MACROINVERTEBRATE FAUNA OF AN IRON-RICH STREAM IN THE WET TROPICS OF AUSTRALIA: A COMPARATIVE ANALYSIS OF COMMUNITIES USING A RAPID BIOASSESSMENT PROTOCOL

PIETER T.J. JOHNSON AND EUAN G. RITCHIE

Johnson, P.T.J. & Ritchie, E.G. 2003 06 30: Macroinvertebrate fauna of an iron-rich stream in the Wet Tropics of Australia: a comparative analysis of communities using a rapid bioassessment protocol. *Memoirs of the Queensland Museum* **49**(1): 331-338. Brisbane. ISSN 0079-8835.

The present study examined an iron-rich stream in the Wet Tropics of Queensland, Australia, and used a Rapid Bioassessment Protocol to compare its macroinvertebrate fauna with that of (1) a nearby, undisturbed stream and (2) the second order stream formed from their junction. The undisturbed stream supported significantly greater levels of macroinvertebrate abundance and taxonomic richness than either the iron-rich or junction stream. The latter two streams did not differ significantly for either measure, suggesting that iron-layering effects maintain potency even at increased distances from the source (>1km). Percent Similarity (PS_{ij}) and Shannon-Weiner Diversity (*H*') indices were used to compare the streams' macroinvertebrate communities, while two biotic indices (SIGNAL) were employed to estimate water quality. The undisturbed stream exhibited greater invertebrate diversity and higher water quality relative to the other two streams. Species assemblage patterns were comparable to iron-rich stream studies from the temperate region: mayfly and caddisfly nymphs were almost completely absent from the sites of iron-deposition while they comprised the majority of the invertebrates in the undisturbed stream. The conservation issues and management implications surrounding the release of water from stratified dams and reservoirs are discussed. ❒ *Iron-rich, rapid bioassessment protocol, macroinvertebrate communities, Wet Tropics, dams.*

Pieter T.J. Johnson & Euan G. Ritchie (e-mail: Euan.Ritchie@jcu.edu.au), School of Tropical Biology, James Cook University, Townsville, Queensland 4811, Australia. (*Present address: Centre for Limnology, University of Wisconsin, Wisconsin 53706, U.S.A.); 26 March 2002.*

Freshwater organisms confront a unique set of problems that are largely absent from terrestrial and marine environments. Bodies of freshwater, whether rivers, streams, ponds, or lakes, tend to be (1) small with respect to occupied volume and surface area, (2) patchy pattern across the landscape, and (3) sinks for pollutants and terrestrial run-off. Consequently, freshwater systems are highly sensitive to disturbance and pollution. The most frequent forms of aquatic pollution include thermal effluent, cultural eutrophication, acidification, build-up of sediments or suspended solids, and leakage of pesticides, petroleum products, and heavy metals (Hynes, 1960; Wiederholm, 1984; Kim & Chon, 2001; Mascaro et al., 2001). Construction of dams and other flow impediments may accelerate or intensify these processes. In addition to changing normal flow regimes, dams increase bank erosion, disturb flood cycles, impede migrations, displace native species, and alter pH, temperature, salinity, and natural chemistry of the waterway (Lake, 1967; Walker, 1981; Palmer & O'Keefe, 1990).

Anthropogenic sources of iron that may affect lotic systems include mining, logging, peat production, and agricultural run-off (Vuori, 1995). Less commonly, iron deposition may occur downstream from a stratified dam or reservoir. Thermal stratification in reservoirs creates an anoxic hypolimnion, and older dams with deep-release outlets may send ammonium-rich, oxygen-poor water downstream (Walker et al., 1978; Krenkel et al., 1979; Marcus, 1980). High quantities of iron can dissolve and concentrate within the anoxic water and, upon re-exposure to the oxygen-rich lotic environment, precipitate out to form a layer of ferrichydroxide. This deposition can seriously impact the resident flora and fauna, and iron deposition has been associated with diminished diversity and abundance for most recorded taxa (Hildrew & Townsend, 1976; Wellnitz et al., 1994; Wellnitz & Sheldon, 1995; Vuori, 1995). The occurrence of any anthropogenic impacts within the relatively pristine Wet Tropics is a major concern. The region is known as an area of significant ecological importance sustaining high

