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Biological and ecological diversity of aquatic macroinvertebrates in response to hydrological and physicochemical parameters in tropical forest streams of Gunung Tebu, Malaysia: implications for ecohydrological assessment

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ABSTRACT

In this study, we have investigated the effects of some hydrological and physicochemical parameters such as water quality, velocity, water depth, river width, water pH, water temperature, ammonia-N, biochemical oxygen demand (BOD), chemical oxygen demand (COD) and dissolved oxygen (DO) on diversity of aquatic macroinvertebrates in forest streams of Gunung Tebu (GT), Malaysia. The results of canonical correspondence analysis identified three groups of the aquatic macroinvertebrates according to their relationships with hydrological and physicochemical parameters. The stream velocity, water quality (i.e. DO, BOD and ammonia-N) in addition to canopy cover, total habitat score and substrate quality were the determinant factors controlling the diversity pattern of the aquatic macroinvertebrates in GT streams. Alteration in the hydrological and physicochemical parameters showed to influence the ecological diversity of the aquatic macroinvertebrates in GT streams. The predators were found to be highly associated with the elevated concentrations of BOD and COD. Shredders were positively correlated with pH, stream velocity, DO and habitat quality indicators (total habitat score, embeddedness, epifaunal and canopy cover). However, the collector-gatherers correlated negatively with all of these parameters. It was concluded that stream velocity, substrate structure and water quality were strong attributes for variation in aquatic macroinvertebrate assemblage structure in tropical forest streams of GT. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS biodiversity; tropical forest streams; hydrological and physicochemical parameters; ecological diversity

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INTRODUCTION

Loss of biodiversity is the major concern in recent ecological research as it occurs at high rate driven by modification of the natural habitats, human disturbance, as well as climate changes (Sodhi *et al*., 2006). Deterioration of biodiversity has been proven to alter the performance of ecosystems because of loss of genetic resources, productivity, ecosystem buffering against ecological perturbation and loss of valuable resources (Naeem *et al*., 1994; Tilman and Downing, 1994; Griffin *et al*., 2009). Extinction rates were reported to occur faster among aquatic organisms compared with their terrestrial counterparts. Despite the high extinction rates in tropical aquatic habitats, less attention has been paid towards investigating the aquatic biodiversity (Strayer and Dudgeon, 2010).

It is well documented that the decrease in numbers of trophic levels in the aquatic ecosystems negatively affects the ecosystem functioning processes (Duffy *et al*., 2007). Consequently, understanding the role of functioning diversity of aquatic macroinvertebrates becomes state of the art in modern ecological and conservational research. Recently, much attention was given towards understanding the conceptual role of the aquatic macroinvertebrates' functional ecology and its importance for the stability of aquatic ecosystems. Estimating the ecological biodiversity and the way it responds to various disturbances has proven to be an effective tool in conservational research of endangered aquatic fauna (Larsen and Ormerod, 2010).

Hydrological processes at various spatial and temporal scales result in different ecological responses (Poff *et al*., 1997; Stubbington *et al*., 2009a; Coleman *et al*., 2011; Webb *et al*., 2012). Hydrological conditions, such as discharge and water disturbance, play important roles in aquatic ecosystem functioning (Wetzel, 2001; Alcocer and Filonov, 2007; Stubbington *et al*., 2009a, 2009b; Zhang *et al*., 2010b). For example, flow regime has been found to be a key factor influencing the community structure of stream vertebrates and invertebrates (Stubbington *et al*., 2009a; Webb *et al*., 2012). Hence, alterations in water

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quality, hydrological and physicochemical features of rivers were found to cause profound changes in diversity and abundance patterns of aquatic macroinvertebrates (Poff, 2002; Bona *et al*., 2008; Al-Shami *et al*., 2011; Che Salmah *et al*., 2013; Al-Shami *et al*., 2013).

Several studies have highlighted the importance of hydrological and physicochemical factors controlling the community structure of stream invertebrates. For instance, Kennen *et al*. (2010) found negative effect of hydrologic modification on aquatic communities due to basin urbanization. Diversity and ecological functioning of stream communities are strongly controlled by variation in the hydrological processes (Poff *et al*., 1997; Biggs *et al*., 2005). Thus, some species showed to be sensitive to alteration in hydrological settings because of their substantial requirements for feeding, reproduction and growth (Grossman, 1982; Poff and Ward, 1989), meanwhile, others are tolerant to temporary and/or persistent changes of hydrological, thermal, physical or chemical conditions.

Many researchers suggested that landscape modifications (e.g. urbanization and deforestation) are related to various hydrological alterations that disturb ecological functioning processes of aquatic ecosystems and reduce species diversity by gradient elimination of sensitive species (Resh *et al*., 1988; Poff, 2002). Such landscape modifications also cause irreversible changes in the ecosystem for example alterations in flow regime and streambed structure, siltation, soil erosion, loss of riparian cover and forest fragmentation (Kennen *et al*., 2008; Coleman *et al*., 2011; Che Salmah *et al*., 2013).

