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Effects of sediment pollution on food webs in a tropical river (Borneo, Indonesia)

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Abstract. The impact of pollution on the trophic ecology of the Kelian River (Borneo, Indonesia) was studied by comparing food webs (on the basis of gut analysis and field and laboratory observations) at six sites. The upper sites were in pristine rainforest but the river became increasingly polluted downstream, largely owing to sedimentation from alluvial gold mining activities. Four previous studies all showed a downstream decrease in macroinvertebrates (mean abundance: 272 per 400 cm^2 at Site 1 dropped to 2.6 at Site 6; mean number of taxa: 37.6 at Site 1 down to 1.6 at Site 6), and this was highly correlated with suspended solids. Food webs also reflected the effect of pollution. Cleaner sites had more complex food webs, with more elements, links, higher linkage density and higher complexity than did downstream polluted sites, which lacked grazers, shredders and filterers. Several taxa that were grazers at clean sites became collector-gatherers at polluted sites. Despite the enormous impact of pollution, cessation of alluvial mining activities resulted in some recovery. The resilience of the fauna is likely to be enhanced by the tropical conditions with high rainfall, rapid flow rates and high temperatures, coupled with rapid life cycles. Fish distribution and diets did not appear to be affected by pollution.

Additional keywords: dietary groups, gold mining, gut content analysis, Kelian River, macroinvertebrates, resilience.

Introduction

Little is known of the ecology of tropical rivers and streams compared with their temperate counterparts (Boyero 2000), yet they are becoming increasingly threatened by a variety of anthropogenic influences (Moulton and Wantzen 2006). Pollution is one of the most obvious threats to the ecological health of rivers and streams and to the survival of their biota (Allan and Flecker 1993). Pollution may alter the trophic pathways through which aquatic organisms obtain energy (Shieh *et al*. 2002). For example, any perturbation that increases (e.g. nutrients) or decreases (e.g. heavy metals, turbidity) primary production will potentially have an impact on secondary production and trophic links. However, most studies on the ecological effects of pollution focus on changes in the community structure (e.g. Cairns and Pratt 1993; Resh and McElravy 1993; Wantzen 2006) rather than on effects on functional characteristics of communities and ecosystems (e.g. Schultheis *et al*. 1997; Merritt *et al*. 2002).

Asian rivers are severely affected by human and industrial effluent and catchment degradation (Dudgeon 2000) and these problems are escalating with rapid economic development and population growth. Pollution in Indonesia is an increasing problem, particularly as the rivers are typically used for sewage disposal. For example, less than 3% of Jakarta's population (of over 9.5 million people) is connected to a sewerage system (Sukarma and Pollard 2002). Indonesian freshwaters support an exceptionally rich biota, with 900 amphibian species, at least 1200 fishes and more dragonflies (>660 species) than any other country (Dudgeon 2000). However, the understanding of longitudinal zonation in Asian rivers is confounded by the influence of pollution, so it can be difficult to distinguish natural communities from those under anthropogenic influences (Dudgeon 1988).

The Kelian River, in Kalimantan (Borneo, Indonesia), offers a good opportunity to study the effects of pollution in a tropical river. Alluvial gold miners have operated in the Kelian and its tributaries since the 1950s, and a large open pit gold mine (P. T. Kelian Equatorial Mining) operated next to the river from 1991 until 2005. As many as 2000 miners were recorded to be operating in the area in 1980, some using pumps and other equipment which severely disturbed the banks and bed of the river. The source of the alluvial gold was discovered in 1976, a substantial gold deposit located on Prampus Hill, 170 m from the river. An open-cut gold mine was constructed next to the river in late 1990 and, until it ceased production in 2005, it was the second-largest gold mine in Indonesia. Whereas the headwaters of the Kelian River lie in pristine tropical rainforest, the lower reaches, nearing its confluence with the Mahakam River, are polluted, mostly owing to sediment from gold-mining activities (alluvial and open cut) and logging, as well as by human effluent.

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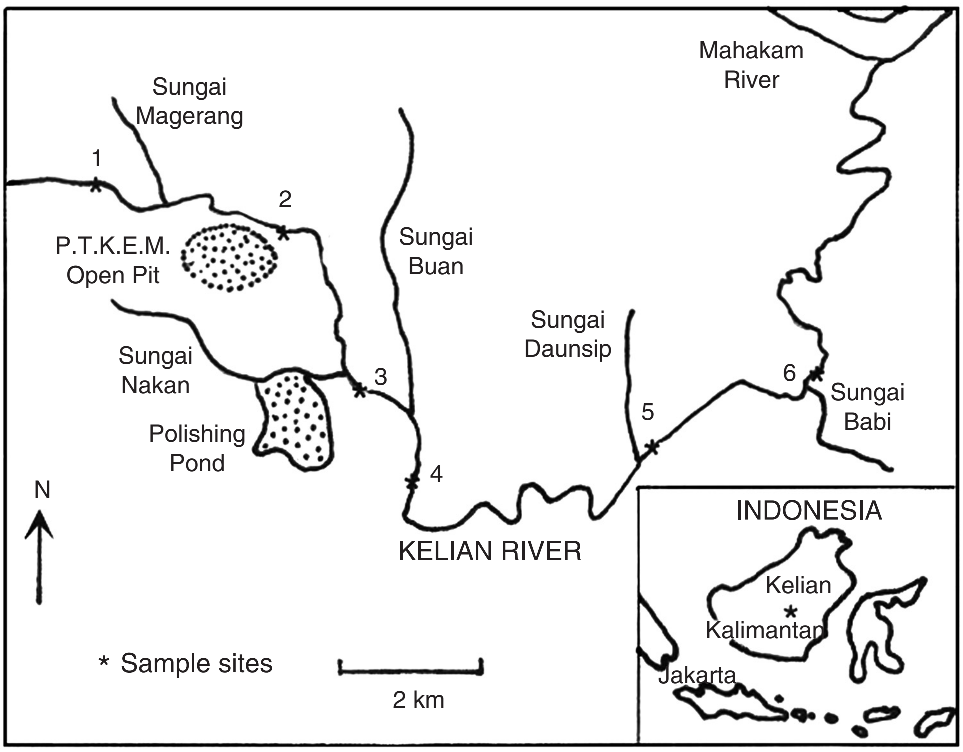

Fig. 1. Location of sampling Sites 1–6 at the Kelian River. The mine site is at 0°0.1′38.2″S, 115°26′36.95″E.

