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EFFECTS OF RURAL DEVELOPMENT ON THE WATER QUALITY OF CENTRAL THAILAND STREAMS

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ABSTRACT

Tropical streams provide a variety of valuable goods (e.g., food, water) and services (e.g., swimming, effluent disposal) to local inhabitants. Rural development of catchments threatens these resources as forests adjacent to streams are removed and replaced with other land uses. This study examined the effect of rural development on the water quality of a tropical stream as reflected by the benthic macroinvertebrate fauna. Differences in the composition of benthic macroinvertebrate fauna were noted among sites that differed in riparian forest cover. The density of benthic macroinvertebrates was higher at three rural sites compared with a forested reference site; taxa richness was slightly higher. The percent of local forest cover along the stream accounted for the difference in benthic macroinvertebrate and scraper density at the sites. Solar irradiance explained many of the differences in the benthic fauna. It appears that the benthic fauna in tropical streams responds to changes in land use in a similar manner to those in temperate streams.

Keywords : Benthic ecology; bioassessment, riparian forest; tropical stream, land use, lotic limnology.

INTRODUCTION

Watercourses abound throughout Thailand, as elsewhere in Southeast Asia. These systems have greatly influenced the development of human society because they freely provide a continuous supply of essential goods and services (i.e., resources). The goods provided include freshwater for potable, domestic, agricultural (e.g., irrigation) and industrial (e.g., process and cooling) needs; food in the form of fish (e.g., snakeheads, swamp eels), macroinvertebrates (e.g., shrimp, crabs, water

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roaches, diving beetles), waterfowl (e.g., ducks) and wildlife (e.g., turtles); and power (e.g., water power, hydroelectric),while the services provided include recreational activities such as swimming, boating, and fishing; a ready transportation corridor for domestic travel and commercial goods; an effluent disposal system for agricultural, domestic, and industrial wastes; and others (e.g., esthetics, spiritual, border marking). However, only watercourses with unimpaired water quality conditions produce the goods and services expected by local inhabitants. With declining water quality, watercourses yield fewer and fewer resources. In severe circumstances, watercourses may even become a source of diseases and pests that can profoundly affect local inhabitants. These watercourses that fail to provide expected goods and services are commonly referred to as polluted.

Water quality impairment can result from a direct modification to a watercourse (e.g., dams) or by exceeding the ability of watercourses to assimilate specific wastes from industrial (e.g., metals, acids, organics, heat), mining (e.g., metals, arsenic, mercury), agricultural (e.g., suspended solids, nutrients, pesticides) or domestic (e.g., sewage) operations. Typically, however, water quality impairment is caused by landscape modifications within the watershed. Beyond a specific limit, the replacement of native vegetation with agricultural (e.g., sugar cane, pineapple, rice, cashew, rubber, fruit trees, shrimp), silvicultural (e.g., eucalyptus plantations), industrial, and urban land uses affects the functional interactions between a watercourse and adjacent lands. Clearing of natural vegetation has proceeded rapidly in the latter part of the twentieth century. Thailand's estimated annual deforestation rate of 2.0 to 2.5% prior to the mid-1980s was among the highest in the world (Laurance, 1999; Rigg, 1995). Meanwhile, Thailand's rapidly expanding population, increasing at 4.6% per year (Rigg, 1995), continuously requires more land for rural and urban uses.

Replacement of native forests with other land uses impairs the water quality of watercourses through several indirect mechanisms. For example, loss of trees reduces transpiration of water. Consequently, a greater proportion of precipitation drains to watercourses thereby increasing their flows (Bishop, 1973). Filling depressions and wetlands and increasing the imperviousness of the land through the construction of buildings, roads, and infrastructure results in less water storage during the rainy season and thus reduced flows during the dry season when water is most needed. Combined, these processes increase the frequency and intensity of flood flows during the rainy season and increase the frequency and intensity of low or no-flow conditions in the dry season (Dudgeon, 1999). Deforestation was found to be the prime factor for the devastating floods of 1988 that claimed several hundred lives (Rigg, 1995), and subsequently resulted in Thailand proclaiming a ban on logging operations (Bangkok Post, April 19, 1998). Today, Thailand is a net importer of wood (Rigg, 1995). Illegal logging, however, continues, with logs hauled to neighboring countries and then exported to Thailand (Campbell and Parnrong, 2000).

Native vegetation along watercourses (riparian forests) typically is the first to be replaced with buildings, roads and agriculture when rural development occurs within a watershed. This activity may reduce the productivity of watercourses since allochthonous inputs decline, which are an important component of the diet of invertebrates (e.g., shrimps, crabs) and fishes (Dudgeon, 2000). Furthermore, the loss of trees may increase soil erosion. In a watercourse, these soils increase turbidity and suspended solids that may reduce primary production. When flows slow, these materials settle on the bottom, thereby filling interstitial spaces and reducing secondary production of benthic macroinvertebrates. However, rural development may also promote higher productivity within the watercourse. Increased solar radiation from the reduction of shade will stimulate autothchonous (periphyton) primary production. Furthermore, added nutrients from adjacent lands may also promote primary production. Since inland fishery resources are heavily exploited in Thailand (FAO, 1999), and local inhabitants heavily rely upon these resources as a protein source, understanding the relationship between rural development and water quality is essential for social planning and environmental management.

One of the best means of measuring water quality is through an assessment of the structure and composition of the benthic macroinvertebrate fauna. These animals are continuously exposed to the environmental conditions in the watercourse during their larval life, which typically lasts from a few weeks to a few months, and thus they reflect the environmental conditions over a period of time. Benthic macroinvertebrates are known to be sensitive to a wide variety of abiotic and biotic variables (Hellawell, 1986; Hynes, 1970, 1960), many of which are altered through land use changes, and are functionally dependent on their associated riparian vegetation (Vannote et al., 1980; Cummins, 2001). Consequently, they provide a direct ecological measure of the quantity and quality of goods and services afforded by the local ecosystem. A marked shift in the benthic composition indicates the effect of a specific stress on the system and signals a reduction in resources and services provided by the watercourse. Although, this group of organisms is widely used to assess water quality conditions in temperate environments (Rosenberg and Resh, 1993), only recently has this group been used in tropical watercourses (e.g., Thorne and Williams, 1997).

The purpose of our study is to examine the effect that rural development, as reflected by near-stream forest cover, has on the water quality of a tropical stream, as reflected by the benthic macroinvertebrate fauna.

METHODS

Study area and design

A number of central Thailand watercourses draining the hills along the Burmese or Cambodian borders to the Gulf of Thailand were examined for this study, exclusive of the Chao Phraya watershed (Latitude of 11° to 15°N). Flows in these watercourses are typically minimal in late winter (March) and peak in late summer (August-September) since 90% of the annual 1.4 to 1.8 m of rainfall falls from May through November (Tyler, 1984). These highland streams are found at an elevation of 100 to 400 m. Rarely would these streams experience air temperatures less than 15°C and daily mean water temperatures would rarely drop below 20°C because the temperature of groundwater inflows is close to the annual mean air temperature (Bishop, 1973; Weber, 1959).