The faunal biodiversity of Southeast (SE) Asian aquatic habitats, including those in tropical forests of Malaysia, is increasingly threatened by various anthropogenic activities such as deforestation, agricultural land use, industrialization, road construction and building of new settlements (Douglas *et al*., 1993; Yule and Yong, 2004; Gopal, 2005; Dudgeon, 2006; Sodhi *et al*., 2006; Cannon *et al*., 2007; Morse *et al*., 2007; Struebig *et al*., 2008). Strikingly, the deforestation rates in SE Asian forests are at least three times higher than in other tropical areas (Sodhi *et al*., 2006; Sodhi *et al*., 2009), changing the runoff patterns and increasing siltation of the rivers (Dudgeon, 2000a, 2000b; Dudgeon, 2007).

Several studies highlighted the adverse effects of anthropogenic forest disturbance on SE Asian biotas (Castelletta *et al*., 2000; Laidlaw, 2000; Liow *et al*., 2001; Lee *et al*., 2007; Sodhi *et al*., 2006; Sodhi *et al*., 2009; Sodhi *et al*., 2010). However, ecological aspects concerning the influence of various hydrological and physicochemical factors on the aquatic macroinvertebrates biodiversity is scarcely investigated (Dunn, 2004; Sodhi *et al*., 2009).

Although there is growing interest in understanding the way in which anthropogenic disturbances modify natural hydrological regimes and how they lead to permanent changes in the ecological processes, there is still knowledge gap in understanding the hydroecological linkages in affecting the ecosystems functioning (Krezek *et al*., 2008). Undoubtedly, hydrology, biodiversity, ecology and evolutionary history of tropical streams are unique compared with those in temperate regions (Gopal, 2005; Dudgeon, 2008; Boyero *et al*., 2009). Although the amount of research in tropical SE Asian streams has increased over the last two decades (see Che Salmah *et al*., 2013; Al-Shami *et al*., 2013), there is still lacking in research concerning the hydrology, fauna and ecology of the tropical streams in SE Asia particularly those in Malaysia (Dudgeon, 2000a; Dudgeon, 2006; Morse *et al*., 2007; Dudgeon, 2008; Al-Shami *et al*., 2011). In addition to that, incomplete taxonomic information of aquatic macroinvertebrates in SE Asia is hindering intensive ecological research (Yule and Yong, 2004).

In view of limited information on various ecological aspects of aquatic macroinvertebrates in SE Asia specifically Malaysia, the present study aimed to investigate the influence of several hydrological and physicochemical parameters on biological and ecological diversity of aquatic macroinvertebrates in forest streams of Gunung Tebu (GT, Malaysia).

METHODS

Study site

The Gunung Tebu Forest reserve is located in Terengganu in the eastern part of Malaysia Peninsula (Figure 1). It occupies an area of about 50 ha and is located at 244- to 472-m elevation on a granite soil. Forest vegetation is mainly a combination of lowland and highland dipterocarp species. The forest is described as having a typical tropical monsoon climate with high temperatures (from 24·2 °C to 29·9 °C) and high humidity (from 70% to 98%). GT is an isolated forest of unique geomorphological characteristics. The substrata of the streams in this forest are mostly made of bedrocks with little clay and peat soil. The forest is easily accessed through a tarred road from the main road leading to the telecommunication tower located at the forest fringe. Five streams were investigated in this forest, coded as GT1, GT2, GT3, GT4 and GT5 streams were identified as first to second order streams. It was perceived that occasional recreational and illegal logging activities would disturb the natural habitats of GT1 and GT2. However, GT3, GT4 and GT5 streams are located in active areas in the vicinity of cultivated and urbanized areas. Consequently, various anthropogenic activities such as logging, road construction and agricultural land use were assumed to influence the habitat integrity in these streams. Physical and chemical characteristics of the five streams in GT forest are shown in Table I.

Sampling of aquatic macroinvertebrates

Collection of samples began at the downstream end of the reach and proceeded upstream. Benthic macroinvertebrates were sampled from 18 to 23 June 2008 using a D-frame aquatic net of 0·3-m diameter. A long pole was attached to the frame fitted with a cone-shaped, 300-μm mesh net to capture the macroinvertebrates. At each stream, the macroinvertebrates were sampled along approximately 100-m reach. The aquatic net was placed on the river substratum against the water current and an area approxi-

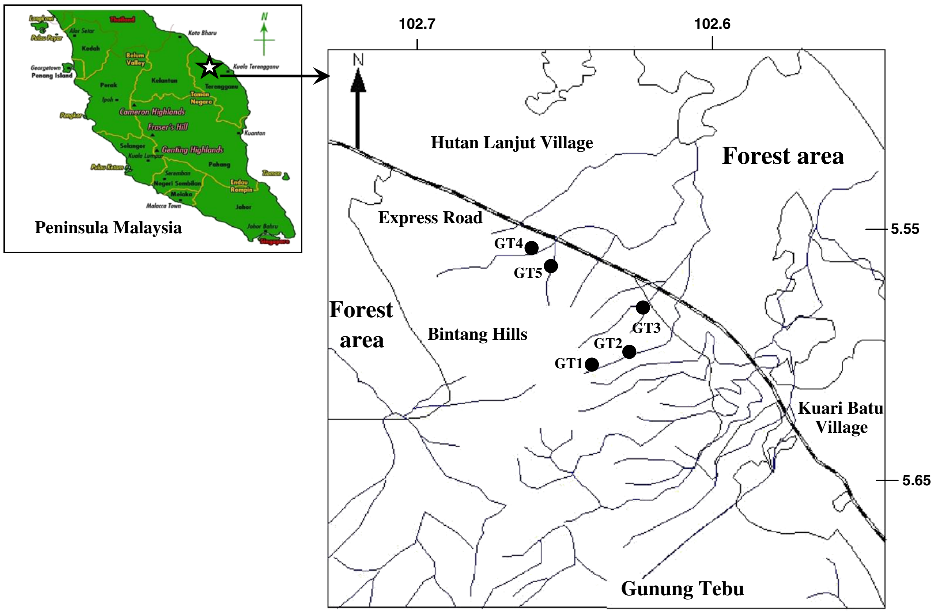

Figure 1. Location of the study sites in Gunung Tebu forest, Malaysia. Ten sites were sampled in each stream.