Surveys of the invertebrate fauna before and after construction of the mine showed that communities were severely disturbed by alluvial mining, which had caused a highly significant decrease in benthic invertebrate numbers and diversity, related to the high levels of suspended sediment (Yule 1995). The impact of alluvial mining was evident from above the open-cut mine, escalating in severity with increasing distance downstream. Organic pollution because of the disposal of human waste into the river also had a negative effect on the river fauna (Yule 1995). The present study further investigates the effects of pollution from mining activities in the Kelian River by describing the trophic ecology of macroinvertebrates along the river and comparing food-web complexity between pristine and polluted sites. We also describe changes in community composition through time (1990–1995, including wet and dry seasons) and determine whether composition becomes more variable as environmental disturbance increases (from 1994). Such a reaction has been suggested for marine benthos (Clarke and Warwick 2001) but not commonly for freshwater benthos. It was hypothesised that sedimentation could influence trophic ecology through its negative impact on the benthic flora (and hence grazing invertebrates) and filter-feeding invertebrates.

Materials and methods

Study area

The Kelian River is in the interior of Kalimantan, the Indonesian part of the island of Borneo (Fig. 1). It flows into the Mahakam River, the largest river in East Kalimantan, which enters the Makassar Straits near the town of Samarinda. The upper reaches of the Kelian lie in primary rainforest, with increasing areas of clearing and secondary regrowth nearer the confluence with the Mahakam. The open-cut gold mine operated next to the river (0°0.1′38.2″S, 115°26′36.95″E) from 1991 until 2005. The climate is tropical with an average annual rainfall of 4000 mm. It is typically wetter from September to April and drier from May to August, although there is no distinct dry season. Average daily flow of the Kelian River is ~10 $m^3 s^{-1}$, but the mean daily flow can vary greatly; measurements taken near Site 3 ranged from 26.5 $m^3 s^{-1}$ in April down to 3.0 $m^3 s^{-1}$ in October 1994. The average flow of the Mahakam River is ~3000 $m^3 s^{-1}$.

Six sites were sampled along the Kelian River (Fig. 1), with Site 1 situated in pristine rainforest and the other sites affected by mining activities to variable degrees (Table 1).

In the absence of disturbance, the river would have been surrounded by rainforest at all sites and remnants of rainforest were still present along the length of the reach studied. The substrate characteristics of riffle and pool habitats and the size of the river were similar at all sites, suggesting that discharge did not vary greatly among sites. The width varied from ~15 to 25 m, whereas the maximum depth in the riffles was ~30–40 cm at all sites.

Sampling and taxonomic identification

Samples were taken in September 1990 (wet season), August 1993 (dry season), June 1994 (dry season) and March 1995 (wet season). Benthic macroinvertebrates were sampled with a Surber sampler (20 × 20 cm, 300-μm mesh). On each sampling occasion, 10 samples were taken at each site from riffle habitat and preserved in 70% ethanol. Benthic algae were scraped from

Table 1. Location and characteristics of sampling sites at the Kelian River

Site	Benthic flora	Riparian vegetation	Substrate
1	Green algae (several species) Diatoms (many species)	Undisturbed rainforest	Boulders, cobbles, gravel, sand Hyporheic zone undisturbed
2	Green algae (several species, including *Spirogyra*) Diatoms (many species) Fungi Blue-green algae	Western side: mostly cleared, with some regrowth of e.g. grasses and ferns Eastern side: cleared for gardens	Boulders, cobbles, gravel, sand Hyporheic zone impacted with fine sediment
3	Green algae (several species, including *Spirogyra*) Diatoms (uncommon) Fungi Blue-green algae Protozoa (abundant)	Western side: mostly cleared Eastern side: rainforest	Boulders, cobbles, gravel, sand Layer of fine silt Hyporheic zone impacted with fine sediment
4	Several species of filamentous green algae (e.g. *Spirogyra*), unicellular green algae, fungi and blue-green algae forming algal-sediment mat	Fairly open rainforest, some recent disturbance	Boulders, cobbles, gravel, sand Layer of fine silt Hyporheic zone impacted with fine sediment
5	Blue-green algae Diatoms (several species, but uncommon) Protozoa (abundant)	Western side: rainforest Eastern side: partially cleared for gardens	Boulders, cobbles, gravel, sand Layer of fine silt Hyporheic zone impacted with fine sediment
6	Blue-green algae Fungi Protozoa (abundant)	Mostly cleared, village gardens	Boulders, cobbles, sand, mud Hyporheic zone impacted with fine sediment

cobbles and boulders at each site, and placed in jars with stream water from the same site. Water temperature was recorded and a water sample was taken at each site and sent to the Environment Department, P. T. Kelian Equatorial Mining for analysis (using standard methods) of pH, total suspended solids, turbidity, conductivity, alkalinity, SO_4, Fe, As, Se, Sb, Cu, Zn, Pb, Cd, Ni, Hg and Mn.

Macroinvertebrates were sorted and identified to the lowest taxonomic level possible (by C.M.Y.), being assigned to morphospecies when they could not be identified to species. Benthic algae were also identified to the lowest taxonomic level possible. Data on the fish (distribution and diets) were obtained from a study by Powell and Powell (1993).

Macroinvertebrate distribution

Variation in macroinvertebrate abundance (log-transformed) and species richness among sampling sites and years was examined by ANOVA followed by the Tukey–Kramer method for multiple comparisons. Variation in macroinvertebrate community composition was examined with multidimensional scaling (MDS) using the Bray–Curtis similarity index, and two-way analysis of similarities (ANOSIM) on 4th-root-transformed data (as implemented by PRIMER version 6; Clarke and Gorley 2006). Relative variability in composition at each site was measured using the MVDISP routine in PRIMER.

The relationship between chemical variables and the average abundance and species richness at each sampling site was tested with Spearman rank correlations. Complete chemical data were available only for 1994; however, data were similar from year to year.

Dietary groups

Samples from 1994 were used to describe dietary groups and food webs. The diets of all the macroinvertebrate species represented by specimens with at least partly filled guts were determined by gut-content analysis (by C.M.Y.). Up to 24 individuals of each species were examined, with an average of 3.2 ($\pm$3.1 s.d.) individuals per species (depending on availability), excepting chironomids, for which every larva was studied. The foreguts were dissected and the contents squashed (for very small specimens, the entire animal was squashed) on a microscope slide and mounted in polyvinyl alcohol lactophenol mountant. The slides were examined under a microscope at magnifications of $\times$200 and $\times$400.

