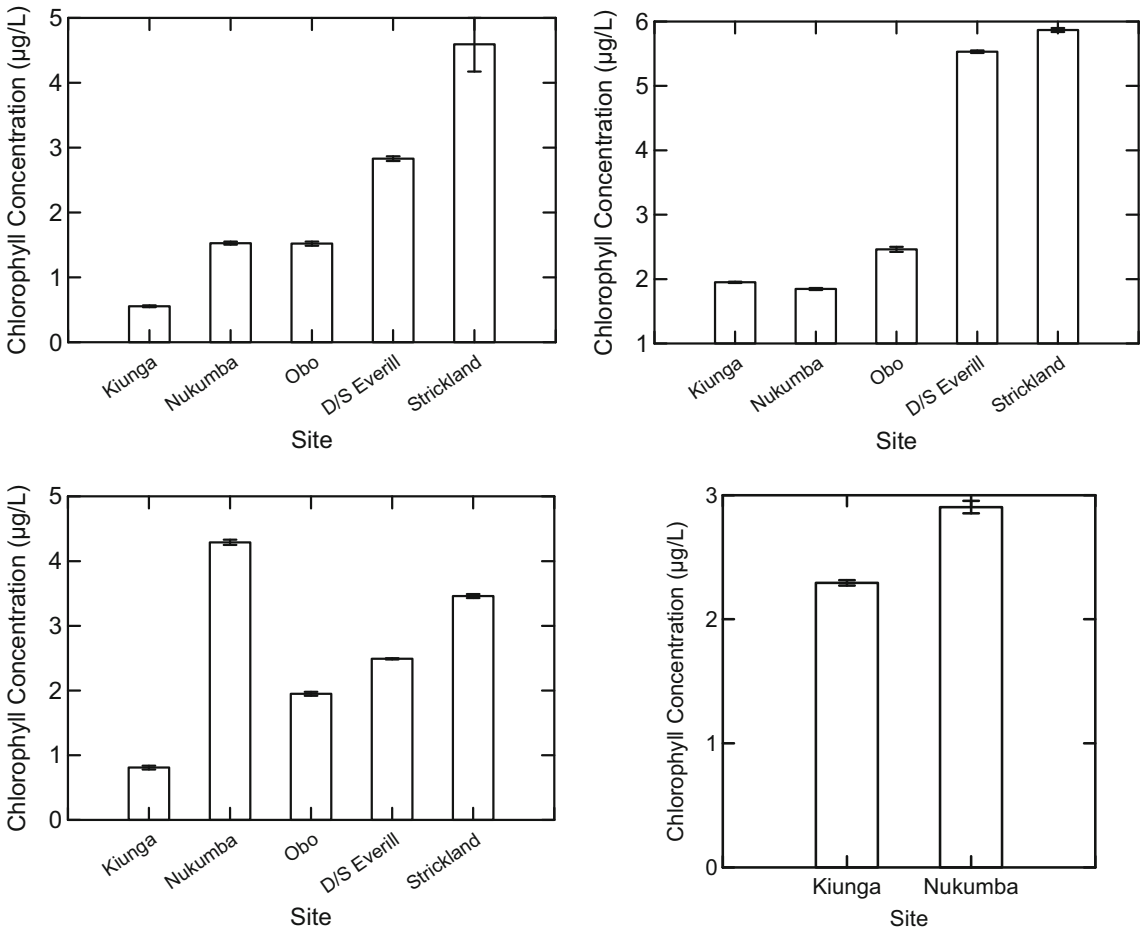

Fig. 2 **a** (*top left*) Total chlorophyll concentrations (mean and standard error) at four sites along the Fly River, and the Strickland River in June and July 2007; **b** (*top right*) same in October and November 2007; **c** (*bottom left*) same in January 2008, **d** (*bottom right*) same for Kiunga and Nukumba in February 2008

Table 2 Percentage change in the four algal groups and gelbstoff between the Kiunga site upstream of the Ok Tedi junction and the Nukumba site downstream on the four sampling occasions