mately 1 m^2 was disturbed following the kick-sampling technique of Merritt and Cummins (1996) for about 2 min. Collected samples were washed through a plastic sieve and placed into labelled polyethylene bags. Benthic samples required to yield a representative estimate of macroinvertebrate populations were calculated using the index of precision (Elliott, 1971) based on a preliminary collection following which 10 samples were collected from each stream. All samples were transported to the laboratory in a Coolman® ice container. Each sample was washed under tap water through a sieve (200-µm pore) and transferred into a white plastic pan filled with sufficient amount of water. All macroinvertebrates were sorted and preserved in 80% ethanol. The macroinvertebrates were identified using keys of Morse *et al*. (1994) and Yule and Yong (2004). It was difficult to identify most of the specimens to species because of the lack of taxonomic keys of Malaysian macroinvertebrates. In such cases, we identified most of the specimens to genus level, which is still useful in biodiversity studies (Heino and Soininen, 2007).

Table I. Mean ± SE and Kruskal–Wallis results of hydrological and physicochemical parameters in the five tropical streams of Gunung Tebu (GT) Forest.

	GT1	GT2	GT3	GT4	GT5	Chi square$_{4,15}$
Hydrological and physicochemical parameters						
Width (m)	2·67 ± 0·45	4·67 ± 0·88	2·83 ± 1·09	1·14 ± 0·24	2·09 ± 1·32	7·46
Depth (cm)	0·40 ± 0·06	0·66 ± 0·37	0·20 ± 0·05	0·18 ± 0·01	0·633 ± 0·09	7·16
Temperature (°C)	24·20 ± 0·50	25·47 ± 0·27	25·20 ± 0·20	24·30 ± 0·20	25·17 ± 0·15	10·66*
pH	6·01 ± 0·10	6·59 ± 0·20	6·27 ± 0·02	5·49 ± 0·34	6·11 ± 0·13	10·05*
Velocity (m/s)	0·00 ± 0·00	0·00 ± 0·00	0·30 ± 0·12	0·40 ± 0·10	0·07 ± 0·03	12·01*
DO (mg/l)	6·50 ± 0·41	7·63 ± 0·10	7·80 ± 0·07	5·79 ± 0·23	6·65 ± 0·38	11·27*
BOD (mg/l)	1·43 ± 0·19	0·67 ± 0·19	0·63 ± 0·03	0·28 ± 0·04	2·60 ± 0·15	12·27*
Ammonia-N (mg/l)	0·00 ± 0·00	0·00 ± 0·00	0·08 ± 0·01	0·08 ± 0·01	0·26 ± 0·03	13·07*
COD (mg/l)	1·33 ± 0·33	1·57 ± 0·23	8·00 ± 0·58	1·00 ± 0·00	10·00 ± 1·53	12·04*
Habitat quality indicators						
Habitat quality score	157·67 ± 2·03	161·33 ± 1·86	200·67 ± 4·81	120·67 ± 2·85	141·67 ± 4·91	13·03*
Embeddedness	13·33 ± 0·88	17·00 ± 0·58	25·00 ± 2·89	15·00 ± 2·89	14·33 ± 1·67	8·84
Epifaunal	15·00 ± 0·58	14·67 ± 1·33	20·33 ± 0·67	18·00 ± 0·58	16·00 ± 1·53	10·37*
Canopy cover (%)	62 ± 0·15	70 ± 0·06	78 ± 0·33	77 ± 0·11	57 ± 0·05	12·15*
	Natural area with occasional disturbance through frequent recreational activities	Natural area with occasional recreational activities and some individual illegal logging	Logging activities (>30 years ago). Development of the area for agricultural purposes	Logging activities (>30 years ago). Urbanization development (road network and residential development)	Logging activities (>30 years ago). Heavy disturbed with urbanization and agricultural land use	

*Significant at $P < 0{\cdot}05$.

Functional feeding groups

The collected aquatic macroinvertebrates were categorized into five functional feeding groups on the basis of the earlier description of Merritt and Cummins (1996) for aquatic insects and expert opinion for other minor groups of macroinvertebrates (Heino, 2005). The functional feeding groups included collector-filterers, collector-gatherers, scrapers, predators and shredders.