Six major categories of food were present in the guts, including (1) fine particulate organic matter (FPOM, particles $<$500 μm), (2) coarse particulate organic matter (CPOM, particles 500 μm–1 mm), (3) fungal hyphae, (4) leaf litter (and wood) fragments ($>$1 mm), (5) algae (diatoms, green algae, blue-green algae) and (6) animal tissue. Each gut was considered to be 100% full and the percentage of material in each food category was estimated for each gut (this assessment was subjective but consistent).

Species or morphospecies were assigned to feeding groups, i.e. collectors, grazers, shredders or predators (Merritt and Cummins 1996), depending on their diet. Collector-gatherers and collector-filterers could not be distinguished by their diet; however, field and laboratory observations on their mode of feeding and, when necessary, examination of mouthparts under the microscope, allowed their separation for the construction of food webs.

Food webs

Food webs were constructed for each site, using the following information: (1) distribution and dietary habits of macroinvertebrate species or morphospecies (Accessory publication, available on the web); (2) presence and dietary habits of fish

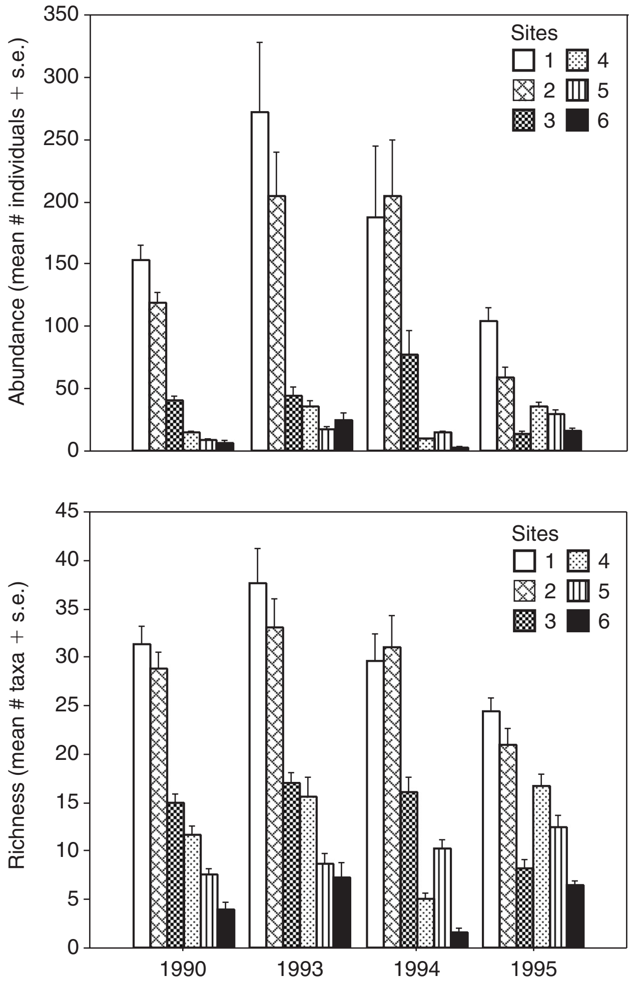

Fig. 2. Average (+ s.e.) macroinvertebrate abundance and species richness per sample at the different sampling sites and years in the Kelian River.

species (Accessory publication, available on the web; from Powell and Powell 1993); and (3) presence of benthic algae genera. Benthic algae, leaf litter, particulate organic matter and the input of terrestrial insects were not quantified. The food web was described with the following statistics: number of elements (S; species plus food categories, separating algal genera); number of links (L); linkage density (L/S); linkage complexity (S/connectance, where connectance = 2L/S(S − 1)).

Results

Macroinvertebrate distribution

In total, 16 424 individuals were found from at least 179 macroinvertebrate species. Macroinvertebrate abundance decreased downstream ($F_{5,18} = 16.3$, $P < 0.0001$), with non-significant differences only between Sites 1 and 2 and between Sites 4 and 5 (Fig. 2). Species richness showed a similar trend ($F_{5,18} = 24.5$, $P < 0.0001$), with non-significant differences between Sites 1 and 2, 3 and 4, and 4 and 5 (Fig. 2). Mean macroinvertebrate abundance per sample (400 cm^2) ranged from 272 (Site 1 in 1993) to 2.6 (Site 6 in 1994), whereas mean number of taxa per

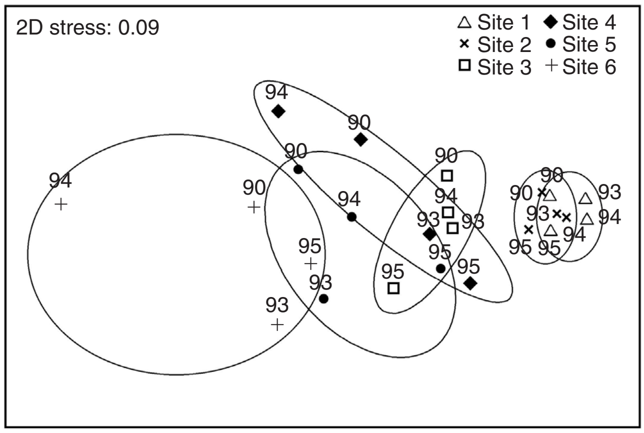

Fig. 3. Ordination (multidimensional scaling) of macroinvertebrate community composition at the different sampling sites and years in the Kelian River.

sample ranged from 37.6 at Site 1 in 1993 to 1.6 at Site 6 in 1994. Both the MDS (Fig. 3) and ANOSIM ($R = 0.633$, $P = 0.001$) showed a clear change in community composition downstream. Composition was more similar between Sites 1 and 2 than any of the other sites (Fig. 3).

Yearly variation was not significant for abundance ($F_{3,20} = 0.12$, $P = 0.95$) or richness ($F_{3,20} = 0.19$, $P = 0.90$). ANOSIM ($R = 0.002$, $P = 0.427$) indicating no differences in taxonomic composition among years. Relative variability of composition (from MVDISP) was lowest at Sites 1 (0.33) and 2 (0.4), intermediate at Sites 3 (0.94) and 5 (1.38) and greatest at Sites 4 (1.50) and 6 (1.46). Thus, Sites 1 and 2 had the lowest compositional variability with time, Sites 6 and 4 had the highest, whereas Sites 3 and 5 were intermediate to high. These patterns are obvious in the MDS (Fig. 3).