A similar land use pattern was observed throughout these drainage basins. The height of land typically forms the border between Thailand and southern Burma in the east and southern Cambodia in the west. Watercourses thus originate along the border regions and flow initially through relatively undisturbed jungle (bamboo and dipterocarpous rainforest). However, within a short distance of the border and at a slightly lower elevation, the jungle is effectively replaced with agriculture crops (e.g., rubber, coconut, fruit trees, sugar cane, tapioca) and small villages (i.e., rural development). In addition, large reservoirs have been constructed on a number of watercourses for the supply of electricity, irrigation water and potable water. Numerous small in-stream dams and off-stream ponds are also found within the drainage basins. Large urban centers and resorts are mainly located along the lower reach of these watercourses within a short distance of the Gulf of Thailand.

To assess the effects of rural development on water quality, four sampling sites were established along the Huay Kayeng (upper tributary of the River Kwai Noi) upstream of the reservoir formed by the Khao Laem dam (Figure 1). Site 1 was located just within the Thong Pha Phum National Forest at the border post on the road leading to Burma. It was reported that only 10 families lived within the upstream watershed. The stream was well shaded by a native bamboo forest that occurred throughout the upstream watershed. The substrate was composed of large rocks, cobble, and gravels with accumulations of sands in depressions and on the downstream sides of large rocks. Leaf litter and woody debris was evident throughout the watercourse.

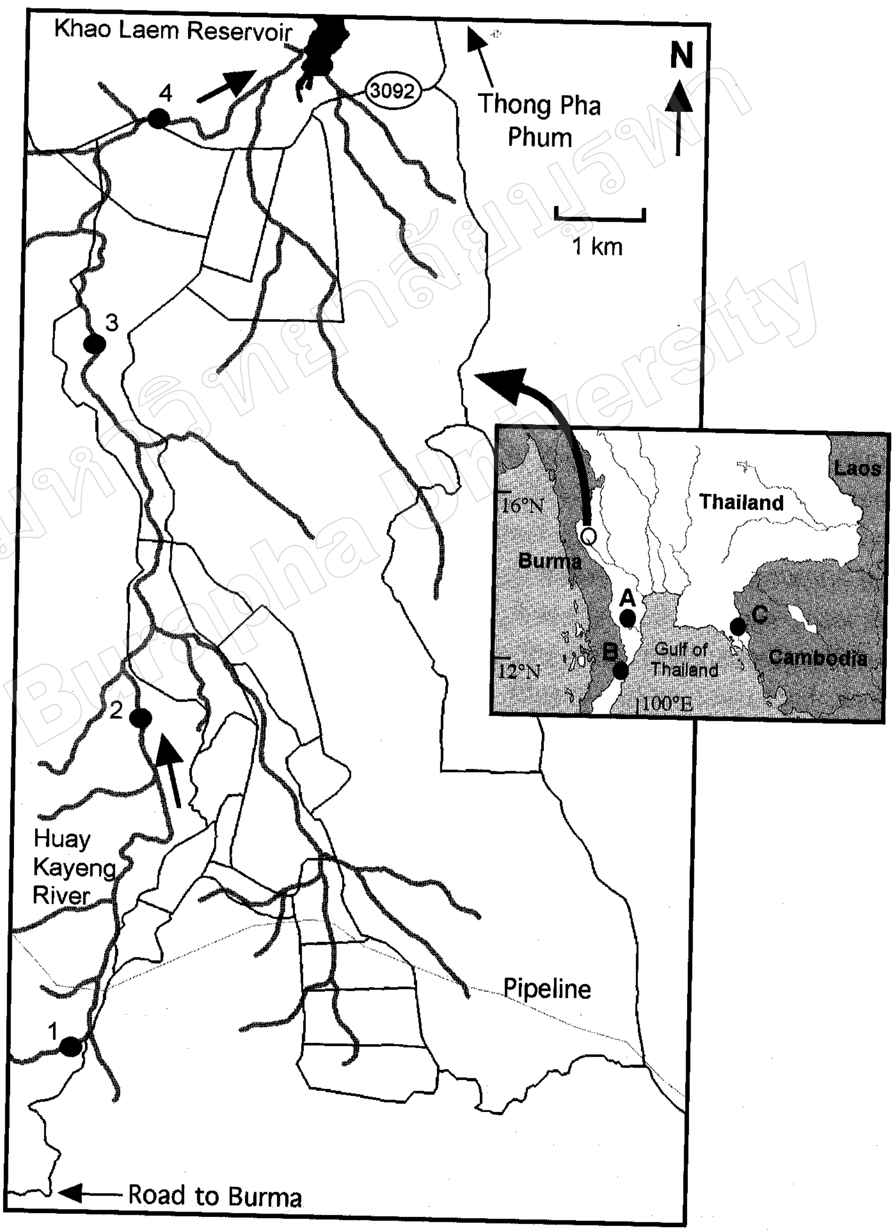

Figure 1. Location of sampling sites in central Thailand.

The three other sites (sites 2-4) were located between the Thong Pha Phum National Forest and the reservoir. From Site 1, Site 2 was located about 4.5 km downstream, Site 3 about 10 km downstream and Site 4 about 13 km downstream at the bridge over the main road (Road 3092). Land use outside of the National Forest was characteristic of rural development, consisting mainly of farmland, small villages, unpaved roads and patches of native vegetation. A measure of the amount of rural development surrounding a sampling site was determined by estimating the per cent of land under forest cover (in one of ten categories: 0-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-90%, 90-100%) in the area enclosed by a 100 m by 100 m square (1 ha) with the sampling site located at the centre of the downstream edge. This measure is referred to as per cent local forest cover, with 100% local forest cover indicating an absence of rural development around the site and 0% local forest cover indicating complete rural development around the site.

Our measure of water quality was based on the similarity in the composition of the benthic macroinvertebrate fauna relative to the upstream reference site (Site 1). We assumed that the water quality conditions at Site 1 provided reasonable "reference conditions" for comparison with the three downstream rural sites because of the short distance between sites and the similarity in substrate and slope. Thus in the absence of any anthropogenic effects, the benthic fauna at sites 2-4 should be similar to that at Site 1. To assess the representativeness of the reference site in the Thong Pha Phum National Forest, the benthic fauna in three additional central Thailand watercourses was sampled. Since these additional sites were located at the interface between the upstream native forest and downstream rural land use, we assumed that they also reflected reference water quality conditions.

Methods of sampling and analysis

Benthic macroinvertebrates were collected at all sites using BioMAP sampling protocols (Griffiths, 1999) in March of 2001 or 2002. Quantitative samples were collected in a riffle area at each of the four sites along the Huay Kayeng using a Surber sampler that enclosed an area of 0.09 m^2 and had a 600 μm mesh collecting net. Qualitative samples were collected at each of the four reference sites by sweeping an A-frame net through the water while disturbing the various substrates (e.g., sand, gravel, woody debris, aquatic vegetation) at the sampling site (i.e., kick and sweep method). Contents of the A-frame net were frequently emptied into a bucket with stream water. In addition, organisms found on large individual stones and pieces of wood were added to this sample. All macroinvertebrates collected over a period of about 30 minutes were included in the sample. Each sample was filtered through a 500 μm sieve. The organisms and debris retained in the sieve were placed in a labelled bottle filled with 95% ethanol.