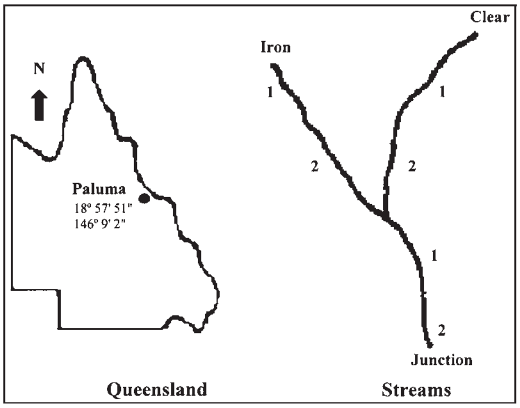

FIG. 1. Location of the study site. (Numbers indicate locations of sampling sites)

biodiversity, including many endemic and rare species. To illustrate this point, the area is known to contain 40% of Australia's fish species (Pusey & Kennard, 1996) and 25% of the terrestrial vertebrates (Williams et al., 1996) and 37% of the plants (Keto & Scott, 1986) are known to be regionally endemic.

We examined the macroinvertebrate fauna of a stream with heavy ferric-hydroxide deposition within the Wet Tropics of Australia. The stream flowed from a base-level leak in a peripheral saddle dam, wherein the iron is dissolved and concentrated. As a natural 'control', samples were also collected from a nearby stream which neither originated from the dam nor showed any signs of iron-deposition, but flowed over identical topography, soil type, and vegetation. The two streams eventually united into a second order stream, and the fauna below this junction was also sampled. Taxonomic richness, total abundance, and species composition were compared among the three areas. Two biotic indices of water quality were also calculated: the Stream Invertebrate Grade Number (SIGNAL) average family level and the weighted index (Chessman, 1995). The primary objective of this study was to use a rapid bioassessment protocol (RBP) to assess the effects of iron deposition on macroinvertebrate communities in an Australian tropical stream.

MATERIALS AND METHODS

Paluma is situated in the Wet Tropics of North Queensland (146º13'E, 19ºS) and supports both rainforest and eucalypt forest areas. Study sites were located in an area of rainforest approximately 500m downstream from the Paluma dam (Fig. 1). At 890m above sea level, the dam itself has a maximum capacity of 9.5 billion litres and an average depth of approximately 15m. The 'iron stream' stems from a small leak at the base of a peripheral saddle dam (R. Pearson, pers. comm.) and is characterised by a distinctive, ochre deposit covering all rocks and leaf litter within the stream. An ostensibly undisturbed stream (henceforth referred to as the 'clear-stream') flowing from a nearby tributary was also sampled. The third sample site was located in the second order stream formed via the junction of the clear and iron streams.

In each stream, two sites were sampled: one at 50m and one at 100m from the point of junction. At each sample site, flow rate, canopy cover, mean width, mean depth, temperature, and substrate composition (percentages of cobble and leaf-litter) were estimated. For each sample, five similarly sized rocks were selected. Area was estimated by measuring the two longest axes of the rock; minimum and maximum recorded areas among the samples were 10,400mm^2 and 51,300mm^2, respectively. Each rock was lifted rapidly from the substrate and placed in a 400µm mesh dipnet, wherein the rock's surface was rigorously scraped free of all sediment and organisms. After a final visual inspection, the rock was replaced to the substrate while contents of the net were transferred to 70% ethanol and returned to the laboratory for sorting and identification. Macroinvertebrate specimens were identified to the level of family. A total of 30 rocks was examined.

Differences in macroinvertebrate abundance and taxonomic richness (family level) among the three streams were tested using Kruskal-Wallis tests followed by paired Mann-Whitney U-tests to isolate differences. To compare the structure and assemblage of macroinvertebrate communities, Shannon-Wiener Diversity (H') and Percent Similarity (PS_{ij}) indices (see equation 6.5 Jongman et al. 1995) were calculated. In accordance with Chessman's (1995) river rapid assessment protocol, the weighted index (SIGNAL-W) and the average family index (SIGNAL) were estimated. In these indices, specimens are keyed to family level and given an interim pollution sensitivity grade value (1-10). Chessman (1995) provided such grades for common families of Australian macroinvertebrates. For the weighted index, each family is also assigned an occurrence value (1-4), and the product of the occurrence value and the pollution sensitivity grade are summed across the sample. The resulting SIGNAL values give an indication of water quality: clean water (value greater than 6), doubtful quality (values between 5 and 6), probable moderate pollution (values between 4 and 5), and probable severe pollution (values less than 4). The protocol was designed to yield rapid results and minimise time spent sampling and sorting. Chessman et al. (1997) has revised the grade numbers for a suite of macroinvertebrate families. We decided against using this updated SIGNAL index on the basis that the well represented families in our data set have not changed in grade number, and in addition some families do not have an updated grade number, hence allowing only a partial reanalysis.