	Chlorophyta	Cyanobacteria	Diatoms	Cryptophyta	Gelbstoff
June	+720	+250	−16	−90	−15
October	+160	+16	−68	−81	−5
January	+5	+850	−100	−100	−95
February	+222	+123	−69	−100	−65

All percentages expressed as percentages of the Kiunga value

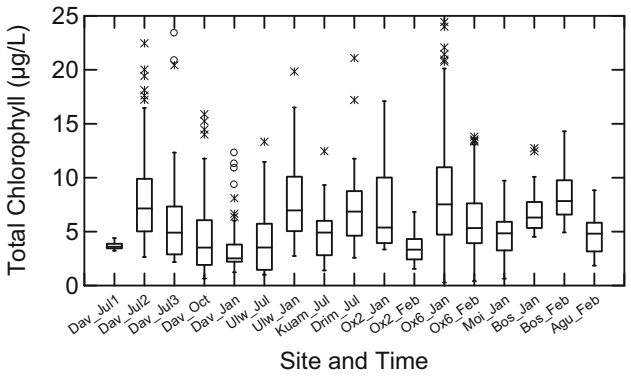

Fig. 3 Box and whisker plots of chlorophyll concentrations in nine Off-river water bodies in the floodplain of the Fly River between July 2007 and February 2008. The *horizontal line* indicates the median value, the *box* indicates the 25th and 75th percentile values and the *whiskers* indicate the values lying within an additional 1.5 times the difference between the 25th and 75th percentile values. Values outside this range are indicated by *asterisks* and *circles*

while the abundance of greens and cyanobacteria increased. On three of the four occasions the relative increase in the greens was substantially larger than that in the cyanobacteria, the exception being January. Note that, in October, when there was a slight decrease in total chlorophyll between Kiunga and Nukumba (Fig. 2b), the decrease resulted from a major decline in the diatom abundance, while green and cyanobacteria algae both increased in abundance.

An analysis of variance of the total ORWB chlorophyll measurements (summarized in Fig. 3) by sampling trip, water body, location of the water body in relation to the Fly River junction, and site within the water body, indicated significant differences within all categories ($p < 0.001$ in each case) with the exception of location in relation to the Fly River junction which was not a significant factor ($p = 0.96$). The statistical analysis gave the same outcomes with raw data and log transformed and square root transformed data. An NMDS showed no obvious separation between the ORWBs upstream and those downstream of the Ok Tedi junction, and ANOSIM found no significant difference ($p = 0.9$).

The relative abundances of the major algal groups were variable between water bodies and within a single water body over time (Table 3). For example in Daviumbu over five sampling occasions we recorded diatoms and green algae as most abundant on two occasions each and cyanobacteria as most abundant on the fifth (Table 3). However, these three algal groups were all present and fairly abundant in each water body on each occasion, with green algae most abundant on 9 of 17 occasions, diatoms on 6 and cyanobacteria on two. These relative abundances differed markedly from those in the river transects where cyanobacteria were always the most abundant. An NMDS analysis separated the ORWB algal assemblages from those of the river (Fig. 4) and an ANOSIM found that they were significantly different ($p = 0.001$, $R = 0.664$).

The vertical distribution of chlorophyll within an ORWB was not necessarily even. In the shallower water bodies: Moian, Bossett, Drimdamasuk and Daviumbu (e.g. Fig. 5a, b) there was generally an even vertical distribution of chlorophyll, or a higher concentration near the surface. However, in the deeper water bodies: Oxbow 2, Oxbow 6, Agu wetlands, Kuambit and Ulawas there was an obvious sub-surface maximum in chlorophyll at some depth (e.g. Fig. 5c, d). The algal sub-surface maximum did not coincide with a thermocline, as is evident in the figures.

Discussion

Methods

Fluorometric techniques have been used as standard laboratory methods for the assessment of phytoplankton pigments for many years (e.g. see Eaton et al. 1995; Strickland and Parsons 1968), and had also been identified as a method for in situ assessments (e.g. Strickland 1968). However, the development of multi-wavelength LED based field instruments is relatively recent. These instruments are extremely powerful tools for aquatic ecologists because they allow large numbers of measurements to be collected quickly and cheaply. Use of an effective and rapid field method has enabled us to take a large number of measurements. That has allowed us to compare results from different sites with a high level of statistical power, and also to measure the spatial distribution of pigments in water bodies with a high level of resolution.