Chemical characteristics varied little among the sites in 1994 (Table 2), apart from total suspended solids and turbidity, which were the only variables correlated with macroinvertebrate abundance and species richness ($r = -0.89$ for both variables). When data from all years were included, both variables were still highly correlated with macroinvertebrate abundance and species richness ($r = -0.71$ to -0.94). Manganese was the only heavy metal to increase downstream, owing to discharge from the polishing pond and natural seepages. Manganese is an essential trace element for aquatic fauna and, according to Nagpal (2001), it is only slightly to moderately toxic to aquatic organisms.

Manganese bacteria were observed in the river below Site 2. These filamentous bacteria metabolise manganese present in the water and deposit it on and in their mucilaginous secretions, forming a slimy sludge, particularly on cobble surfaces, which traps very fine sediment and organic detritus and is home to a variety of protozoans, filamentous and unicellular green algae, diatoms, fungi and blue-green algae. Filamentous bacteria were observed in fish guts. Protozoa such as amoebae, euglenoids and ciliates, and also rotifers and microscopic turbellarians were observed amongst live samples of green algae and filamentous bacteria. They were particularly abundant within the algal sediment mats.

Table 2. Chemical characteristics (mean values) and temperature at the six sampling sites in the Kelian River, 1994

Characteristic	Site					
	1	2	3	4	5	6
Temperature (°C)	25.6	26.8	26.6	26.9	27.0	27.1
pH	7.3	7.5	7.4	7.1	7.3	7.3
Total suspended solids (ppm)	7.00	24.0	61.3	214.3	76.0	179.0
Turbidity (NTU)	3.52	14.11	32.18	131.4	61.6	120.97
Conductivity (mS cm^{-1})	40.0	66.0	166.0	–	169.0	146.5
Alkalinity-$CaCO_3$ (ppm)	13.47	25.00	20.20	28.00	18.73	18.93
SO_4 (ppm)	5.00	5.00	29.67	46.00	43.67	35.00
Fe (ppm)	0.06	0.10	0.09	0.08	0.08	0.07
Mn (ppm)	0.01	0.04	1.37	1.56	1.39	1.32
Hg (ppb)	0.03	0.03	0.03	0.03	0.03	0.03
As (ppb)	0.67	0.67	0.67	1.00	0.67	0.50
Se (ppb)	0.83	1.00	0.83	0.50	1.00	1.17
Sb (ppb)	0.50	0.50	1.00	8.00	2.17	2.33
Cu (ppm)	0.00	0.00	0.00	0.00	0.00	0.00
Zn (ppm)	0.01	0.01	0.13	0.01	0.09	0.03
Pb (ppm)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd (ppm)	<0.002	<0.002	<0.002	<0.002	<0.002	<0.002
Ni (ppm)	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02

Table 3. Mean % contribution to gut contents of each macroinvertebrate feeding group (range in parentheses)

Feeding group	FPOM	CPOM	Algae	Leaf litter	Fungi	Animals	No. of species
Collector-gatherers	86.5 (49–100)	10.0 (0–51)	2.7 (0–20)	0	0.7 (0–5)	0	39
Collector-filterers	84.0 (51–100)	8.8 (0–45)	6.2 (0–30)	0.2 (0–1)	0.8 (0–2)	0	5
Grazers	71.1 (0–95)	7.1 (0–50)	21.3 (5–100)	0	0.4 (0–3)	0	31
Shredders	0	0	0	99.3 (99–100)	0.7 (0–1)	0	3
Predators	16.8 (0–66)	0	0.8 (0–5)	0	0.1 (0–0.5)	82.4 (34–100)	16

Feeding groups

Diets were analysed for 94 species (64% of the total) (Table 3, Fig. 4) and 79% of the examined species were collectors and grazers with different levels of specialisation in their diets. Collector-gatherers and collector-filterers had a high proportion of FPOM and sometimes also CPOM in their guts. A few of these species also contained some algae. Individuals of Hydropsychidae sp. 1 contained some animal tissue, although they were considered collectors because the majority of their gut contents was FPOM. Grazers ate a large proportion of algae but also ingested some FPOM. The diets of chironomids tended to vary among individuals of the same species and it was often difficult to assign them to feeding groups. For the three species of specialist shredders, 99–100% of their gut contents was leaf tissue. Most collectors were considered collector-gatherers from observations of their feeding mode in the field and laboratory (C.M.Y, pers. obs.). Only four species (Hydropsychidae sp. 1, Philopotamidae sp. 1, Polycentropodidae sp. 1 and Simuliidae nr *Cnephia* sp. 1) were classified as collector-filterers. The simuliid guts also contained 30% algae. Simuliids do not rely entirely on filter-feeding as they are also capable of gathering organic material from the substrate (Crosskey 1990). The three trichopteran species construct nets to filter particles suspended in the water column (Morse 2004) and thus eat a variety of food types that are trapped in the net, including some animal tissue (Hydropsychidae sp. 1) and algae (Philopotamidae sp. 1).

Four species that were classified as grazers at Sites 1, 2, 3 and 5 were observed to exhibit a dietary shift to collector-gatherers at Sites 4 and 6, where algae were uncommon. These included the most abundant invertebrate – the mayfly *Platybaetis* sp. 1 (44.4% of total invertebrate numbers) – and also Ecdyonuridae sp. 1, Leptophlebiidae sp. 1 and the chironomid *Cardiocladius* sp. 1.

Food webs

The composition of food webs at Sites 1, 2 and 3 was similar (Table 4) with respect to functional feeding groups present. At Site 5, the abundance and diversity of grazers, shredders and collector-filterers was lower than that at the upstream sites (e.g. there were 10 grazing species at Site 1 but only 2 at Site 5). However, these groups were absent from Sites 4 and 6. The effects of severe pollution at Site 6, eliminating most species and drastically reducing the abundance (only 26 animals in 11 taxa collected in 1994), reflected a very simple food web, not only lacking shredders, grazers and collector-filterers, but also predators (Table 4). Although one specimen of a potential filter-feeder (a hydropsychid) was collected, its gut was empty.