Hydrological and physicochemical parameters of the forest streams

At each stream, measurements of physicochemical parameters such as water depth, river width, water pH, water temperature, velocity and dissolved oxygen (DO) were made *in situ* at the investigated streams. DO and temperature were measured with a YSI-57 meter (YSI Inc., Yellow Springs, Ohio), and measurement of water pH was recorded using a Termo-Orion Model 210 pH meter. The depth and width of the river were measured using a metal measuring tape. To analyse selected chemical parameters [biochemical oxygen demand (BOD), chemical oxygen demand (COD) and ammonia-N], water samples were randomly collected into 500-ml plastic bottles from each stream. Each bottle was labelled and thoroughly rinsed with the stream water immediately prior to collecting a sample. Thereafter, water samples were transported to the laboratory under cool conditions and stored at 4 °C for further analysis. The ammonia-N content of the water was measured at appropriate wavelength using the YSI 9100 photometer test kit. The ammonia-N, BOD and COD contents of the water were measured using a Hach digestion and calorimeter DRB200 and DR/890, respectively. To ensure the similarity of habitat characteristics, four criteria of the stream were measured and compared among stations, namely substrate embeddedness, canopy cover, epifaunal characteristics and total habitat score, following Barbour *et al.* (1999).

Statistical analysis

The statistical software of SPSS (Version 13) was used to conduct Kruskal–Wallis test ($P < 0{\cdot}05$) for comparing the hydrological and physicochemical parameters among the streams. The Species Diversity and Richness software (Version 4.1.2, Seaby and Henderson, 2006) was employed to calculate richness and biodiversity indices for aquatic macroinvertebrates in the different streams.

Prior to analysis, the abundance data of the aquatic macroinvertebrates were transformed using log $(x + 1)$. The canonical correspondence analysis (CCA) of the CANOCO (ter Braak and Prentice, 1988; ter Braak, 1989) programme was employed to plot the relationship between aquatic macroinvertebrates and the hydrological and physicochemical parameters. The Monte Carlo test ($P < 0{\cdot}05$) with 1000 iterations was used to examine the significance of the produced canonical axes.

Non-multidimensional scale (NMDS) based on Euclidean distance measures was used to investigate the similarity among the streams based on their hydrological, physical and chemical characteristics. Similarly, the NMDS was also used to produce the ordination plot of the feeding functional groups (FFGs) in GT forest streams using the proportional data, which were transformed using the *arcsin* function. Thereby, the eigenvalues obtained from the NMDS of the FFGs data were correlated with various hydrological, physical and chemical parameters using the non-parametric correlation test of Spearman at $P < 0{\cdot}05$.

RESULTS

Hydrological and physicochemical parameters

Hydrological and physicochemical properties of the five streams in GT forest showed remarkable variations (Table I). Except for stream depth, width and substrate embeddedness, all parameters showed significant differences among the five streams in GT forest (Kruskal–Wallis, $P < 0{\cdot}05$). Significant difference in stream velocity indicated considerable variation in hydrology of the studied streams. Notably, pH in GT4 was as low as 5·49 indicating acidic habitat. The highest DO (7·8 mg/l) was reported in GT3, whereas GT4 had the lowest DO value of 5·79 mg/l. The GT5, characterized by low canopy cover, was associated with high BOD, COD and ammonia-N. The highest stability of the habitat, expressed as habitat score, was observed in GT3. Meanwhile, the lowest habitat score was reported in GT4 (Table I).

The ordination plot of NMDS showing the Euclidean distance among streams is illustrated in Figure 2. Based On the NMDS plot, the GT1, GT2 and GT5 showed higher resemblance in their hydrological, physical and chemical characteristics. However, segregation of GT3 and GT4 revealed that these two streams differed distinctively in their properties from other streams.

Biodiversity of aquatic macroinvertebrates in Gunung Tebu forest streams

A total of 70 taxa and morphospecies (1012 individuals) belonging to 45 families and 12 orders were identified in GT forest streams (Appendix 1). The abundance and species richness of aquatic macroinvertebrates in the five streams of GT forest is depicted in Figure 3. The mean density of aquatic macroinvertebrates (individual/m^2) in

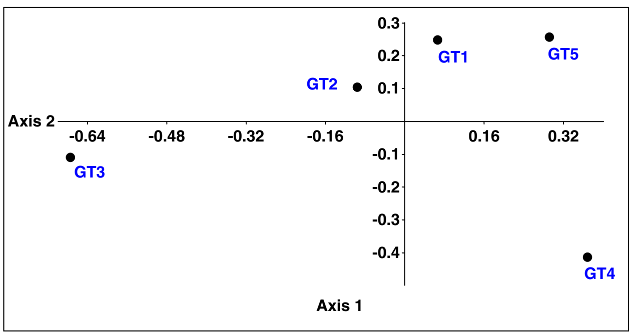

Figure 2. The non-multidimensional scale Euclidean distance plot of the investigated streams in the Gunung Tebu tropical forest based on their hydrological and physicochemical characteristics.

GT forest streams was 23·18. As shown in Figure 3, the highest diversity of macroinvertebrates was recorded in GT2 (50 species) followed by GT5 and GT1 with species richness of 30 and 29, respectively. The species richness in GT3 and GT4 were 26 and 20, respectively. The highest number of individuals was observed in GT2 (427) followed by GT3 (165). Meanwhile, the total number of individuals collected from GT1, GT4 and GT5 were 149, 140 and 131, respectively.

The Shannon–Weinner (H') and Simpson (1-D) diversity indices were 2·88 and 0·946, respectively. However, the Simpson E evenness index was 0·281. The alpha biodiversity of aquatic macroinvertebrates in GT forest streams ranged from 20 to 50 with average of 31. The beta diversity expressed as Harrison1 and Harrison2 indices were 30·92 and 10·42, respectively, whereas the gamma biodiversity was 70.