Table 3 The average pigment concentrations (μg/L) of major algal groups in ORWBs

ORWB	Date	Chlorophyta	Cyanobacteria	Diatoms	Cryptophyta	Gelbstoff
Daviumbu	3/07/2007	1.87	1.50	1.99	1.07	1.52
Daviumbu	3/10/2007	1.29	1.30	1.28	0.34	1.32
Daviumbu	2/07/2007	2.63	1.46	3.04	1.21	1.69
Daviumbu	1/07/2007	1.77	0.71	0.94	0.26	1.68
Daviumbu	27/01/2008	1.05	0.94	0.77	0.58	1.59
Ulawas	5/07/2007	1.45	0.69	0.93	0.92	0.81
Ulawas	30/01/2008	1.08	2.37	3.38	0.82	0.61
Kuambit	6/07/2007	2.49	1.19	0.52	0.49	0.46
Drimdamasuk	7/07/2007	2.17	1.35	1.49	1.77	0.62
Oxbow 2	28/01/2008	3.45	2.58	1.13	0.28	1.22
Oxbow 2	28/02/2008	1.09	1.10	1.12	0.22	0.39
Oxbow 6	28/01/2008	1.80	2.40	4.16	0.60	1.37
Oxbow 6	27/02/2008	0.71	1.61	3.00	0.82	0.45
Moian	29/01/2008	2.05	1.32	0.88	0.39	0.71
Bossett	27/01/2008	3.84	1.27	1.42	0.15	0.77
Bossett	25/02/2008	4.19	2.58	1.37	0.27	0.67
Agu	26/02/2008	1.83	2.07	0.49	0.24	0.37

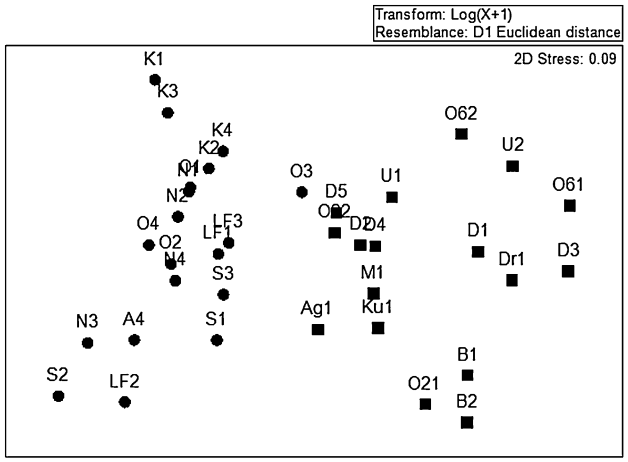

Fig. 4 An NMDS plot of the algal component results for samples from ORWBs (*square symbols*) and the river (*circles*) over the course of the study, showing the separation between the two sets of samples

Impact of Ok Tedi mine on riverine phytoplankton

On three of the four sampling occasions the inflow from the Ok Tedi, which carries the runoff and dumped rock material from the Ok Tedi mine, clearly stimulated rather than depressed chlorophyll concentrations in the Fly River. On the fourth, in October, although the concentration in the river downstream was 5% lower than upstream, because the Ok Tedi contributes approximately 40% of the river flow at Nukumba (EGI 2005), and appears to contribute no chlorophyll, for the concentration of chlorophyll at Nukumba to remain at 95% of the upstream concentration implies more than a 30% increase of the chlorophyll load between the two sites. Based on these data, we conclude that the effect of the discharge of the Ok Tedi, containing the mine wastes, is to stimulate rather than to inhibit overall algal growth in the river.

The stimulation is likely to be caused by elevated nitrogen concentrations. These rivers are poor in nutrients because of their high flows, short longitudinal extent and because they largely flow through only lightly disturbed, vegetated, catchments. OTML do not monitor nutrients but Meybeck (1982) cites a nitrate nitrogen concentration of 40 μg/L for the Purari River, and the average of the five measurements given by Mitchell et al. (1980) for the concentration of inorganic nitrogen in the Sepik River is 255 μg/L with lower concentrations in ORWBs. ANZECC (2000) identify a trigger level of 10 μg/L for nitrate nitrogen in tropical lowland rivers in northern Australia. So we expect nitrogen levels to be naturally low.