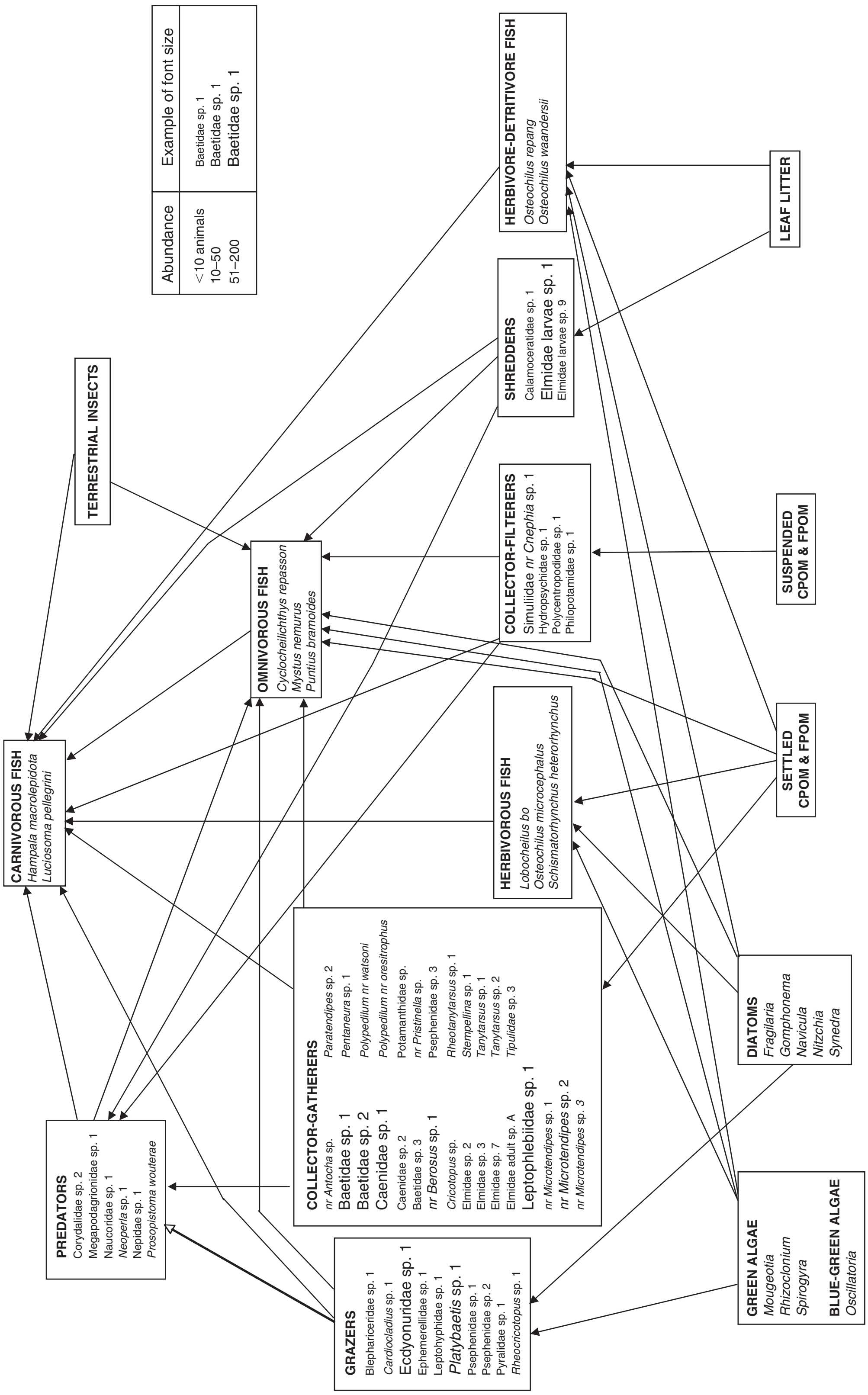

Fig. 4. Food web for Site 1.

Table 4. Number of species in each feeding group at each site

Feeding group	Site					
	1	2	3	4	5	6
Invertebrates						
Collector-gatherers	28	29	27	15	19	4
Collector-filterers	4	3	3	0	2	0
Grazers	10	11	10	0	2	0
Shredders	3	2	2	0	1	0
Predators	6	8	8	2	4	0
Fish						
Herbivores	3	5	5	4	5	2
Herbivore-detritivores	2	2	2	2	2	2
Omnivores	3	5	5	6	3	6
Carnivores	2	3	3	3	3	3

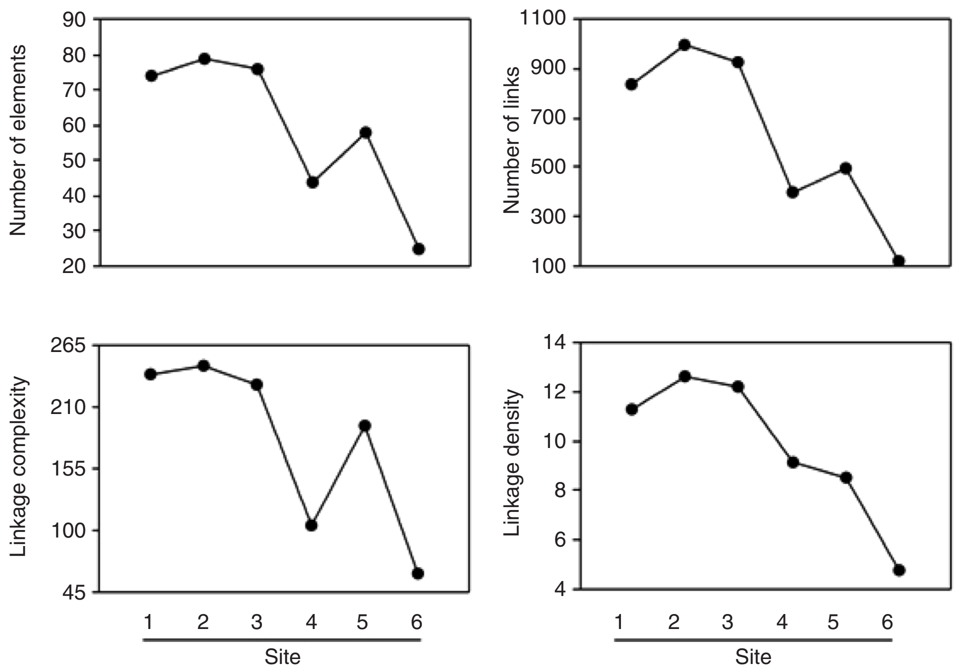

Fig. 5. Food-web characteristics at each sampling site. Number of elements: S = species plus food categories; L = number of links; S/connectance = linkage complexity, where connectance = 2L/S(S − 1); L/S = linkage density.