RESULTS

The substratum of each stream was composed of rocks and leaf litter. The mean size of rocks (iron - 1101cm^2 ±46, junction - 1609cm^2 ±252 and clear - 1555cm^2 ±96) did not differ significantly between sites (ANOVA, d.f. = 2, 5, F = 3.11, p = 0.19). The abiotic characteristics of each stream are presented in Table 1.

The three streams differed significantly with respect to both macroinvertebrate abundance and taxonomic richness (Kruskal Wallis test, df=2, $p<0.0002$). The clear stream had significantly higher levels of both macroinvertebrate abundance and taxonomic richness than either the iron or junction stream (Mann-Whitney U test, $n_1 = n_2 = 10$, $p<0.005$; see Figs 2 and 3). No differences were noted for either measure between the iron and junction streams (Mann-Whitney U test, $n_1 = n_2 = 10$, $p>0.05$). Thus, at the scale of study, no increase in faunal abundance or taxonomic richness was noted with increasing distance from the anoxic source. Accordingly, visual observations showed no obvious decline in the layering of ferrichydroxide, even beyond the junction of the clear and iron streams. In both streams, several rocks were completely devoid of macroinvertebrates, in marked contrast to the densely populated rocks of the clear stream.

The similarity, diversity, and water quality analyses supported the trends noted for abundance and taxonomic richness. With respect to the collected families, percent similarity calculations (PS_{ij}) demonstrated a 40% similarity between the iron and junction communities, compared to 10.8% similarity between the junction and the clear streams and a 4.4% similarity between the clear and iron streams. For the Shannon-Weiner diversity index and the biotic indices of water quality, the clear stream had considerably higher values than either the junction stream or the iron stream (Table 2). The SIGNAL values classified the water of the clear stream as ‘clean’, while both the iron and junction streams fell into the ‘moderately polluted’ category (Chessman, 1995). Species assemblages from the different streams also differed substantially. The fauna list for the iron stream had no representatives of either Trichoptera or Ephemeroptera, which comprised approximately 50% and 25% of the clear stream fauna, respectively. The junction sample included one family in Trichoptera but lacked Ephemeroptera (Table 3).

DISCUSSION

Despite the temporal and spatial limitations inherent to the Rapid Bioassessment Protocol used in this study, it appears that iron deposition had substantial negative impacts on macroinvertebrate abundance and family-level richness. All indices had high values in the clear stream and low values in the iron and junction streams. This trend was most extreme for abundance, and clear stream samples supported more than ten times the number of macroinvertebrates found in either of the other streams. Another intriguing aspect of the results was the persistence of these effects with distance downstream. The fauna of the uppermost iron

TABLE 1. Abiotic descriptors for each stream. All values represent the mean for each stream.

	Iron Stream	Clear Stream	Junction Stream
% Leaf	37.5	16	22.5
% Cobble	45	60	60
% Canopy Cover	91	90	85
Width (m)	1.5	1.75	1.9
Depth (cm)	7.5	28.75	15
Flow (m/s)	0.24	0.03	0.13

TABLE 2. Results of the three indices calculated for each stream: Shannon-Weiner Diversity Index, SIGNAL (Stream Invertebrate Grade Number – Average Level per family), and SIGNAL-W (weighted by the occurrence of each family).

	Iron Stream	Clear Stream	Junction Stream
Shannon-Weiner	2.07	2.19	2.07
SIGNAL	4.14	6.44	4.71
SIGNAL-W	4.20	6.50	4.23