The likely source is the ammonium nitrate used for blasting in the mine leaching into the river. The mine uses about 30 tonnes of ammonium nitrate each day (Wilson and Murray 1997) or 10,000 tonnes a year. Ammonium nitrate explosive is water soluble and the failure rate is high in wet environments such as that at Ok Tedi. Forsyth et al. (1995) suggest that losses of ammonium nitrate and fuel oil explosive (ANFO) amount to between 5 and 15% during the loading of the blasting holes, with 10–20% of blast holes misfiring. That suggests that at least 1500 tonnes and probably in excess of 3000 tonnes of ammonium nitrate are being released from the pit each year and potentially entering the river. That would be sufficient to raise the concentration of nitrogen in the water by about 50 μg/L assuming continuous median flows, which would be

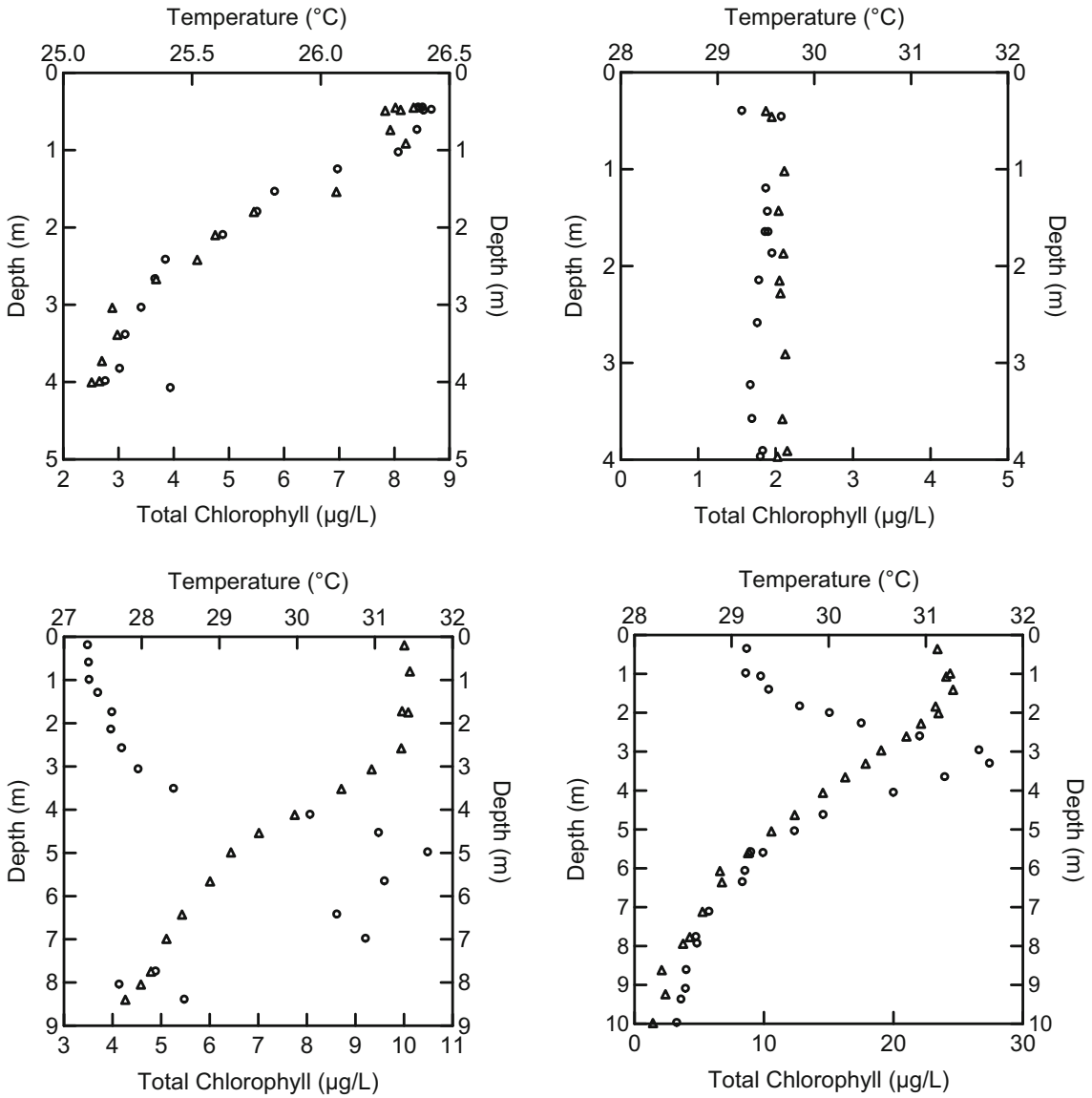

Fig. 5 **a** Chlorophyll (*circles*) and temperature (*triangles*) plotted against water depth measured at **a** one site in Lake Daviumbu in October 2007 (*top left*), **b** one site in Lake Daviumbu in October 2007 (*top right*), **c** one site in Oxbow 2 in January 2008 (*bottom left*)and **d** one site in Oxbow 6 in January 2008 (*bottom right*)

sufficient to stimulate algal growth in systems which are naturally nutrient poor.

Comparison with previous studies

Although reviews on the environmental impact of the mining of metals have often focussed attention on the impacts on rivers and waterways (e.g. Down and Stocks 1977; Dudka and Adriano 1995; Salomons 1995), and although occasional early papers identified contamination from explosives as an issue (Forsyth et al. 1995), most investigations have focussed almost entirely on metal toxicity or acid mine drainage as sources of environmental impacts (e.g. Hudson-Edwards et al. 2008; Galán et al. 2003; Ramirez et al. 2005; Tarras-Wahlberg et al. 2001). However, several recent studies from Finland have focussed on nitrogen contaminants from explosives (e.g. Jermakka et al. 2015; Karlsson and Kauppila 2015). Sadly, even in environments where the streams are naturally nutrient depauperate, which would be expected a priori to be particularly sensitive to nutrient contamination, as is the case in tropical Australia, the impact of nitrogen resulting from use of explosives does not appear as a consideration in environmental impact assessments of mining projects (e.g. DERM 2011).