The GT1 was dominated by *Orectochilus* sp. (Coleoptera) and Blattidae. The chironomid larvae, *Enithares* sp. (Hemiptera), *Potamyia* sp. (Trichoptera) and *Agriocnemis* sp. (Odonata) were also abundant. The aquatic macroinvertebrates community in GT2 was dominated by *Rhagovellia* sp. (Hemiptera). Other taxa such as trichopteran species of *Potamyia* sp. and *Chimarra* sp., *Campsoneuria* sp. (Ephemeroptera), *Habrophlebiodes* sp. (Ephemeroptera) and dipteran *Simulium* sp. were also dominant. Meanwhile, *Simulium* sp., chironomids, *Ectrocorema* sp. (Plecoptera) and *Campsoneuria* sp. (Ephemeroptera) were the most abundant taxa in GT3. *Enithares* sp. (Hemiptera), *Amemboa* sp. (Hemiptera) and *Orectochilus* sp. (Coleoptera) were the dominant taxa in GT4. Freshwater shrimps (*Macrobrachium* sp.), water bug *Rhagovellia* (Veliidae) and *Campsoneuria* sp. (Ephemeroptera) were the most abundant taxa in GT5.

The influence of the hydrological and physicochemical on the aquatic macroinvertebrates

The aquatic macroinvertebrates abundance and composition were affected by several hydrological and physicochemical variables. CCA Ordination biplot illustrated the relationship between these parameters and distribution of the aquatic macroinvertebrates (Figure 4). The first two axes of the CCA model explained 67% of the macroinvertebrates–environmental variations.

As shown in Figure 4, Odonata species of *Ictinogomphus* sp. and *Devadatta* sp. in addition to unknown species of Thiaridae (Mollusca) and Tabanidae (Diptera) were negatively affected by stream velocity, but they were associated with elevated concentration of BOD and ammonia-N. Another assemblage of Hemiptera, Mollusca and Odonata taxa (indicated as group A in the CCA plot) correlated with stream velocity and high concentrations of ammonia-N, BOD and low DO, and habitat quality (embeddedness, canopy and total habitat score). Although high concentration of COD was recorded in GT3 and GT5 (Table I), the impact of the COD on the distribution of the aquatic macroinvertebrates was weak as indicated by the CCA biplot (Figure 4).

The second group of taxa (indicated as group B in the CCA biplot), which belongs to different orders (Odonata, Diptera, Plecoptera, Ephemeroptera and Trichoptera), showed high preference for better habitat quality (i.e. high canopy cover, total habitat score, stream velocity and substrate quality) as well as high DO, which was the determinant factor for their abundance.

The third species assemblage (distinguished in the CCA diagram as group C) showed moderate preference for pH, BOD, water temperature and less canopy cover, stream velocity and streambed diversity. However, this group showed high dependence on DO and river width (Figure 4).

Ecological functioning diversity of aquatic macroinvertebrates

The mean number of functional feeding groups (FFGs) in each stream of GT is shown in Table II, and the proportion of the different FFGs is illustrated in Figure 5. The highest proportion of shredders was reported in GT5 and the lowest percentage was in GT3. No collector-filterer was recorded in GT4. Meanwhile, the highest percentage of collector-filterer was reported in GT3. Predators were found in all streams, and their proportion varied considerably. The highest proportion of predators was recorded in GT4. Scrapers were almost absent in GT1, yet they comprised high proportions in GT2 and GT3.

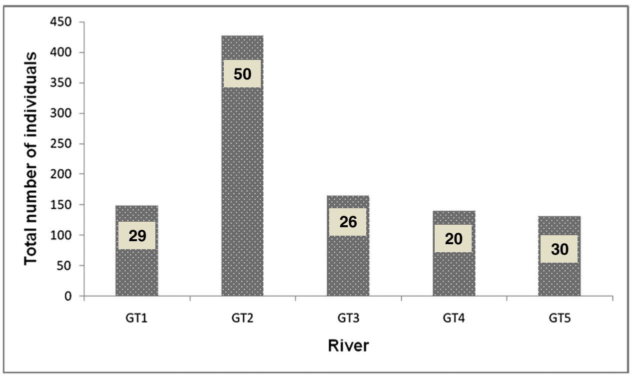

Figure 3. Abundance of aquatic macroinvertebrates in tropical forest streams of the Gunung Tebu forest, Malaysia. The species richness is shown inside the bars.