Feeding statistics (Fig. 5; number of elements, number of links, linkage density and complexity) were similar for Sites 1–3, and decreased downstream. Site 5 showed an improvement with more feeding groups present (Table 4) and an increase in linkage complexity.

Fish feeding groups varied much less than the invertebrate feeding groups (Table 4). All feeding groups were present at all sites and variations in numbers of species in each feeding group varied modestly, with no clear downstream trend.

Discussion

Longitudinal changes in the fauna

Under pristine conditions in the past, before disturbance by alluvial mining, Sites 1 to 6 would have been expected to have similar invertebrate communities, given the similar substrates and discharge at each site. Furthermore, the fish fauna varied little among sites, emphasising the similarity of the habitats. There was little variation in composition of the invertebrate communities at Sites 1 and 2 among years, despite samples being collected in different seasons (Fig. 3). Water temperature was constantly warm (>25°C) and discharge, although variable, was typically always high. Such environmental stability facilitates the rapid continuous life cycles that are typical of tropical aquatic invertebrates (Marchant and Yule 1996) and results in the lack of seasonality that is characteristic of rainforest streams in South-east Asia (Bishop 1973; Yule and Pearson 1996). Sites downstream showed a greater variation in community composition among years (Fig. 3). Such instability has been strongly associated with increased disturbance in marine ecosystems

(Clarke and Warwick 2001) and is a result of the elimination of taxa because of pollution.

The Kelian River supports a high diversity of macroinvertebrates (179 taxa identified since sampling commenced in 1990) and benthic flora (>20 taxa) (see Yule 1995). This diversity has been severely depressed by pollution in the lower reaches, with the worst impact at the lowest site. Surveys in 1990 and 1993 already indicated a significant decrease downstream in macroinvertebrate abundance and species richness, which were highly correlated with elevated levels of suspended solids and turbidity (Yule 1995). The 1990 survey was performed before construction of the open cut, although alluvial miners had been operating downstream of Site 1 for many years. Construction and operation of the open-cut mine must have also had an adverse effect on the fauna, although this was largely masked by the immense impact of the alluvial mining.

Other studies have shown an effect of mining activity on stream macroinvertebrate densities because of a change in sediment load, rather than to solutes and particles in the water (Marqués *et al*. 2003). Although mining causes some physicochemical changes in the water (such as changes in pH, ion concentration and water transparency), a surprising diversity of algae and invertebrates has been reported from streams and rivers degraded by acidic mine drainages in various parts of the world (Winterbourn 1998). On the contrary, increased sediment load resulting from riparian grazing and deforestation negatively affect macroinvertebrate densities (Wohl and Carline 1996) and diversity (Bishop 1973; Dudgeon 1988).

The higher spatial scale of movement of fish can make them less vulnerable to disturbances that affect macroinvertebrates (Thompson *et al*. 2001). Also, omnivorous fish were often seen feeding on human wastes (C.M.Y., pers. obs.). These reasons could explain why abundance, species richness, composition and feeding habits of fish in the Kelian River exhibited no significant changes due to pollution (Powell and Powell 1993). These fish are an important component of the diet of local people, and possibly of small crocodiles, large tortoises and otters that also occur in the Kelian River (C.M.Y., pers. obs.).

Recovery of fauna

In the 1994 survey, performed after a decrease in alluvial mining activities, there was an improvement in water quality and, concomitantly, an increase in species richness at Site 5. Some species intolerant to pollution (e.g. in the Psephenidae and Polycentropodidae) were found at this site, which is an indication of the high resilience of macroinvertebrate communities to pollution. The resilience exhibited by the macroinvertebrate fauna of the Kelian River is likely to be enhanced by tropical conditions such as high rainfall, rapid flow rates and high temperatures, coupled with rapid life cycles (e.g. Hynes and Williams 1962; Corbet 1980; Marchant and Yule 1996; Yule and Pearson 1996). With the cessation of mining, the high flow rates promoted the rapid removal of sediment deposits and the scouring of algal-sediment mats, enabling the return of a healthy algal flora, as well as carrying drifting invertebrates. However, the recovery of the aquatic invertebrate fauna following the cessation of mining activities and the recuperation of the trophic ecology must be reliant on a source of recolonising adults and larvae from upstream pristine catchments. It is possible that Site 5 was recolonised from tributaries, given the very poor conditions immediately upstream (Site 4).

Further indication of this potential for recovery is the diverse and abundant macroinvertebrate community supported by Site 2, which exhibited few significant differences from the pristine Site 1, even though Site 2 had been affected by alluvial mining, removal of riparian vegetation, and construction and operation of the nearby open-cut mine (Yule 1995). The benthic flora at this site was similar to that of Site 1, although it was more profuse owing to the decrease in shading and it appeared to have more blue-green algae, which indicates some degree of disturbance. This capacity for recovery of macroinvertebrate communities has been shown after other disturbances such as dam removal (Doyle *et al*. 2005). However, there is also evidence of long-term consequences of metal contamination from mining on riparian vegetation and aquatic macroinvertebrates (Marcus *et al*. 2001).

Kelian Equatorial Mining ceased its production in February 2005 and is converting its ex-mine site into a protection forest. To ensure that there will be no further mining by alluvial miners, the company is presently conducting a sterilisation process by involving the community until all parties can be certain that no more gold exists in the area. This is to guarantee the conservation of the protection forest because otherwise it cannot be assured if the community believes that gold still exists in the forest. Because this study has revealed a capacity for the macroinvertebrate fauna to recover, the opportunity presently exists for the rehabilitation of the Kelian River ecosystem. Protection of all the forested catchments, not only those occupying the ex-mine site, is vital for the restoration of the riverine ecosystem.

Food webs

Food-web complexity decreased downstream in the Kelian River (Table 4, Fig. 5), largely as a result of higher levels of suspended solids and turbidity provoked by mining activities. Shredders and filterers disappeared, whereas grazers either disappeared or modified their diet because benthic algae were replaced by an algal-sediment matrix and filamentous bacteria, which flourished in response to the sediment as well as high levels of manganese discharged from the polishing pond above Site 3. It is known that manganese preferentially binds to sediment (Nagpal 2001), and so the filamentous bacterial mat present in the downstream reaches of the Kelian (Table 1) could contain toxic levels of manganese, further affecting the fauna.