Previous studies by Stauber et al. (2009) and Storey (WRM 2005, 2006) have argued that the discharge from the Ok Tedi has a negative impact on algae in the Fly

River. However, none of the previous studies directly assessed algae in the river. The algal toxicity studies conducted by Stauber et al. (2009) were conducted in a laboratory in Australia. In the tests conducted after 2004, the controls were either synthetic river water or Fly River water treated with the chelating agent EDTA to remove the copper. There was no clear relationship between either dissolved or ASV labile copper concentrations and algal growth inhibition in those tests (Stauber et al. 2009). Hart et al. (2005) felt that the toxicity tests were unlikely to be able to identify anything but very major changes in copper concentrations and possible acute toxic effects. We are not convinced that the growth inhibition detected was related to copper concentrations.

The initial stable isotope food web study by WRM (2005) was intended to test a number of hypotheses, including whether the foodweb downstream of the Ok Tedi River junction was more dependent on riparian/detrital carbon than that upstream, whether sites downstream had lost species known to depend on algal carbon, whether species using riparian carbon were more abundant downstream, and whether there were species that had switched from algal carbon upstream to other carbon sources downstream.

The study by WRM was collected data on the algal carbon signatures of species, but not data on the relative contributions of the species themselves to the food web. Such a study can indicate whether algae are used as a carbon source, as did the studies by Bunn et al. (1999) and Power (2001), but is unlikely to detect a difference in algal importance unless it is quite dramatic, which the earlier algal toxicity studies suggested was unlikely to be the case.