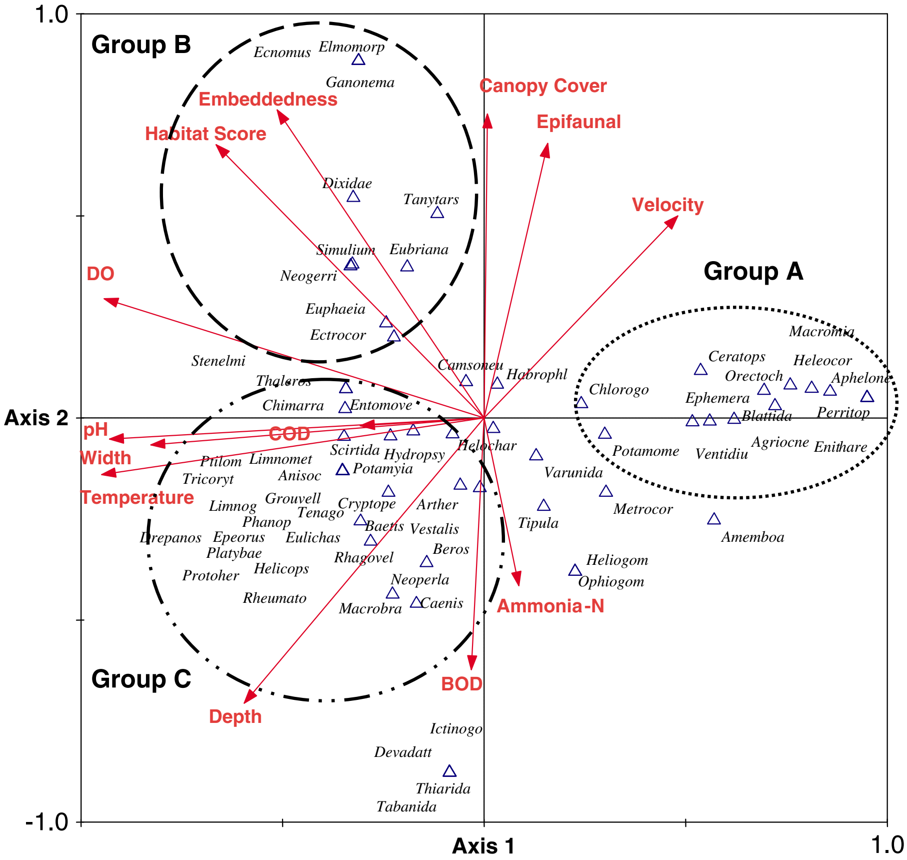

Figure 4. The canonical correspondence analysis (CCA) biplot of the aquatic macroinvertebrates in relation to the hydrological, physical and chemical parameters in Gunung Tebu forest streams, Malaysia.

Table II. Ecological diversity (functional feeding groups) of macroinvertebrates in the Gunung Tebu (GT) forest streams.

	GT1	GT2	GT3	GT4	GT5
Collector-filterer	3·33 ± 1·26 (30)	12·44 ± 4·46 (112)	7·33 ± 3·92 (66)	nd	0·67 ± 0·24 (6)
Collector-gatherer	3·20 ± 1·32 (16)	6·60 ± 4·21 (33)	2·80 ± 1·85 (14)	3·00 ± 2·05 (15)	3·80 ± 1·59 (19)
Predator	2·24 ± 0·76 (85)	4·53 ± 1·27 (172)	1·39 ± 0·61 (53)	2·53 ± 0·97 (96)	1·42 ± 0·49 (54)
Scraper	0·20 ± 0·13 (2)	6·50 ± 2·66 (65)	2·30 ± 1·97 (23)	1·30 ± 1·19 (13)	1·80 ± 1·12 (18)
Shredder	2·29 ± 1·61 (16)	6·14 ± 3·40 (43)	1·00 ± 0·58 (7)	2·14 ± 1·49 (15)	4·86 ± 3·33 (34)

The data are shown as mean ± SE and the total number of individuals is shown in parenthesis. nd: not detected.

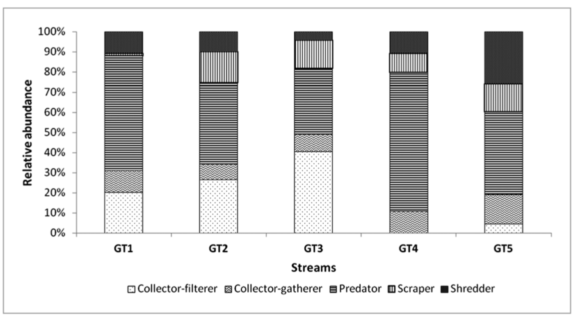

Figure 5. Composition of the ecological functions groups of aquatic macroinvertebrates in forest streams of Gunung Tebu Malaysia.

Collector-gatherers were found in all streams with high percentages in GT1, GT4 and GT5.

The distribution of the ecological functioning guilds in the streams of GT forest is illustrated in Figure 6. The functional feeding guilds diversity based on transformed percent data (*arcsin*) and Euclidean distance is shown in the NMDS plot. Specifically, predators were positively correlated with the first axis, whereas collector-filterers and scrapers were correlated negatively with the same axis. Shredders were correlated positively with the second axis. In contrast, collector-gatherers were negatively correlated with the second axis (Table III).

Thus, the first NMDS axis of the ecological groups consisted of collector-filterers, predators and scrapers (Figure 6), which were positively correlated with BOD and COD. Consequently, predators showed high affinity to elevated concentrations of BOD and COD (Table IV). The second axis of NMDS comprised collector-gatherers and shredders. Shredders correlated positively with pH, stream velocity, DO and habitat quality indicators (total habitat score, embeddedness, epifaunal and canopy cover). However, the collector-gatherers correlated negatively with all of these parameters.