In contrast with other sites, in the 1994 survey Sites 4 and 6 showed deterioration from previous years, with a decrease in macroinvertebrate abundance and species richness. Shredders, filterers and grazers were lacking at these sites, and Site 6 also lacked predators (apart from fish). Some species that were grazers at cleaner sites were collector-gatherers at Sites 4 and 6, because of the lack of benthic algae. Abundance and species richness of collector-gatherers and predators were also reduced. Given the low macroinvertebrate abundance at these sites, fish predators might be maintained by smaller fish or by swimming to upstream reaches or tributaries to feed. Further evidence for this pattern is the presence of filamentous bacteria in fish guts (especially *Lobocheilus bo*; Powell and Powell 1993) even at sites where there were no bacteria.

Dietary analyses were undertaken only on the invertebrate fauna collected in 1994. Food-web statistics vary with collecting effort in much the same way as species richness (Ings *et al*. 2009) and thus may have been somewhat different if they had been based on data from all years. However, the downstream gradient shown by the ordination (Fig. 3) was stable through time, despite the increased variation in composition at Sites 3–6. These downstream sites were always less diverse than Sites 1 and 2 (Fig. 2), because of the pervasive impact of high levels of sediment, and it is most likely that the trends displayed by the food-web statistics in 1994 (Fig. 5) remained much the same in years when diets were not recorded.

Previous studies of the trophic ecology of tropical streams have revealed great variation among different regions (e.g. Hong Kong: Mantel *et al*. 2004; Australia: Cheshire *et al*. 2005; Brazil: Brito *et al*. 2006; Caribbean Islands: Coat *et al*. 2009), and at different altitudes (e.g. Bougainville Island: Yule 1996; Malaysia: Yule *et al*. 2009) and there is an ongoing debate as to whether tropical streams function differently from temperate streams with respect to food-web organisation and organic-matter dynamics (Boulton *et al*. 2008; Wantzen *et al*. 2008; Boyero *et al*. 2009). Despite such complexities, the consistent patterns in invertebrate community composition from year to year in the Kelian River, evident in the present study, suggest that the trophic organisation of these communities is also robust. The resilience of the invertebrate fauna may well have more to do with the lack of seasonality in the aquatic habitat with constant high flow rates, rapid life cycles and the close proximity of upstream refuges rather than the availability of different food sources.

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References

Allan, J. D., and Flecker, A. S. (1993). Biodiversity conservation in running waters. Identifying the major factors that threaten destruction of riverine species and ecosystems. *BioScience* **43**, 32–43. doi:10.2307/1312104

Bishop, J. E. (1973). 'Limnology of a Small Malayan River Sungai Gombak.' (Junk: The Hague, The Netherlands.)

Boulton, A. J., Boyero, L., Covich, A. P., Dobson, M. K., Lake, P. S., and Pearson, R. G. (2008). Are tropical streams ecologically different from temperate streams? In 'Tropical Stream Ecology'. (Ed. D. Dudgeon.) pp. 257–284. (Academic Press: San Diego, CA.)

Boyero, L. (2000). Towards a global stream ecology. *Trends in Ecology & Evolution* **15**, 390–391. doi:10.1016/S0169-5347(00)01957-1

Boyero, L., Ramirez, A., Dudgeon, D., and Pearson, R. G. (2009). Are tropical streams really different? *Journal of the North American Benthological Society* **28**, 397–403. doi:10.1899/08-146.1

Brito, E. F., Moulton, T. P., Souza, M. L., and Bunn, S. E. (2006). Stable isotope analysis indicates microalgae as the predominant food source of fauna in a coastal forest stream, south-east Brazil. *Austral Ecology* **31**, 623–633. doi:10.1111/J.1442-9993.2006.01610.X

Cairns, J., and Pratt, J. R. (1993). A history of biological monitoring using benthic macroinvertebrates. In 'Freshwater Biomonitoring and Benthic Macroinvertebrates'. (Eds D. M. Rosenberg and V. H. Resh.) pp. 10–27. (Chapman and Hall: New York.)

Cheshire, K., Boyero, L., and Pearson, R. G. (2005). Food webs in tropical Australian streams: shredders are not scarce. *Freshwater Biology* **50**, 748–769. doi:10.1111/J.1365-2427.2005.01355.X

Clarke, K. R., and Gorley, R. N. (2006). 'PRIMER Version 6: User Manual/Tutorial.' (PRIMER-E: Plymouth, UK.)

Clarke, K. R., and Warwick, R. M. (2001). 'Change in Marine Communities: An Approach to Statistical Analysis and Interpretation.' 2nd edn. (PRIMER-E: Plymouth, UK.)

Coat, S., Monti, D., Bouchon, C., and Lepoint, G. (2009). Trophic relationships in a tropical stream food web assessed by stable isotope analysis. *Freshwater Biology* **54**, 1028–1041. doi:10.1111/J.1365-2427.2008.02149.X

Corbet, P. S. (1980). Biology of Odonata. *Annual Review of Entomology* **25**, 189–217. doi:10.1146/ANNUREV.EN.25.010180.001201

Crosskey, R. W. (1990). 'The Natural History of Blackflies.' (John Wiley and Sons: New York.)

Doyle, M. W., Stanley, E. H., Orr, C. H., Sellec, A. R., Sethib, S. A., *et al.* (2005). Stream ecosystem response to small dam removal: lessons from the Heartland. *Geomorphology* **71**, 227–244. doi:10.1016/J.GEOMORPH.2004.04.011

Dudgeon, D. (1988). The influence of riparian vegetation on macroinvertebrate community structure in four Hong Kong streams. *Journal of Zoology* **216**, 609–627. doi:10.1111/J.1469-7998.1988.TB02461.X

Dudgeon, D. (2000). The ecology of tropical Asian rivers and streams in relation to biodiversity conservation. *Annual Review of Ecology and Systematics* **31**, 239–263. doi:10.1146/ANNUREV.ECOLSYS.31.1.239

Hynes, H. B. N., and Williams, T. R. (1962). The effect of DDT on the fauna of a central African stream. *Annals of Tropical Medicine and Parasitology* **56**, 78–91.