The results of the 2005 study were also problematical. Comparing the calculated percentages of algae in diets between the report of WRM (2005) and other studies (Table 4), there appear to be some striking differences with WRM reporting very low algal carbon in the tissues of species such as Barramundi (*Lates calcarifer*), the Papuan herring (*Nematolosa*) and the mayfly *Plethogenesia*, *w*hereas other studies recorded those species as being close to 100% algal dependant which agreed with biological information. On the other hand, WRM cite terrestrial grasshoppers (Orthoptera) with up to 100% algal carbon while other studies (e.g. Bunn et al. 1999) cite them as 0% algal carbon, which is rather more credible for a group of phytophagous consumers of terrestrial leaf material (Rentz and Su 2003). We conclude that there were most likely major analytical errors in the stable carbon analyses conducted by WRM 2005). Whether all the results are in error cannot be determined from the data, but there are sufficient obviously erroneous results that the entire data set should be disregarded.

Comparison with potamoplankton in other rivers

Previous studies on phytoplankton in large rivers have generally found that diatoms and chlorophytes predominate (Reynolds 1995; Reynolds and Descy 1996; Wehr and Descy 1998). That is not the case in the Fly River system. The data reported here were all collected at sites where the river was navigable, but even at points further up the Ok Tedi, where the river was shallow, stony and far more turbulent, cyanobacteria algae were the most abundant phytoplankton, at least between December 2007 and February 2008 (Campbell, unpublished data). Several authors have also suggested that the longitudinal pattern of phytoplankton biomass in large rivers includes four phases: no plankton in the headwaters, increasing, maximal, and declining. The pattern we have found is an increase downstream with the highest chlorophyll concentrations at the most downstream site, which is only a short distance upstream of the estuary.

The large rivers of PNG differ from many elsewhere. The Fly River is large in terms of discharge—with a mean annual discharge of 6000 m^3/s (Markham and Day 1994) it is one the 25 largest rivers globally (van der Leeden et al. 1990). However, it has a relatively small catchment area of 75,000 km^2 (Pickup and Marshall 2009) and a relatively short catchment length—only about 500 km. This reflects the geography of PNG. The island is only about 700 km wide, and the rivers drain from the central mountain range. However, much of the island has a very high annual rainfall, with the Ok Tedi mine recording annual rainfalls in excess of 10,000 mm (Pickup and Marshall 2009), which gives rise to the large rivers.

The river distance along the Fly River from the Kiunga sampling site to the river mouth is only about 750 km. It may be that the relatively short riverine length influences both the dominant phytoplankton group, and the longitudinal pattern of biomass.

Reynolds (1995) in a review of the paradox of the plankton of rivers noted that the key puzzle is why the plankton is not simply washed out. Various explanations for the persistence of plankton in rivers have been put forward including continuous recruitment from the benthos, wash in from floodplain water bodies or turbulent fluvial behaviour in the channel creating storage zones (Hynes 1970; Reynolds 1995). The pronounced differences between the chlorophyll composition in the ORWBs and in the river channel suggests that the explanation for the Fly River is not recruitment of phytoplankton from floodplain water bodies, and the depth and turbidity of the water makes it unlikely that recruitment from the benthos is a substantial source of plankton. The river is quite obviously turbulent even as it passes through the well-developed floodplain with a very low slope (Pickup and Marshall

Table 4 Comparison of the percentage algal consumption based on stable isotope ratios in the WRM (2005) report and four other studies

Species	WRM[a] (2005)	Apte and Smith (1999)	Bunn et al. (1999)	Power (2001)	Douglas et al. (2005)
Barramundi (*Lates calcarifer*)	0	100	50–75 (estimated)	Almost all algal carbon	"Nearly all" algal carbon
Herring (*Nematolosa*)	0	100	50–100	Algal feeder	–
			Large specimens		
Grasshoppers (Orthoptera)	47	–	0	–	–
Mayflies (*Plethogenesia*)	0.6		97–100		
Thryssa scratchleyi	0		0–19		
Strongylura krefftii	1		69–89		
Ambassus agrammus	0		100		
Macrobrachium rosenbergii	24		0–7		
Toxotes chartareus	78		0–32		
Glossamia aprion	0–17		67–100		
Melanotaenia sp.	16 (0–41)		24–100		
Neosilurus ater	0		0–42		
Odonata	0		72–100		

[a] WRM 2005 present data from two sites ARM450 and Kuambit, and multiple specimens. Results presented here are means, and where species were sampled from both sites the mean over all specimens from both sites is given

2009), which supports the paradigm developed by Reynolds (1995).