The benthic macroinvertebrates (insects, crustaceans, molluscs, annelids, flatworms) were separated from the debris in each sample under a low-power microscope. Only organisms with a body width greater than 500 μm were retained and counted. Organisms were identified to family, and then common taxa were identified to the lowest practical level using available keys (e.g., Dudgeon, 1999; Zettel, 1998; Morse et al., 1992; Upatham et al., 1983) and species descriptions (e.g., Lee and Yang, 2002; Sites et al., 1997; Muller-Liebenau, 1984). Scrapers (functional-feeding group) were identified among the benthic taxa using Dudgeon (1989) and Merritt and Cummins (1996) and by directly examining the mouthparts of specimens.

In addition to the benthic samples, water conductivity, temperature, turbidity and pH were measured with calibrated meters and the concentration of dissolved oxygen, total phosphorus, phosphate, silica, ammonia and nitrate and alkalinity were determined through chemical means (APHA, 1981). It is assumed that the water temperature, dissolved oxygen concentration and pH measurements were near the maximum daily values and that the conductivity measurements were near the daily minimum values, which typically occur in the late afternoon (Griffiths, 1999). Furthermore, a variety of site characteristics (e.g., fish, algae, macrophytes, substrate type, riparian vegetation) were also recorded including the width of the watercourse under bankfull conditions.

Percent Model Affinity (Novak and Bode, 1992) was used to calculate the similarity in the relative abundance of benthic macroinvertebrates at the familial level between the Thong Pha Phum reference site and the three downstream rural sites as well as between the Thong Pha Phum reference site and the three additional reference sites. Least-square regression analyses were used to examine the relationship between benthic community structure and per cent local forest cover.

RESULTS

The upstream reference site on the Huay Kayeng compared well to the physicochemical (Table 1) and benthic data (Table 2) obtained at the other three reference sites in central Thailand. Despite the great variation in discharge (20-250 L/s), the water at all these sites was low in dissolved ions (conductivity < 80μS/cm), alkalinity (<50 mg/L), and turbidity (<6.0 NTUs) and was circumneutral (pH of 6.8 to 7.3 at noon). Total phosphorus varied from 0.1 to 0.4 mg/L and was lower than the concentration of nitrate at all sites, which varied from 0.2 to 1.5 mg/L. Ammonia was below detection (<0.01 mg/L) at all sites. Dissolved oxygen varied from 6.6 to 7.5 mg/L and was always near saturation.

Table 1. Physicochemical characteristics at seven watercourse sites in central Thailand in early March 2001 (Site A) or 2002 (other sites). Sites 1-4 were along the Huay Kayeng upstream of the Khao Laem Reservoir, Kanchana Buri. Site A was on the Pran Buri River in the Pa Lao U National Park, Phetcha Buri. Site B was at the Yat Sai Koo Waterfall, Phachuap Kiri Khan. Site C was in the Khao Kaeo National Park, Trat.

	Pran Buri	Waterfall	Nat'l Park	Huay Kayeng			
	A	B	C	1	2	3	4
Bankfull width (m)	10	9	6	12	14	11	15
Discharge (L/s)	250	80	20	160	170	460	570
Max. Temperature (°C)	25	26	27	23	27	25	26
Turbidity (NTU)	1.8	6.0	<1.0	1.6	3.0	6.6	8.2
Conductivity (μS/cm)	80	70	60	50	80	290	330
Alkalinity (mg/L)	46	19	23	25	40	132	176
pH	7.0	7.1	7.3	6.8	7.3	8.1	8.1
Ammonia-N (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Nitrate-N (mg/L)	0.8	1.5	0.2	1.5	1.6	1.0	0.9
Total Phosphorus (mg/L)	0.2	0.2	0.1	0.4	0.4	0.3	0.2
Phosphate (mg/L)	0.02	0.06	0.02	0.10	0.08	0.01	N/A
Silica (mg/L)	10.0	29.6	20.4	17.0	22.4	14.4	18.6
Dissolved Oxygen (mg/L)	6.6	6.6	7.2	7.5	7.9	6.4	6.8

Table 2. Relative abundance (%) of benthic macroinvertebrates at 4 reference stream sites in central Thailand. Site 1 was along the Huay Kayeng upstream of the Khao Laem Reservoir, Kanchana Buri. Site A was on the Pran Buri River in the Pa Lao U National Park, Phetcha Buri. Site B was at the Yat sai Koo Waterfall, Phachuap Kiri Khan. Site C was in the Khao Kaeo National Park, Trat. Samples collected in March of 2001 (Site C) or 2002 (others). See Figure 1 for location of sites.

	Pran Buri River A	Yat sai Koo Waterfall B	Khao Kaeo Nat'l Pk C	Huay Kayeng 1
Insects:				
BEETLES:				
Dryopidae		<1.0	1.3	3.7
Elmidae	<1.0	3.1	<1.0	1.5
Hydrophilidae	1.6	10.0		5.2
Lampyridae				<1.0
Limnichidae			<1.0	<1.0
Psephenidae	1.6	3.1	1.8	0.7
Scirtidae	2.4	1.3	<1.0	1.5
BUGS:				
Aphelocheiridae		<1.0		3.7
Corixidae	3.1		2.3	
Gerridae	<1.0	<1.0	<1.0	<1.0
Helotrephidae				<1.0
Naucoridae	<1.0	1.3		1.5
Nepidae		<1.0		
CADDISFLIES:				
Calamoceratidae				<1.0
Ecnomidae			<1.0	
Goeridae		1.3		
Hydropsychidae	15.0	7.5	5.4	9.0
Leptoceridae	<1.0	1.3	1.3	<1.0
Odontoceridae	<1.0	1.9		
Philopotamidae	<1.0	5.6	2.3	
Polycentropodidae		1.3	<1.0	
Psychomyiidae			<1.0	
Stenopsychidae	8.7	1.3	<1.0	<1.0
Xiphocentronidae	6.3			

	Pran Buri River A	Yat sai Koo Waterfall B	Khao Kaeo Nat'l Pk C	Huay Kayeng 1
DAMSELFLIES:				
Euphaeidae	<1.0	<1.0	1.0	
DRAGONFLIES:				
Corduliidae				<1.0
Gomphidae		1.9		3.7
Libellulidae		<1.0		
Macromiidae		1.3		
MAYFLIES:				
Baetidae	17.3	14.4	14.8	10.4
Caenidae	1.6	<1.0	13.5	1.5
Ephemerellidae			2.0	3.7
Ephemeridae	<1.0	3.8		
Heptageniidae	5.5	2.5	14.0	1.5
Leptophlebiidae	10.2	12.5	8.9	13.4
Neoephemeridae		2.5		
Prosopistomatidae				5.2
Teloganodidae	2.4		<1.0	<1.0
MOTHS:				
Pyralidae		<1.0	1.5	2.2
STONEFLIES:				
Perlidae	6.3	1.9	<1.0	6.0
TRUE FLIES:				
Athericidae				1.5
Blephariceridae			<1.0	
Ceratopogonidae			1.3	
Chironomidae	2.4	4.4	22.2	6.7
Culicidae			<1.0	
Muscidae	<1.0			
Simuliidae		1.3		<1.0
Tipulidae	<1.0	3.1	1.0	2.2