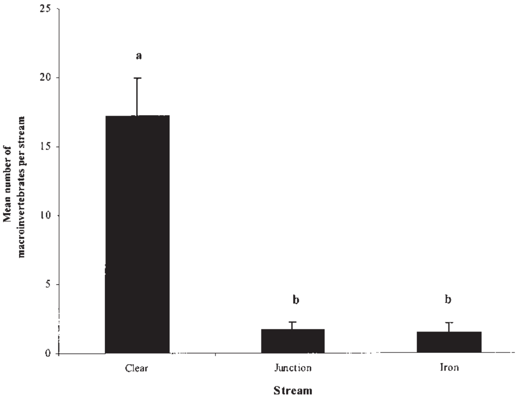

FIG. 2. Mean number of macroinvertebrates per stream. (Letters indicate significance groupings)

sampling site and the lower junction site were equally depauperate, despite more than a kilometre separation, and supported similar macroinvertebrate communities. An exceptionally large distance may be necessary to observe any indications of 'recovery'. A study by Palmer & O'Keefe (1990) of the downstream effects of impoundments on water chemistry, has shown polluted streams may require up to 100km before regaining natural assemblages. In their study potential pollutants included agricultural runoff and urban effluents.

Iron-rich streams negatively impact macroinvertebrate abundance and diversity and alter the remaining species assemblage by affecting taxa differentially (Hynes, 1960). Previous studies of iron-rich streams correlate increases in iron deposition with the disappearance of most flora and fauna (Wellnitz et al., 1994). While still requiring experimental confirmation, the sediment layer created by the iron is the most likely causative agent. After leaving the reservoir, water from the iron stream is no longer anoxic, as the stream is shallow, fast flowing, and the iron has oxidised out of solution. The ochre layer of ferrichydroxide may negatively influence macroinvertebrates in at least five ways: by (1) reducing habitat complexity and available shelter, (2) interfering with holdfast mechanisms of certain species, (3) limiting periphytic algae colonisation, thus decreasing primary productivity and disturbing trophic relationships, (4) coating and blocking animals' respiratory surfaces, and (5) inhibiting proper ion exchange and osmoregulation (Hynes, 1960; Hildrew & Townsend, 1976; McKnight & Feder, 1984; Vuori, 1995). The possibility of toxic effects of iron traces in the water cannot be discounted, especially when levels are well above what is perceived as normal for rainforest streams in an undisturbed state. Unfortunately, few of these possibilities have been satisfactorily tested and their relative importance remains unknown. Presumably, the vertebrate fauna of streams is also affected by iron deposition, whether directly or indirectly. Within this study at least, *Myxophyes schevilli* tadpoles were found within the clear stream but not in either the iron or junction sites.

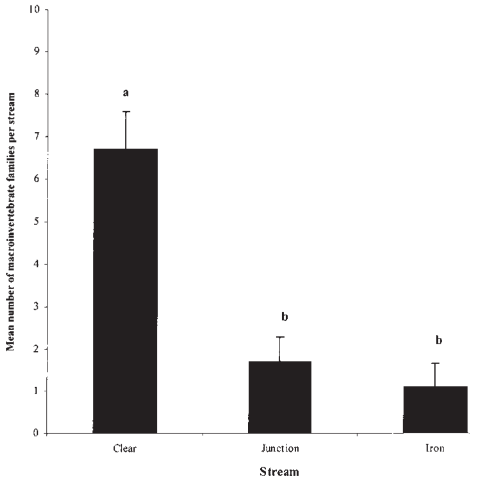

FIG. 3. Mean number of macroinvertebrate families per stream. (Letters indicate significance groupings)

The impacts observed in the current RBP study parallel those of previous studies of iron-rich streams: a diminished fauna consisting of select macroinvertebrate orders. While the order Ephemeroptera is usually well represented in pristine, lotic streams, its absence from iron-rich streams is a universal trend in the literature. In general, mayfly nymphs are among the most sensitive aquatic insects to pollution (Wiederholm, 1984). Chessman (1995) gave Leptophlebiidae, three genera of which were represented in the clear stream but not in neither iron-rich stream, a pollution sensitivity grade of ten. Wellnitz et al., (1994) found three mayfly species showing increased mortality when caged within an area of high ferrichydroxide deposits. Similarly, Harding & Winterbourn (1995) noted poor mayfly representation in pastoral streams with high levels of iron relative to low-iron forest streams. The heightened sensitivity of mayflies is probably related to (1) the exposed nature of

Ephemeroptera gills and (2) their dietary dependence on periphytic algae (Roback, 1974).

The paucity of Trichoptera representatives in iron and junction streams also mirrors results from past studies in temperate areas (Wiederholm, 1984; Harding & Winterbourn, 1995). The two trichopteran families abundantly represented in the clear stream, Helicopsychidae and Leptoceridae, have sensitivity grades of ten and seven, respectively (Chessman, 1995). In contrast, the one caddisfly family found in the junction stream, Ecnomidae, is ranked with a grade of four (Chessman, 1995).