The overall levels of chlorophyll in the Fly River are not as high as those recorded elsewhere. For example, Reynolds and Descy (1996) record chlorophyll levels in middle order rivers of 20–200 μg/L. Levels in the Fly are well below that, but given the short river length, turbidity of the water and generally forested catchment—which presumably keeps nutrient levels low—chlorophyll concentrations between 2 and 5 μg/L are appreciable, and certainly sufficient to play a significant ecological role in the river. Alin et al. (2008) noted that aquatic primary production constituted a larger source of organic carbon in the Fly than the Strickland River.

Phytoplankton in the ORWBs

The composition of the algal assemblages in the ORWBs differed significantly from that in the river, with cyanobacteria the most abundant at only two water bodies, and even in those they were only slightly more abundant that the chlorophytes. Clearly the potamoplankton is a distinct assemblage in this river system, and not simply comprised algae washed out of the ORWBs. However, we did not find a significant difference in phytoplankton based on chlorophyll concentrations between ORWBs upstream and downstream of the Ok Tedi junction. This was true both in terms of total chlorophyll concentration and abundance of major algal groups. Previous algal investigations conducted based on single grab samples collected within a metre of the water surface (WRM 2007) found consistent differences in algal assemblage species composition between ORWBs upstream and downstream of Ok Tedi junction, but no difference in total number of algal taxa. We have no taxonomic data on the algae present during our sampling periods.

The algal concentrations in the ORWBs are quite variable. For Daviumbu, for which we have the largest data set, and which we sampled on five different occasions the median chlorophyll concentrations ranged from 2.52 μg/L, the lowest median recorded from any site, to 7.32 μg/L, the second highest median recorded. However, it is notable that there was significant variability between sites within an ORWB on any given occasion—phytoplankton in these systems is patchy both spatially and temporally. The chlorophyll concentrations in these systems are generally higher than those in the river—presumably at least in part because of the lower flushing rates. Although median and mean chlorophyll concentrations are not high, ranging around 5 μg/L, the concentrations at the algal plates in some water bodies are considerably higher between 10 and 30 μg/L.

Conclusion

Although there was a widespread concern that algal growth in the Fly River must be inhibited by the toxic impact of copper and possibly other metals released into the Ok Tedi tributary by the Ok Tedi copper mine, fluorescence data on

phytoplankton in the Fly River unexpectedly demonstrated a stimulatory rather than a toxic effect. That is not consistent with the effects found downstream of releases from other copper mines, where toxic impacts were found, but in many cases the mines which produced the effluents were no longer active (e.g. Galán et al. 2003; Hudson-Edwards et al. 2008).

The observed changes in the Fly River are consistent with the impact from the use and leakage of nitrogen-based explosives from the mine operation. The literature on the impact of discharges from metal mines on waterways has rarely paid attention to impacts other than those from toxic metals or sediment deposition. While both of those impacts can be severe and persistent long after mine closure, the impacts of fertilization through use of nitrogenous explosives in active mines may be substantial (Jermakka et al. 2015), particularly in environments where nutrient concentrations are naturally low, or in closed catchments with internal drainage, or where an open cut mine void is to be "rehabilitated" by filling with water and creating a lake.

At Ok Tedi, we found no evidence of any systematic impact of the mine on algae in the floodplain water bodies. Differences between the algal composition in floodplain water bodies and the river indicate that the riverine phytoplankton is not primarily derived from washout from those water bodies.

The potential consequences for fish and other aquatic resources used by local people are unclear. Obviously the reduction in fish biomass documented by Storey et al. (2009) is not caused by a drop in algal biomass, but whether changes in algal assemblage composition may be a contributing factor is not known. However, the data did not show suggestive patterns such as a change from green algae to potentially distasteful or toxic cyanobacteria. So it would seem that other factors, such as change in fish habitats may be more important drivers of the change in fish biomass.

Acknowledgements Thanks to the staff at the Environment Department, Ok Tedi Mining Ltd., particularly Markson Yarrao, Dexter Wagambie and Phillip Atio, who assisted with the field work.

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