DISCUSSION

Biodiversity of aquatic macroinvertebrates and influence of hydrological and physicochemical parameters

In general, GT forest streams supported high diversity of aquatic macroinvertebrates as most of the streams provided suitable habitats to different macroinvertebrate taxa. High total number of macroinvertebrate taxa (70) was reported from these forest streams; hence, species richness and abundance were much higher compared with communities in other Malaysian rivers such as Juru River (32 taxa, Al-Shami *et al.*, 2011), Langat River (54 taxa, Azrina *et al.*, 2006), Kerian River (53 taxa, Siregar *et al.*, 1999), montane tropical streams of Ecuador (37 taxa, Bücker *et al.*, 2010) and boreal forest streams of Finland (Heino *et al.*, 2009). Nonetheless, richer macroinvertebrate communities were recorded from

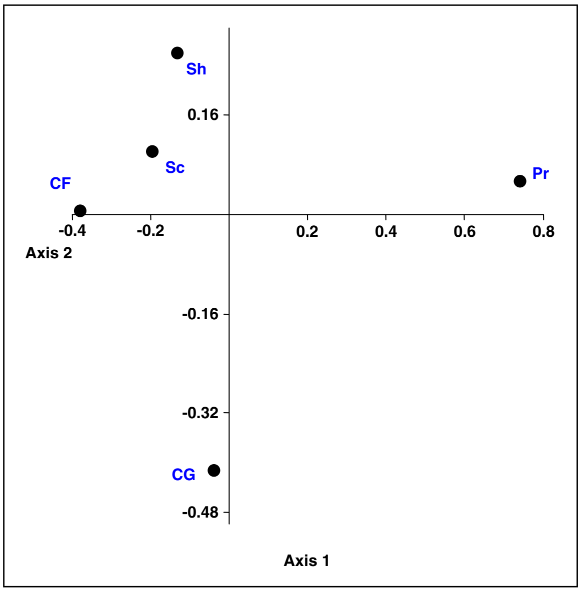

Figure 6. Non-multidimensional scale plot of the ecological functional groups in streams of the Gunung Tebu forest. CF, collector-filterer; CG, collector-gatherer; Pr, predator; Sc, Scraper; Sh, Shredder.

Table III. Eigenvalues of the first two non-multidimensional scale axes based on Euclidean measures for the functional feeding groups using transformed percentage data (*arcsin*).

	Axis 1	Axis 2
Collector-filterer	**−0·378**	0·003
Collector-gatherer	−0·037	**−0·414**
Predator	**0·741**	0·053
Scraper	**−0·195**	0·100
Shredder	−0·132	**0·258**

Values in bold indicate the significant correlation with respective axis at $P < 0{\cdot}05$.

Table IV. Spearman correlation coefficients of functional feeding group axes obtained from non-multidimensional scale with hydrological, physical and chemical parameters of Gunung Tebu forest streams.

Parameters	Axis 1	Axis 2
Width (m)	0·019	**0·456**
Depth (cm)	0·221	nd
Temperature (°C)	0·253	nd
pH	0·017	**0·517**
Velocity (m/s)	0·300	**0·733**
DO (mg/l)	0·083	**0·233**
BOD (mg/l)	**0·778**	0·503
Ammonia-N (mg/l)	0·333	nd
COD (mg/l)	**0·526**	0·450
Habitat quality score	0·017	**0·213**
Embeddedness	0·452	**0·783**
Epifaunal	0·450	**0·571**
Canopy cover (%)	0·683	**0·783**

Values in bold indicate the significant correlation with respective axis at $P < 0{\cdot}05$.
nd: not detected.

other parts of tropical Asia. During the recent monsoon, Leung and Dudgeon (2011) recorded a total of 268 945 macroinvertebrates representing 88 species in perennial hill streams of Hong Kong. In the Indonesian 278 islands of Sulawesi, Dudgeon (2006) collected 54 invertebrate families of 127 morphospecies, mostly insects. In the forests, diversity of species in headwater streams (intermittent, first, second and third order) contributes to the biodiversity of a river system and its riparian vegetation (Herlihy *et al.*, 2005; Clarke *et al.*, 2008).

High diversity and abundance of streams invertebrates were observed in GT1 and GT2 where the natural habitats are minimally impacted. Although no apparent logging activity was reported in these areas, they may be slightly affected by human disturbance during frequent recreational activities. Remarkable deterioration in diversity of aquatic invertebrates in GT3 and GT4 confirmed that deforestation and intensive modifications of natural habitats for new settlements, construction of road network and urban development influenced the biodiversity of stream invertebrates (Benstead *et al*., 2003; Bojsen and Jacobsen, 2003; Iwata *et al*., 2003; Dudgeon, 2006; Wantzen, 2006; Kasangaki *et al*., 2008; Al-Shami *et al*., 2011; Che Salmah *et al*., 2013). Naturally, landscape modifications including urbanization and logging activity influence hydrological, physical and chemical characteristics of adjacent aquatic ecosystems (Heino *et al*., 2009; Zhang *et al*., 2010b) leading to severe soil erosion and irreversible changes in stream velocity regime, riverine streambed, which all in turn have an adverse effect on the aquatic communities (Dudgeon, 2000a, 2000b). Alteration in stream velocity has been reported to cause profound changes in the diversity patterns of aquatic organisms (Stubbington *et al*., 2009a, 2009b; Kennen *et al*., 2010).

On the other hand, diminishing in riparian canopy cover impinges on aquatic macroinvertebrate communities by increasing in-stream temperature and acceleration of the primary production in the river (Vannote *et al*., 1980; Herlihy *et al*., 2005). In addition, litter inputs from surrounding riparian vegetation sustain energy source (allochthonous) for stream invertebrates (Encalada *et al*., 2010). Although less attention has been paid to investigate the impact of deforestation on tropical stream invertebrates (but see Che Salmah *et al*., 2013), various evidences proved that conversion of natural habitats in the forests has pervasive impacts on benthic communities (Lorion and Kennedy, 2009).