The report of an iron-rich stream within the relatively undisturbed Wet Tropics of north Queensland is potential cause for concern. The volume of water contributed by the iron and clear streams into the junction stream are comparable, but the biotic parameters of the second order stream are clearly more aligned with the iron stream. This finding was supported by all tested indices. In many respects, streams represent the veins of the surrounding landscape, upon which the health of the entire ecosystem may depend. Disturbances impacting waterways can create a type of 'ripple effect', influencing aquatic and terrestrial systems for a considerable distance. In this study, the ripple created by the anoxic stratification of Paluma dam maintained a nearly constant, negative amplitude for over a kilometre downstream. Mono- and biphasic aquatic vertebrates, not to mention terrestrial flora and fauna could suffer direct or indirect harm in areas close to iron-enriched streams. A number of stream breeding frogs have disappeared or are in decline in the Australian Wet Tropics, and further deleterious anthropogenic effects must be minimised (Williams & Hero, 1998).

The absence of multi-depth release valves in a dam or the presence of a fracture leak in a reservoir may seem of minor consequence, but the ecological reverberations can be intense. Iron-rich streams have an altered macroinvertebrate community structure and a shorter trophic chain than their unaffected counterparts (Hildrew et al., 1985). An iron sheath bacteria, *Leptothrix ochracea*, predominates in the presence of iron sediment but is absent in streams undisturbed by ferric hydroxide deposition. *Leptothrix ochracea* reduces naturally important populations of diatoms upon which many aquatic insects and other invertebrates graze (Sheldon & Skelly, 1990). Much of the natural periphyton is similarly lost following an influx of iron sediment. In England, several studies have focussed on iron streams due to the simplicity of their trophic structure (Hildrew et al., 1985; Lancaster & Robertson, 1995). Although little work has been done on iron-rich streams in tropical regions, the Rapid Bioassessment Protocol used in this study yielded the results one would expect with a more quantitative procedure, as illustrated by previous studies of temperate iron streams. Chessman et al. (1997) highlighted the uncertainty around the application of SIGNAL to other river systems, as the relationship between pollution-sensitivity grade numbers and types of polluting agents and disturbances remains unclear. We therefore acknowledge that the results of this study should be considered with appropriate caution until grade numbers developed for specific disturbances become available.

Results of this study are of importance as they demonstrate one of many impacts dam construction can have on local freshwater systems. This is especially disturbing if we consider the future plans for water resources in Queensland. In a recent release from the Department of Natural Resources (1997), 93 proposals for waterway development were recommended as having merit for inclusion in the Queensland Water Conservation Strategy. Considering that construction of dams typically alters the flow regime and water quality of local waterways, these proposals have the potential to increase environmental degradation of Queensland's aquatic habitats. This warrants an increased effort to monitor the impacts of dam construction on the health of aquatic ecosystems and employ such information in subsequent plans for further dam development. Without such research, Queensland, and possibly other regions of the world are in danger of jeopardising the future of their natural waterways.

Continued study of these Paluma streams will focus on three aspects: (1) persistence of the effects of iron deposition with increasing distance from the dam, (2) consequences of iron deposition on aquatic macroinvertebrates and streamside fauna, and (3) exact mechanisms through which deposited iron acts as such a potent disturbance.

ACKNOWLEDGEMENTS

We extend sincere appreciation to Gordon Kovacs for considerable advice and assistance in the keying of macroinvertebrate samples, and to Richard Pearson, for initially directing us toward the study of iron-rich streams and supplying

TABLE 3. Taxonomic list and relative abundance of macroinvertebrates in the Clear, Iron and Junction streams at Paluma.