	Pran Buri River A	Yat sai Koo Waterfall B	Khao Kaeo Nat'l Pk C	Huay Kayeng 1
Crustaceans:				
CRABS:				
Potamidae		<1.0		<1.0
SHRIMPS:				
Atyidae				1.5
Palaemonidae	<1.0	1.3		<1.0
Molluscs:				
SNAILS:				
Thiaridae		1.9		3.7
Paludomidae	3.9	<1.0		<1.0
Annelids:				
LEECHES:				
Hirudinidae		<1.0		
WORMS:				
Naididae	<1.0		<1.0	
Platyhelminthes:				
FLATWORMS:				
Tricladida	2.4	1.9		
Total Families	**28**	**37**	**29**	**35**
Total Taxa	**41**	**52**	**46**	**46**

A total of 107 benthic taxa in 56 families were found at the four reference sites (Table 2). The Huay Kayeng reference site had 46 taxa representing 35 families, which was similar to that found at the other reference sites. Fourteen families occurred at all sites including the mayfly families: *Baetidae*, *Caenidae*, *Heptageniidae*, *Leptophlebiidae*, the caddisfly families: *Hydropsychiidae*, *Leptoceridae*, *Stenopsychidae*, and the beetle families: *Elmidae*, *Psephenidae*, *Scirtidae*. The relative abundance of insects exceeded 90% at all sites, with mayflies being the predominant group of insects (39% to 54%) followed by caddisflies (10% to 35%) (Figure 2). Crusteaceans, molluscs, annelids and flatworms each accounted for generally less than 4% of the fauna. Ten species were common to all sites, including the beetles: *Zaitzevia* and *Hydrocyphon*, the caddisflies: *Stenopsyche*, *Cheumatopsyche*, *Hydropsyche*, the mayflies: *Baetis idei*, *Baetis gombaki*, *Caenis*, *Isca*, and the stonefly:

Neoperla. Overall, the relative abundance of the benthic fauna at the Huay Kayeng reference site showed a 45 to 62% similarity with the other three reference sites, as measured by the percent model affinity index.

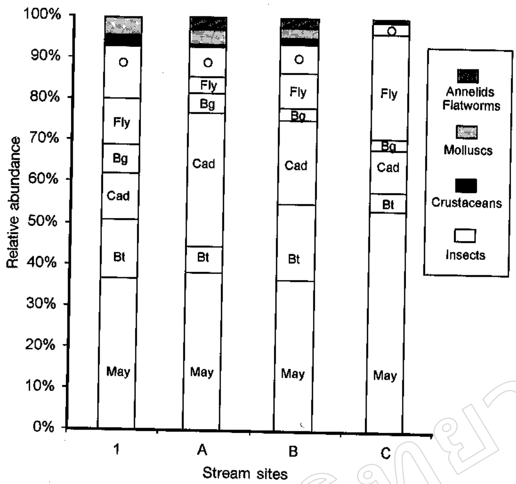

Figure 2. Relative abundance of benthic macroinvertebrates at four Thailand reference stream sites. Insect category separated into orders: May = Mayflies; Bt = Beetles; Cad = Caddisflies; Bg = Bugs; Fly = True Flies; O = Other orders. Samples collected in March 2001 (Khao Kaeo Nat'l Park) or 2002 (others). See Figure 1 for site locations.

Consistent downstream trends along the Huay Kayeng were found in a number of physico-chemical variables (Table 1). Discharge increased with downstream distance with a large increase noted between sites 2 and 3 as several tributaries contributed water between these sites. Water temperature was the coolest at the reference site, although temperatures at the downstream sites were only a few degrees higher. Site 2 had the highest water temperature possibly because the stream here was wide and shallow and open to solar radiation. Air temperatures exceeded 35°C on all sampling days.

Turbidity increased with downstream distance reflecting an increase in suspended solids. The waters were clear and lacked color at all sites. Waters at sites 2-4 were noticeably turbid during and following the rainy season (F.W.H. Beamish, personal observation).

Conductivity also increased with downstream distance indicating an increase in dissolved ions. Alkalinity accounted for some of this increase in conductivity. Since nutrient concentrations (nitrate and phosphorus) declined with downstream distance, these variables did not account for the increase in dissolved ions. Conductivity values as high as 410 µS/cm were measured in tributaries flowing adjacent to a field of lime trees and other agricultural crops.

A total of 95 taxa in 49 families occurred in the riffle habitat of the four sites along the Huay Kayeng (Table 3). The riffle fauna was composed primarily of insect taxa (39 families), with some mollusc taxa (6 families) and a few annelid (2 families), crustacean (1 family), and flatworm taxa (1 family). A total of 45 benthic macroinvertebrate taxa occurred at the upstream reference site (Site 1), which was not significantly different from the 44-51 taxa found at the 3 downstream rural sites (t-test; $p>0.5$).

Table 3. Benthic macroinvertebrate composition (number per 0.09 sq. m.) at 4 sites along the Huay Kayeng upstream of the Khao Laem Reservoir, Kanchana Buri. Samples collected March 2002. See Figure 1 for site locations.

	Huay Kayeng			
	1	2	3	4
Insects:				
ALDERFLIES:				
Corydalidae		3		
BEETLES:				
Dryopidae		1		1
Elmidae	8	22	57	50
Gyrinidae			2	
Hydrophilidae	12	16		
Limnichidae	3	12		
Psephenidae	14	14	51	115
Salpingidae	1			
Scirtidae	1		5	7
BUGS:				
Aphelocheiridae		1		1
Helotrephidae		51	6	29
Hydrometridae				1
Naucoridae	1		7	6
CADDISFLIES:				
Goeridae		1		5
Helicopsychidae			1	1
Hydropsychidae	14	25	11	9
Hydroptilidae		3	1	1
Leptoceridae	1	2	2	5
Odontoceridae		1		1
Philopotamidae				2
Psychomyiidae	2			2
Xiphocentronidae	1			
DAMSELFLIES:				
Euphaeidae		1	2	3

	Huay Kayeng			
	1	2	3	4
DRAGONFLIES:				
Gomphidae	7	4		
Libellulidae		1		
MAYFLIES:				
Baetidae	10	292	29	51
Caenidae		2	1	
Ephemerellidae	5	3		5
Heptageniidae	4	16	78	54
Leptophlebiidae	12	3	7	1
Neoephemeridae	4	1		1
Prosopistomatidae	9	13	20	10
MOTHS:				
Pyralidae	5	8	5	1
STONEFLIES:				
Perlidae	12	16	7	4
TRUE FLIES:				
Chironomidae	44	43	9	14
Ephydridae	1			
Simuliidae	1	4	1	4
Tabanidae		2		
Tipulidae	4	2	7	21
Crustaceans:				
CRABS:				
Potamidae	1			
Molluscs:				
BIVALVES:				
Corbiculidae				1
Sphaeriidae			1	8

In addition to the higher density of snails, higher densities of mayflies, particularly baetids and heptageniids, bugs, especially helotrephids, and beetles, notably elmids and psephenids, were also observed at all rural development sites (Table 3). Furthermore, several species abundant at the rural development sites, such as *Liebebiella*, *Cinygmina*, *Fischerotrephes*, *Microeubria*, *Stenelmis* and *Zaitzevia*, were not detected at the reference site (Table 4). Meanwhile, only a few rare species (*Isca*, *Epeorus*, *P. caenoides*, *Ordobrevia*) present at the reference site were not collected at the downstream sites. Overall, the relative abundance of the benthic fauna at the three downstream sites showed only a 32 to 37% similarity with that at Site 1, as measured by the percent model affinity index. The benthic fauna at these sites thus were consistently less similar to that at Site 1 compared with the fauna found at the three additional reference sites.