Ings, T. C., Montoya, J. M., Bascompte, J., Bluthgen, N., Brown, L., *et al.* (2009). Ecological networks – beyond food webs. *Journal of Animal Ecology* **78**, 253–269. doi:10.1111/J.1365-2656.2008.01460.X

Mantel, S. K., Salas, M., and Dudgeon, D. (2004). Food web structure in a tropical Asian forest stream. *Journal of the North American Benthological Society* **23**, 728–755. doi:10.1899/0887-3593(2004)023<0728:FSIATA>2.0.CO;2

Marchant, R., and Yule, C. M. (1996). A method for estimating larval life spans of aseasonal aquatic insects from two streams on Bougainville Island, Papua New Guinea. *Freshwater Biology* **35**, 101–107. doi:10.1046/J.1365-2427.1996.D01-449.X

Marcus, W. A., Meyer, G. A., and Nimmo, D. R. (2001). Geomorphic control of persistent mine impacts in a Yellowstone Park stream and implications for the recovery of fluvial systems. *Geology* **29**, 355–358. doi:10.1130/0091-7613(2001)029<0355:GCOPMI>2.0.CO;2

Marqués, M. J., Martínez-Conde, E., and Rovira, J. V. (2003). Effects of zinc and lead mining on the benthic macroinvertebrates of a fluvial ecosystem. *Water, Air, and Soil Pollution* **148**, 363–388. doi:10.1023/A:1025411932330

Merritt, R. W., and Cummins, K. W. (1996). 'An Introduction to the Aquatic Insects of North America.' (Kendall/Hunt: Dubuque, IA.)

Merritt, R. W., Cummins, K. W., Berg, M. B., Novak, J. A., Higgins, M. J., *et al.* (2002). Development and application of a macroinvertebrate functional-group approach in the bioassessment of remnant river oxbows in southwest Florida. *Journal of the North American Benthological Society* **21**, 290–310. doi:10.2307/1468416

Morse, J. C. (2004). Insecta: Trichoptera. In 'Freshwater Invertebrates of the Malaysian Region'. (Eds C. M. Yule and H. S. Yong.) pp. 501–539. (Academy of Sciences: Kuala Lumpur, Malaysia.)

Moulton, T. P., and Wantzen, K. M. (2006). Conservation of tropical streams – special questions or conventional paradigms? *Aquatic Conservation: Marine & Freshwater Ecosystems* **16**, 659–663. doi:10.1002/AQC.814

Nagpal, N. K. (2001). 'Ambient water quality guidelines for manganese.' Ministry of Environment and Parks, Water Management Branch, Resource Quality Section, Victoria, BC, Canada.

Powell, J. H., and Powell, R. E. (1993). Assessment of aquatic impacts associated with gold mining operations in the Prampus region of the Kelian River system, East Kalimantan, Indonesia. A review 1990–1993. Unpublished report for P. T. Kelian Equatorial Mining, Kalimantan, Indonesia.

Resh, V. H., and McElravy, E. P. (1993). Contemporary quantitative approaches to biomonitoring using benthic invertebrates. In 'Freshwater Biomonitoring and Benthic Macroinvertebrates'. (Eds D. M. Rosenberg and V. H. Resh.) pp. 159–194. (Chapman and Hall: New York.)

Schultheis, A. S., Sanchez, M., and Hendricks, A. C. (1997). Structural and functional responses of stream insects to copper pollution. *Hydrobiologia* **346**, 85–93. doi:10.1023/A:1002909914774

Shieh, S. H., Ward, J. V., and Kondratieff, B. C. (2002). Energy flow through macroinvertebrates in a polluted plains stream. *Journal of the North American Benthological Society* **21**, 660–675. doi:10.2307/1468437

Sukarma, R., and Pollard, R. (2002). Indonesia. Overview of sanitation and sewerage experience and policy options. Report for the World Bank Urban Development Sector Unit, Indonesia Country Management Unit, East Asia and Pacific Region.

Thompson, A. R., Petty, J. T., and Grossman, G. D. (2001). Multi-scale effects of resource patchiness on foraging behaviour and habitat use by longnose dace, *Rhinichthys cataractae. Freshwater Biology* **46**, 145–160. doi:10.1046/J.1365-2427.2001.00654.X

Wantzen, K. M. (2006). Physical pollution: effects of gully erosion on benthic invertebrates in a tropical clear-water stream. *Aquatic Conservation: Marine & Freshwater Ecosystems* **16**, 733–749. doi:10.1002/AQC.813

Wantzen, K. M., Yule, C. M., Mathooko, J. M., and Pringle, C. (2008). Organic-matter dynamics and processing in tropical streams. In 'Tropical Stream Ecology'. (Ed. D. Dudgeon.) pp. 43–64. (Academic Press: London.)

Winterbourn, M. J. (1998). Insect faunas of acidic coal mine drainages in Westland, New Zealand. *New Zealand Entomologist* **21**, 65–72.

Wohl, N. E., and Carline, R. F. (1996). Relations among riparian grazing, sediment loads, macroinvertebrates, and fishes in three central Pennsylvania streams. *Canadian Journal of Fisheries and Aquatic Sciences* **53**, 260–266. doi:10.1139/CJFAS-53-S1-260

Yule, C. M. (1995). The impact of sediment pollution on the benthic invertebrate fauna of the Kelian River, East Kalimantan, Indonesia. In 'Tropical Limnology. Vol. III'. (Eds K. H. Timotius and F. Goltenboth.) pp. 61–75. (Satya Wacana University Press: Salatiga, Indonesia.)

Yule, C. M. (1996). Trophic relationships of the benthic invertebrate fauna of an aseasonal tropical stream on Bougainville Island, Papua New Guinea. *Journal of Tropical Ecology* **12**, 517–534. doi:10.1017/S0266467400009755

Yule, C. M., and Pearson, R. G. (1996). Aseasonality of benthic invertebrates in a tropical stream on Bougainville Island, Papua. New Guinea. *Archiv für Hydrobiologie* **137**, 95–117.

Yule, C. M., Leong, M. Y., Liew, K. C., Ratnarajah, L., Schmidt, K., *et al.* (2009). Shredders in Malaysia: abundance and richness are higher in cool upland tropical streams. *Journal of the North American Benthological Society* **28**, 404–415. doi:10.1899/07-161.1

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