Order	Suborder	Family	Genus	No. Individuals	% of Total
Iron					
Arachnida		Porohalacaridae		3	0.20
Coleoptera		Elmidae		1	0.07
Diptera		Tanyderidae		2	0.13
Diptera		Thaumaleidae		1	0.07
Diptera		Unidentified		1	0.07
Gastropoda		Planorbidae	*Segnitila*	1	0.07
Hemiptera		Veliidae	*Rhagovelia*	4	0.27
Odonata	Anisoptera	Unidentified		1	0.07
Plecoptera		Gripopterygidae		1	0.07
Clear					
Diptera		Ceraptopogonidae		2	0.01
Diptera		Chironomidae		19	0.11
Diptera		Dixidae		1	0.01
Diptera		Empididae		1	0.01
Diptera		Psychodidae		2	0.01
Ephemeroptera		Caenidae		7	0.04
Ephemeroptera		Leptophlebiidae	*Atalophlebia*	13	0.08
Ephemeroptera		Leptophlebiidae	*Austrophlebiodes*	7	0.04
Ephemeroptera		Leptophlebiidae	*Ulmerophlebia*	8	0.05
Ephemeroptera		Leptophlebiidae	*Unidentified*	8	0.05
Ephemeroptera		Unidentified		2	0.01
Hemiptera		Veliidae	*Rhagovelia*	2	0.01
Odonata	Anisoptera	Corduliidae		2	0.01
Odonata	Anisoptera	Unidentified		1	0.01
Odonata	Zygoptera	Chlorolestidae		2	0.01
Odonata	Zygoptera	Lestoideidae		2	0.01
Plecoptera		Eustheniidae		1	0.01
Trichoptera		Calamoceratidae		5	0.03
Trichoptera		Ecnomidae		4	0.02
Trichoptera		Helicopsychidae		37	0.22
Trichoptera		Leptoceridae		41	0.24
Trichoptera		Philorheithridae		1	0.01
Trichoptera		Polycentropodidae		1	0.01
Junction					
Arachnida		Porohalacaridae		3	0.18
Diptera		Chironomidae		4	0.24
Diptera		Empididae		1	0.06
Diptera		Tipulidae		1	0.06
Diptera		Unidentified		1	0.06
Hemiptera		Veliidae	*Rhagovelia*	1	0.06
Odonata	Anisoptera	Corduliidae		2	0.12
Odonata	Zygoptera	Amphipterygidae		2	0.12
Trichoptera		Ecnomidae		2	0.12

guidance in both experimental design and data analysis for the project. Richard Rowe provided critical information regarding the life histories of some of the collected taxa, for which we are likewise grateful. We are indebted to Zury Soto, Sapna Khandwala, and Eric Beerbohm for editing the manuscript. Marg Criniti deserves special mention for furnishing the necessary supplies and storage space during the course of the study. Logistical support for this project was provided by the Australian Centre for Tropical Freshwater Research.

LITERATURE CITED

CHESSMAN, B.C. 1995. Rapid assessment of rivers using macroinvertebrates: a procedure based on habitat specific sampling, family level identification and a biotic index. Australian Journal of Ecology 20: 122-129.

CHESSMAN, B.C., GROWNS, J.E. & KOTLASH, A.R. 1997. Objective derivation of macroinvertebrate family sensitivity grade numbers for the SIGNAL biotic index: application to the Hunter River system, New South Wales. Marine and Freshwater Research 48: 159-172.

DEPARTMENT OF NATURAL RESOURCES. 1997. Water infrastructure planning and development. (Queensland Government: Brisbane).

HARDING, J.S & WINTERBOURN, M.J. 1995. Effects of contrasting land use on the physico-chemical conditions and benthic assemblages of streams in a Canterbury (South Island, New Zealand) river system. New Zealand Journal of Marine and Freshwater Research 29: 479-492.

HILDREW, A.G. & TOWNSEND, C.R. 1976. The distribution of two predators and their prey in an iron rich stream. Journal of Animal Ecology 45: 41-57.

HILDREW, A.G., TOWNSEND, C.R. & HASHAM, A. 1985. The predatory Chironomidae of an iron-rich stream: feeding ecology and food web structure. Ecological Entomology 10: 403-413.

HYNES, H.B.N. 1960. The biology of polluted waters. (Liverpool University Press: Liverpool).

JONGMAN, R.H.G., TER BRAAK, C.G.F. & VAN TONGEREN, O.F.R. 1995. Data analysis in community and landscape ecology. (Cambridge University Press: Cambridge).

KETO, A. & SCOTT, K. 1986. Tropical rainforests of North Queensland: their conservation significance. (Australian Government Publishing Service: Canberra).

KIM, J.Y. & CHON, H.T. 2001. Pollution of a water course impacted by acid mine drainage in the Imgok creek of the Gangreung coal field, Korea. Applied Geochemistry 16: 1387-1396.