Table 4. Density of specific benthic macroinvertebrates (number per 0.09 sq. m.) at 4 sites along the Huay Kayeng upstream of the Khao Laem Reservoir, Kanchana Buri. Samples collected March 2002. See Figure 1 for site locations.

	Huay Kayeng			
Sites	**1**	**2**	**3**	**4**
BEETLES:				
Elmidae:				
Ordobrevia	2			
Stenelmis		13	27	40
Zaitzevia		9	20	5
Zaitzeviaria			1	5
Psephenidae:				
Psephenoides	14	6	25	80
Microeubria		8	25	35
Scirtidae:				
Hydrocyphon	1		5	7
BUGS:				
Helotrephidae:				
Fischerotrephes		51	6	29

	Huay Kayeng			
Sites	**1**	**2**	**3**	**4**
Naucoridae:				
Gerstroiella limnocoroides			2	1
Naucoris scutellaris	1		5	5
MAYFLIES:				
Baetidae:				
Baetis gombaki		22	15	18
Baetis idei	4	25	6	19
Liebebiella		239	6	13
Plauditus		2	1	1
Heptageniidae:				
Epeorus	4			
Cinygmina		16	78	54
Leptophlebiidae:				
Choroterpes	5	1	1	
Choroterpides	1	1	6	1
Habrophlebiodes	4	1		
Isca	2			
Neoephemeridae:				
Potamanthellus caenoides	4			
Potamanthellus edmundsi		1		1
Prosopistomatidae:				
Prosopistoma	9	13	20	10

The density of benthic macroinvertebrates was negatively related to the percent local forest cover (Figure 4). Similarly, the density of scrapers (e.g. snails, elmids, psephenids, baetids, heptageniids, helicopsychids, goerids) was negatively related to the percent local forest cover. A weaker negative relationship was noted between taxa richness and percent local forest cover (Figure 4).

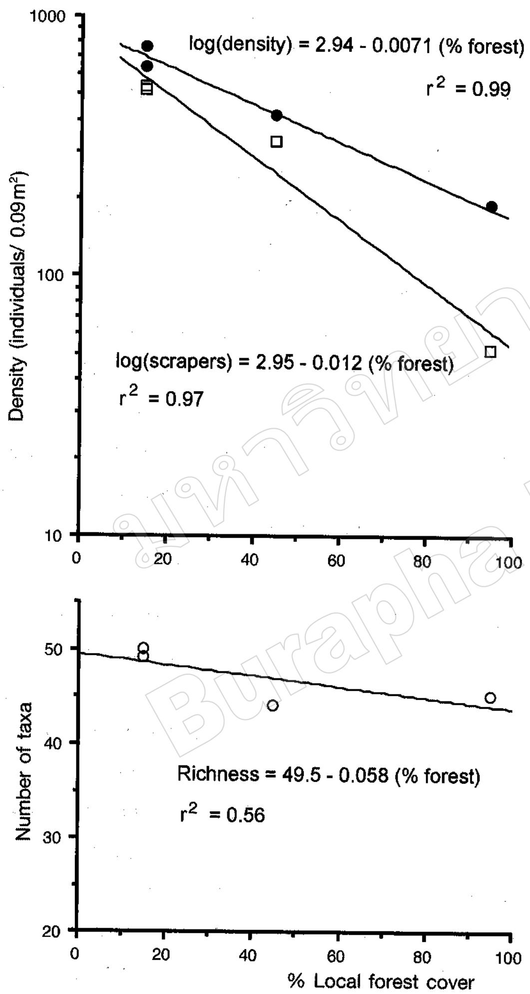

Figure 4. Regression of total benthic macroinvertebrate density (individuals/0.09m^2), scraper density (individuals/0.09m^2) and taxa richness (number of taxa per sample) on % local forest cover at 4 sites along the the Huay Kayeng, March 2002.

DISCUSSION

Our upstream site on the Huay Kayeng appears to characterize the natural conditions of highland streams in Thailand well and thus provided a sound basis to assess changes in water quality. However, it must be stated that the natural physicochemical conditions and native biological faunae of Thailand streams are not well documented. Still, the physicochemical conditions and fauna at Site 1 were similar to those at three other highland sites that also appeared to be exposed to little anthropogenic influence. The water at all sites was circumneutral, clear, and although low in total dissolved ions and alkalinity, enriched with silica (Table 1). Similar conditions have been reported in the little disturbed upper tributaries of the River Kwai Noi in 1975 (Tyler, 1984), the upper Gombak River of Malaysia (Bishop, 1973) and the upper reaches of two Hong Kong streams (Dudgeon, 1990, 1982). The upper catchment of each of our reference streams is still largely forested, contains little farming activity, and is set on bedrock composed of granite, quartzite, and other metamorphic rocks (Wongsawat, 1985). Millar (1961) noted that streamwaters draining granite and quartzite bedrocks had silicate concentrations of 17-30 mg/L, alkalinity of 37-50 mg/L, nitrate of 0- 1.5 mg/L and pH of 6.4 to 7.3. Our measurements are very comparable to those of Millar (1961), suggesting that our reference sites do reflect expected water quality conditions of streams draining catchments with weather-resistant bedrocks and shallow soils.

Aquatic insects accounted for more than 90% of benthos at all reference sites, with mayflies, caddisflies, beetles, bugs and true flies accounting for most of the individuals in the fauna (Figure 2) and the majority of the families at the site (Table 2). This is quite consistent with the benthic composition in streams in other parts of southeast

Asia (Dudgeon, 1999) and other parts of the world (Hynes, 1970), possibly reflecting the origins of these groups on the supercontinent of Pangea. The presence of the mayflies: *Chopralla*, *Platybaetis*, *Epeorus*, *Choroterpides*, *Isca*, *Potamanthellus caenoides*, *Macafertiella*, *Teloganodes*, caddisflies: *Ganonema*, *Ecnomus*, *Chimarra*, *Stenopsyche*, *Melanotrichia*, stoneflies: *Etrocorema*, *Phanoperla*, the bug: *Aphelocheirus femoratus*, the dragonfly: *Macromia* and the restricted abundance of snails and annelids clearly suggest that these sites reflect unimpaired water quality conditions (McCafferty and Wang, 2000; Dudgeon, 1999, 1990; Sites et al., 1997; Wiggins, 1996; Sivec et al., 1988; Müller-Liebenau, 1984; Bishop, 1973).

The transformation of jungle into a rural environment likely accounts for observed differences in the fauna of the Huay Kayeng. The density of benthic macroinvertebrates was consistently higher at the rural sites relative to the upstream reference site (Table 3), inferring a greater standing crop and production of benthos at these rural sites. Local forest cover was able to explain most of the variation in benthic abundance (Figure 4). Furthermore, many of the species that accounted for the higher abundance of macroinvertebrates were scrapers (Tables 3 and 4) that feed on periphyton and associated bacteria and organic matter. This group of organisms is expected to increase in abundance with an increase in light (Vannote et al., 1980). The variation in scraper abundance was also directly linked to local forest cover (Figure 4). Although short lengths of filamentous green algae were noticeable on rocks at the three rural sites, these algae were never sufficiently abundant to produce noticeable green patches within the stream. The decreasing phosphorus and nitrate concentrations from Site 1 to Site 4, however, suggest that these nutrients were being more rapidly removed from the water at the rural sites, probably as a consequence of greater algal production resulting from increased light. The low biomass of periphyton observed at these sites is likely the result of a high grazing rate from the higher abundance of macroinvertebrate scrapers. Snails, in particular, have been shown to prevent an increase in stream periphyton biomass despite an experimental increase in irradiation that increased periphyton production (Steinman, 1992). Similarly, a number of studies have shown that the development of a thick mat of filamentous green algae in streams occurs only following reductions in scraper larval abundance whether through insecticides (Eichenberger and Schlatter, 1978; Ide, 1967), unfavorable environmental conditions (Shea, 1994), experimental manipulations (Lamberti and Resh, 1983), or emergence (Griffiths, 1987). Since the synchronized spring emergence of lotic insects noted in temperate streams (Hynes, 1970) is not generally observed in tropical streams (Dudgeon, 1999), periphyton in tropical streams have little relief from grazing except possibly during the rainy season when high flows and deep and turbid waters would then physically limit algal standing stocks.

Dudgeon (1989) similarly noted that the density of benthic macroinvertebrates was 2 to 3 times higher in Hong Kong streams with a more open canopy than in the completely shaded stream. Furthermore, the density of scrapers was also higher in streams with a more open canopy. The proportion of scrapers in the total community, however, did not vary significantly among streams, in contradiction to the River Continuum Concept (Vannote et al., 1980), which predicts a greater proportion of scrapers in streams with open canopies over streams with closed canopies. In contrast, the ratio of the two regression slopes in Figure 4 (= 0.012/0.0071) suggests that the relative abundance of scrapers in our study showed an instantaneous rate of increase of 70% within the benthos as forest cover declined which does correspond with the prediction of the River Continuum Concept. Finally, Dudgeon found that periphyton biomass was highest in the unshaded streams while detrital biomass was highest in the completely shaded stream thus linking the local forest cover with the food resources in the streams.

In temperate regions, unshaded streams generally also support higher benthic macroinvertebrate densities compared with shaded streams (Hawkins et al., 1982; Behmer and Hawkins, 1986), with algal-feeding taxa showing the greatest increase (Fuller et al., 1986; Towns, 1981; Thorup, 1966). This higher abundance in unshaded streams appears to result from higher production (Sweeny, 1993; Wallace and Gurtz, 1986; Behmer and Hawkins, 1986; Hopkins, 1976). Response of benthos to a reduction in adjacent forest cover thus appears similar in temperate and tropical streams.

Although a number of interacting mechanisms associated with the removal of the riparian forest, such as sedimentation, temperature, nutrients and greater irregularity in discharge, may account for the observed change in the benthic fauna, increased irradiation may be the most prevalent factor. McIntire and Phinney (1965) showed that primary production of periphyton varied linearly with light intensity over a range of 0-12,000 lux. Since mid-day light intensity at the surface of Thailand stream ranged from 2000 lux at shaded sites to over 100,000 lux at open sites (F.W.H. Beamish, unpublished data), primary production along shaded stretches of the Huay Kayeng likely was light limited. Benthic algae are an essential food source for many benthic macroinvertebrates and consequently macroinvertebrate production is coupled with primary production (Gregory, 1983; Minshall, 1978). By simply reducing the irradiation over an unshaded tropical stream reach with a canopy, Dudgeon and Chan (1993) showed that periphyton abundance declined as well as the abundance of benthic macroinvertebrates, especially mayflies. Similar experiments in temperate streams also showed reductions in periphyton and specific algal-feeding macroinvertebrates (Fuller et al., 1986; Towns, 1981). Furthermore, light may exert a direct effect on distribution and abundance of aquatic invertebrates because of its influence on behavior (e.g., drift) and control over development (Ward, 1992; Hynes, 1970). Increased irradiation resulting from the reduction of forest cover thus may explain many of the differences in the benthic composition among the sites along the Huay Kayeng.

In contrast, it is unlikely that erosion, water temperature, nutrient or organic loadings, or a change in runoff volumes associated with the rural development adjacent to the watercourse directly resulted in the differences noted in the benthic community at the rural sites. Erosion resulting from the removal of forest cover along the stream typically causes a reduction in the abundance and richness of the benthic community (Ryan, 1991), which did not occur at our rural sites (Figure 4). Water temperatures were slightly higher at the rural sites than the reference site by 2-4°C (Table 1), possibly a result of reduced shade. However, these temperatures were similar to those found at stream sites A, B and C (Table 1) which supported a native benthic fauna. Nutrient (nitrate, phosphorus) runoff from rural lands typically is enriched relative to that from forested lands (Omernik, 1977) and can promote higher benthic densities and richness at moderate levels (Hynes, 1970). However, nutrient concentrations actually declined along the Huay Kayeng suggesting that inputs from the adjacent lands was not sufficient to maintain the concentrations in the water resulting from the local algal demand. Organically enriched runoff and discharges from agricultural and domestic wastes can also result in higher benthic densities and richness, although taxa richness usually declines even at moderate concentrations of organic enrichment, i.e., BOD_5 of 1-10 mg/L (Thorne and Williams, 1997; Pinder and Farr, 1987). Dissolved oxygen concentrations, however, were always near air saturation suggesting that any organic inputs to the stream were not causing an excessive oxygen demand. Furthermore, taxa richness at the rural sites was not significantly less than that at the reference site. Finally, the conversion of forested lands to rural lands tends to increase the variability of stream flows as less water is stored on the landscape during wet periods and thus less water is available to the streams during dry periods. The scouring effects of wet weather flows combined with the lower velocities and volumes associated with dry weather flows typically results in a reduction in abundance and richness of benthic macroinvertebrates, neither of which were found at the rural sites.

Reduced inputs of leaf and woody material, and consequently lower amounts of in-stream benthic litter, associated with a reduction in forest cover adjacent to watercourses (Webster et al., 1990; Dudgeon, 1989) may have caused some differences noted in the benthic fauna at the rural sites. This organic matter is the primary source of food for shredding invertebrates (Cummins et al., 1989) and may partially explain the absence of the mayfly, *Isca*, and the beetle, *Ordobrevia*, since members in each of these families are associated with leaf packs, wood, and roots (Dudgeon, 1999). However, only 6 out of the 45 taxa occurring at the reference site were not collected at any of the rural sites and since the abundance of each of these taxa was less than 5 individuals per sample, the reduction of leaf and woody debris appears to only account for minor effect on the benthic fauna.