KRENKEL, P.A., LEE, G.F. & JONES, R.A. 1979. Effects of TVA impoundments on downstream water quality and biota. In Palmer, R.W. & O'Keefe, J.H. Downstream effects of impoundments on the water chemistry of the Buffalo River (Eastern Cape), South Africa. Hydrobiologia 202: 71-83.

LAKE, J.S. 1967. Principal fishes of the Murray-Darling River System. Ch. 8. In Weatherly, A.H. (ed.) Australian inland waters and their fauna. (University Press: Canberra).

LANCASTER, J. & ROBERTSON, A.L. 1995. Micro-crustacean prey and macroinvertebrate predators in a stream food web. Freshwater Biology 34: 123-134.

MARCUS, D.B. & ANDERSON, R.D. 1980. Comparative limnology of a deep-discharge reservoir and a surface-discharge lake on the Madison River, Montana. In Palmer, R.W. & O'Keefe, Downstream effects of impoundments on the water chemistry of the Buffalo River (Eastern Cape), South Africa. Hydrobiologia 202: 71-83.

MASCARO, I., BENVENUTI, B., CORSINI, F., COSTAGLIOLA, P., LATTANZI, P., PARRINI, P. & TANELLI, G. 2001. Mine wastes at the polymetallic deposit of Fenice Capanne (southern Tuscany, Italy). Mineralogy, geochemistry, and environmental impact. Environmental Geology 41: 417-429.

MCKNIGHT, D.M. & FEDER, G.L. 1984. The ecological effect of acid conditions and precipitation of hydrous metal oxides in a Rocky Mountain stream. In Wellnitz, T.A., Grief, K.A. & Sheldon, S.P. Response of macroinvertebrate to blooms of iron-depositing bacteria. Hydrobiologia 281: 1-17.

PALMER, R.W. & O'KEEFE, J.H. 1990. Downstream effects of impoundments on the water chemistry of the Buffalo River (Eastern Cape), South Africa. Hydrobiologia 202: 71-84.

PUSEY, B.J. & KENNARD, M.J. 1996. Species richness and geographical variation in assemblage structure of the freshwater fish fauna of the Wet Tropics region of Northern Queensland. Marine and Freshwater Research 47: 563-573.

ROBACK, S.S. & RICHARDSON, J.W. 1974. The effects of acid mine drainage on aquatic insects. In Hart, Jr, C.W. & Fuller, L.H. (eds) Pollution ecology of freshwater invertebrates. (Academic Press: London).

SHELDON, S.P. & SKELLY, D.K. 1990. Differential colonization and growth of algae and ferro-manganese-depositing bacteria in a mountain stream. Journal of Freshwater Ecology 5: 475-485.

VUORI, K.M. 1995. Direct and indirect effects of iron on river ecosystems. Annales Zoologici Fennici 32: 317-329.

WALKER, K.F., HILLMAN, T.J. & WILLIAMS, W.D. 1978. Effects of impoundments on rivers: an Australian case study. In Palmer, R.W. & O'Keefe. Downstream effects of impoundments on the water chemistry of the Buffalo River (Eastern Cape), South Africa. Hydrobiologia 202: 71-83.

WALKER, K. 1981. Effects of weirs on the environment of the Lower River Murray. SAFIC 5(6): 26-29.

WELLNITZ, T.A., GRIEF, K.A. & SHELDON, S.P. 1994. Response of macroinvertebrate to blooms of iron-depositing bacteria. Hydrobiologia 281: 1-17.

WELLNITZ, T.A. & SHELDON, S.P. 1995. The effects of iron and manganese on diatom colonization in a Vermont stream. Freshwater Biology 34: 465-470.

WIEDERHOLM, T. 1984. Responses of aquatic insects to environmental pollution. Ch. 17. In Resh, V.H. & Rosenberg, D.M. (eds) The ecology of aquatic insects. (Praeger Publishers: New York).

WILLIAMS, S.E., PEARSON, R.G. & WALSH, P.J. 1996. Distributions and biodiversity of the terrestrial vertebrates of Australia's wet tropics: a review of current knowledge. Pacific Conservation Biology 2: 327-362.

WILLIAMS, S.E. & HERO, J.M. 1998. Rainforest frogs of the Australian wet tropics: guild classification and the ecological similarity of declining species. Proceedings Royal Society London Series B Biological Sciences 265: 597-602.