The reduced similarity between the structure and composition of the benthic fauna at the rural sites and that at Site 1 compared with the similarity between the three additional reference sites and Site 1 indicates that rural development has impaired water quality and consequently reduced the expected resources and services to the local people. First, the higher abundance of benthos at the rural sites suggests a bottleneck to energy flow, which likely manifests itself in reduced fishery production. Higher primary production supports the higher abundance of macroinvertebrates, particular scrapers, at the rural sites. However, this high abundance can only exist where predation by fishes and other animals is correspondingly low. Reduced spawning, rearing, feeding, or resting habitats likely accounts for this inferred reduction in fishery resources. The removal of the riparian forest is potentially a major factor accounting for the loss of these habitats. Next, the high abundance of thiarid snails, which act as a host for several species of the blood fluke, *Schistosoma* (Dillon, 2000), indicates an increased health risk to local inhabitants living along the watercourse. Furthermore, the high proportion of snails in the fauna suggests that a sizable proportion of the primary production is unavailable to fish production, as snails are consumed by few riverine species. Finally, the higher abundance of benthos reflects a reduction in the ability of the watercourse to assimilate further waste loads, e.g., sewage, nutrients, pesticides. Increased irradiation, organic matter or nutrients typically results in higher benthic productivity and abundance as the ecosystem adjusts to assimilate and dissipate this stress. The system essentially develops a fever, i.e., higher metabolism, in response to this stress. Unfortunately, there is a limit to amount of wastes that a watercourse can assimilate; as stress is increased, a point is reached where the species-rich community collapses and is replaced with a community of a few tolerant species that are very abundant (Hellawell, 1986). At this point, the watercourse virtually ceases providing goods and services expected by the local inhabitants and is considered polluted. Typically the watercourse contains large mats of filamentous green algae or fluffy sewage fungus, virtually lacks any shrimps, crabs, prawns or large-bodied fishes, may generate odours, and becomes a breeding ground for a variety of pest dipterans, such as black flies, midges, mosquitoes, and horse flies.

The riparian forest along the Huay Kayeng is not sufficient to buffer effects of rural development on water quality. It appears from our study that more than 50% of the local forest should remain intact to provide sufficient shade, in particular, to maintain the essential processes within the watercourse. This is contrary to the current situation where the natural vegetation adjacent to watercourses is virtually removed, except for areas that are too steep to farm or construct buildings. Until the environmental and economic trade-offs between the short-term benefits of removing the riparian forest can be quantitatively assessed against the long-term benefits of fishery production, waste assimilation and disease prevention, it is prudent to restrict the removal of the riparian forest to bridges, public access points, water intake and effluent disposal structures, and other public infrastructural necessities. Restoring the water quality of polluted watercourses may begin with reducing effluent discharges, but must include the restoration of the riparian forest community to be successful.

The benthic fauna in tropical streams appears to respond to deforestation and rural development in the same fashion as benthic fauna in temperate streams. Thorne and Williams (1997) similarly showed that benthic macroinvertebrates in tropical streams responded to urban sewage and stormwaters discharges in the same manner as those in temperate streams. Experience gained from and theories developed for temperate systems thus may be widely applicable to tropical systems.

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REFERENCES

APHA 1981. *Standard Methods for the Examination of Waters and Wastewaters.* 15th edition. American Public Health Association, American Waterworks Association, American Water Pollution Control Federation, Washington. Behmer, D.J. and Hawkins, C.P. 1986. Effects of overhead canopy on macroinvertebrate production in a Utah stream. *Freshwater Biology* 16:287-300.

Bishop, J.E. 1973. Limnology of a small Malayan River, Sungai Gombak. *Monographiae Biologicae* 22:1-485. Dr. W. Junk, The Hague.

Burns, C.W. 2002. W(h)iter limnology? - revisited. *Verhandlungen der Internationale Vereinigung fur Limnologie* 28:1-6.

Campbell, I. C. and Parnrong, S. 2000. Limnology in Thailand: present status and future needs. *Verhandlungen der Internationale Vereinigung fur Limnologie* 27:2135-2141.

Cummins, K.W. 2001. Riparian-stream linkage prardigm. *Verhandlungen der Internationale Vereinigung fur Limnologie* 28:49-58.

Cummins, K.W., Wilzbach, M. A., Gates, D. M., et al. 1989. Shredders and riparian vegetation. *Bioscience* 39:24-30.

Dillon, Jr. R.T. 2000. *The Ecology of Freshwater Molluscs.* Cambridge University Press, U.K. 509 pp.

Dudgeon, D. 1982. Aspects of hydrology of Tai Po Kau forest stream, New Territories, Hong Kong. *Archiv fur Hydrobiologie* (Supplement) 64:1-35.

Dudgeon, D. 1989. The influence of riparian vegetation on the functional organization of four Hong Kong stream communities. *Hydrobiologia* 179:183-194.

Dudgeon, D. 1990. Determinants of the distribution and abundance of larval ephemeroptera (Insecta) in Hong Kong running waters. In: I.C. Campbell (ed). *Mayflies and Stoneflies.* Kluwer Academic Publishers. pp. 221-232.

Dudgeon, D. 1999. *Tropical Asian Streams: Zoobenthos, Ecology and Conservation.* Hong Kong University Press. Aberdeen, Hong Kong. 830 pp.

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.

Dudgeon, D. and Chan, I.K.K. 1993. An experimental study of the influence of periphytic algae on invertebrate abundance in a Hong Kong stream. *Freshwater Biology* 27:53-63.

Eichenberger, E. A. Schlatter. 1978. Effect of herbivorous insects on the production of benthic algal vegetation in ourdoor channels. *Verhandlungen der Internationale Vereinigung fur Limnologie* 20:1806-1810.

FAO 1999. *Review of the State of World Fishery Resources: Inland Fisheries.* FAO Fisheries Circular No. 942. Food and Agricultural Organization of the United Nations, Rome. 53 pp.

Fuller, R.L., Roelofs, J.L., and Fry, T.J. 1986. The importance of algae to stream invertebrates. *Journal of the North American Benthological Society* 5:290-296.

Gregory, S.V. 1983. Plant-herbivore interactions in stream systems. In: G.W. Minshall and J. Barnes (eds). *Stream Ecology: Application and Testing of General Ecological Theory.* Plenum Press. pp. 159-190.

Griffiths, R.W. 1987. *Acidification as a Model for the Effect of Stress on Benthic Communities.* PhD. Thesis. University of Waterloo, Waterloo, Ontario.

Griffiths, R.W. 1999. *BioMAP: Bioassessment of Water Quality.* Published by Niagara College, Niagara-on-the-Lake, Ontario, Canada. 110 pp.

Griffiths, R.W. 2001. Mapping the water quality of streams using benthos and satellite imagery. *Verhandlungen der Internationale Vereinigung fur Limnologie* 27:3550-3555.

Griffiths, R.W. 2002. Estimating the agricultural carrying capacity of catchments based on water quality. *Verhandlungen der Internationale Vereinigung fur Limnologie* 28: 1116-1120.

Hawkins, C.P, Murphy, M.L. , and Anderson, N.H. 1982. Effects of canopy, substrate composition, and gradient on the structure of macroinvertebrate communities in Cascade Range streams of Oregon. *Ecology* 63:1840-1856.

Hellawell, J.M. 1986. *Biological Indicators of Freshwater Pollution and Environmental Management.* Elsevier, London.

Hopkins, C.L. 1976. Estimates of biological production in some stream invertebrates. *New Zealand Journal of Marine and Freshwater Research* 10:629-640.

Hynes, H.B.N. 1970. *Ecology of Running Waters.* University of Toronto Press, Toronto, Ontario. 555 pp.

Ide 1967. Effects of forest spraying with DDT on aquatic insects of salmon streams in New Brunswick. *Journal of the Fisheries Research Board of Canada* 24:769-805.

Lamberti, G.A. and Resh, V.H. 1983. Stream periphyton and insect herbivores: an experimental study of grazing by a caddisfly population. *Ecology* 64:1124-1135.

Laurance, W.E. 1999. Reflections on the tropical deforestation crisis. *Biological Conservation* 91:109-117.

Lee, C. and Yang, P. 2002. Notes on the larva of the genus Microeubria Lee and Yang, with description of a new species from Borneo (Coleoptera: Psephenidae: Eubriinae). *The Coleopteristists Bulletin* 56:246-252.

McCafferty, W.P. and Wang, T.Q. 2000. Phylogenetic systematics of the major lineages of pannote mayflies (Ephemeroptera: Pannota). *Transactions of the American Entomological Society* 126:9-101.

McCully, P. 1996. *Silenced Rivers. The Ecology and Politics of Large Dams.* Zed Books, London. 350 pp.

McIntire, C.D. and Phinney, H.K. 1965. Laboratory studies of periphyton production and community metabolism in lotic environments. *Ecological Monographs* 35:237-258.

Merritt, R.W. and Cummins, K.W. 1996. *An Introduction to the Aquatic Insects of North America.* 3rd Edition. Kendall/Hunt Publ. Co., Dubuque, Iowa.

Millar, J.P. 1961. *Solutes in Small Streams Draining Single Rock Types, Sangre de Cristo Range, New Mexico.* U.S. Geological Survey Water Supply Paper 1535-F. 23pp.

Minshall, G.W. 1978. Autotrophy in stream ecosystems. *Bioscience* 28:767-771.

Morse, J.C., Yang, L., and Tian, L. 1992. *Aquatic insects of China Useful for Monitoring Water Quality.* Hohai University Press, Nanjing, People's Republic of China. 570 pp.

Müller-Liebenau, I. 1984. New genera and species of the family Baetidae from West-Malaysia (River Gombak). *Spixiana* 7:253-284.

Novak, M.A. and Bode, R.W. 1992. Percent model affinity: a new measure of macroinvertebrate community composition. *Journal of the North American Benthological Society* 11: 80-85.

Omernik 1977. *Nonpoint Source-stream Nutrient Level Relationships: A Nationwide Survey.* EPA-600/3-77-105. U.S. Environmental Protection Agency, Washington.

Pinder, L.C.V. and Farr, I.S. 1987. Biological surveillance of water quality - 3. The influence of organic enrichment on the macroinvertebrates of a small chalk stream. *Archiv fur Hydrobiologie* 109:619-637.

Rigg, J. 1995. *Southeast Asia.* Raintree Steck-Vaughn Publ. Austin, Texas.

Ryan, P.A. 1991. Environmental effects of sediment on New Zealand streams: a review. *New Zealand Journal of Marine and Freshwater Research* 25:207-221.

Rosenberg, D.M. and Resh, V.H. (eds.). 1993. *Freshwater Biomonitoring and Benthic Macroinvertebrates.* Chapman and Hall, New York.

Shea, S.S. 1994. The effects of water quality, epilithic algae and organic matter on communities of stone-dwelling invertebrates in a Hong Kong River. *Mitteilungen der Internationale Vereinigung fur Limnologie* 24:327-336.

Sites, R.W., Nichols, B.J., and Permkan, S. 1997. The Naucoridae (Heteroptera) of southern Thailand. *Pan-Pacific Entomologist* 73: 127-134.

Sivec, I, Stark, B.P. , and Uchida, S.1988. Synopsis of the world genera of Perlinae (Plecoptera: Perlidae). *Scopolia* 16:1-66.

Steinman, A.D. 1992. Does an increase in irradiance influence periphyton in a heavily-grazed woodland stream? *Oecologia* 91:163-170.

Sweeny, B. 1993. Effects of streamside vegetation on macroinvertebrate communities in White Clay Creek in eastern North America. *Proceedings of the Academy of Natural Sciences Philadelphia* 144:291-340.

Thorne, R.J. and Williams, W.P. 1997. The response of benthic macroinvertebrates to pollution in developing countries: a multimetric system of bioassessment. *Freshwater Biology* 37: 671-686.

Thorup, J. 1966. Substrate type and its value as a basis for the delimitation of bottom fauna communities in running waters. *University of Pittsburg, Pymatuning Laboratory of Ecology* 4:59-74.

Towns, D.R. 1981. Effects of artificial shading on periphyton and invertebrates in a New Zealand stream. *New Zealand Journal of Marine and Freshwater Research* 15: 185-192.

Tyler, P.A. 1984. Water chemistry of the River Kwai, Thailand. *Hydrobiologia* 111:65-73.

Upatham, E.S., Sornmani, S., Kitikoon, V., Lohachit, C., and Burch, J.B. 1983. Identification key for the fresh- and brackish water snails of Thailand. *Malacological Review* 16:107-132.

Vannote, R.L, Minshall, G.W., Cummins, K.W., et al. 1980. The river continuum concept. *Canadian Journal of Fisheries and Aquatic Sciences* 37:130-137.

Wallace, J.B. and Gurtz, M.E. 1986. Response of Baetis mayflies to catchment logging. *American Midland Naturalist* 115:25-41.

Ward, J.V. 1992. *Aquatic Insect Ecology: 1. Biology and Habitat*. John Wiley and Sons, Inc. New York. 438 pp.

Webster, J.R., Golladay, S.W., Benfield, E.F., et al. 1990. Effects of forest disturbance on particulate organic matter budgets of small streams. *Journal of the North American Benthological Society* 9:120-140.

Wiggins, G.B. 1996. *Larvae of the North American Caddisfly Genera (Trichoptera)*. University of Toronto Press, Toronto. 457 pp.

Wongsawat, S. 1985. Status of hydrogeological mapping in Thailand. In: Grimmelmann, W.F., Krampe, K.D., and Struckmeier, W. (eds). Hydrological Mapping in Asia and the Pacific Region: Proceedings of the ESCAP-RMRDC Workshop, Bandung, 1983. *International Contributions to Hydrogeology* 7:231-246.

Zettel, H. 1998. Introduction to the Helotrephidae (Nepomorpha) in Thailand and adjacent countries. In: Zettel, H. (ed). *Amemboa 2: News and Results on Heteroptera of Thailand.* Naturhistorisches Museum Wien, Vienna, Austria. pp. 15-18.