In the present study, we found an association between macroinvertebrate assemblages and hydrological and physicochemical parameters of water (e.g. stream velocity, stream substrate and water quality) and the ambient environment (e.g. habitat stability and canopy cover). The plecopteran *Ectrocorema* sp. (Perlidae), ephemeropteran *Thalerosphyrus* sp. and *Campsoneuria* sp. (Heptageniidae), dipteran *Simulium* sp. (Simulidae) and *Tanytarsus* sp. (Chironomidae), trichopteran *Ganonema* sp. (Calamoceratidae), *Ecnomus* sp. (Ecnomidae), *Chimarra* sp. (Philopotamodae), odonate *Euphaeia* sp. (Euphaeidae) showed high preference for DO, canopy cover and diverse streambed. Silveira *et al*. (2006) also found that the distribution of plecopterans was restricted in water with nearly saturated DO in cold stream. However, other macroinvertebrate assemblages of odonates (*Agriocnemis* sp., *Macromia* sp. and *Ophiogomphu*s sp.) and hemipteran (*Metrocoris* sp., *Amemboa* sp., *Heleocoris* sp., *Aphelonecta* sp. and *Perritoppus* sp.) in addition to coleopteran taxa of *Orectochilus* sp. and crustcean taxa of *Macrobrachium* sp. and megalopteran *Potamometropsis* sp. were correlated to deterioration in the physical and chemical properties of the habitats in GT. Meanwhile, odonates *Ictinogomphus* sp. (Gomphidae), *Devadatta* sp. (Amphiterygidae) (Corbet, 1999) together with molluscs from the family Thiaridae were associated with increases in BOD and ammonia-N concentrations and non-shaded water surfaces.

Influence of hydrological and physicochemical on ecological diversity of aquatic macroinvertebrates

It is known from the river continuum concept that aquatic macroinvertebrate communities change gradually from headwaters to large rivers downstream (Vannote *et al*., 1980). From the ecological point of view, changes in functional diversity (feeding groups) follow the hydrological characteristics of the river from its source to the mouth. For example, the shredders dominate the headwaters, meanwhile, the collectors (filterers and gatherers) are found mostly in the lower reaches of large streams. However, other groups such as scrapers are abundant in the middle reaches (Vannote *et al*., 1980; Heino *et al*., 2005).

Among all the streams studied, GT2 was the widest. Interestingly, the highest percentages of collector-filterer, collector-gatherer, scraper and predators were recorded in this stream confirming the river continuum concept. Dominations of shredders, gatherers or filterers in headwater streams were reported by Heino *et al*. (2005), while scrapers occurred in low abundance there.

In the tropics, influence of hydrological, physical and chemical alterations on the aquatic macroinvertebrates biological and ecological diversity remains poorly understood. However, more intensive research had been focused on investigating the interaction between the aquatic ecosystem integrity and its biological components in boreal forests (Heino, 2005; Heino *et al*., 2005; Heino *et al*., 2009). The present findings revealed that biological and ecological diversity of macroinvertebrates in tropical forest streams of Malaysia were highly affected by changes in the habitat quality as well as hydrological, physical and chemical conditions of the water. Human disturbance of the aquatic habitats is widely known as the key factor explaining the alterations in macroinvertebrate composition, distribution, biodiversity and loss of their ecological functioning in tropical (Dudgeon, 2000a, 2000b, Gopal, 2005; Dudgeon, 2006; Sodhi *et al*., 2006; Dudgeon, 2007; Dudgeon, 2008; Griffin *et al*., 2009; Al-Shami *et al*., 2011; Al-Shami *et al*., 2013) and temperate regions (Duffy *et al*., 2007; Sandin and Solimini, 2009). For instance, Al-Shami *et al*. (2011) found that changes in physical and chemical characteristics of the streams in Juru River Basin (Malaysia) because of different domestic, agricultural and industrial discharges had adverse effect on diversity of aquatic macroinvertebrates. Heavily polluted sites were characterized by severe reduction in species diversity and were mainly dominated by tolerant taxa such as *Chironomus kiiensis*, *Chironomus javanus* (Chironomidae), *Culex* sp. (Culicidae), *Eristalis* sp. (Syrphidae) and Oligochaeta (*Tubifex* spp. and *Branchiodrilus* sp.). Likewise, Zhang *et al*. (2010a) reported that the land-use disturbance and water quality degradation significantly reduced the benthic biodiversity in Pearl River drainage basin, China. The ecological functioning of shredder is known to be related to the process of litter decomposition and release of the nutrients into the aquatic ecosystems. Most of shredders taxa are known for their preference to minimally impacted habitats associated with high quality of the stream water. Therefore, the reduction in the shredder diversity will affect the processing of the litter decomposition and the ecosystem functioning (Naeem *et al.*, 1994; Encalada *et al.*, 2010). The abundance of shredder especially *Phylloicus* sp. (Trichoptera) is generally high in forest streams (Encalada *et al.*, 2010). In the present study, high abundance of shredder was observed in GT1 and GT2. Both streams are typical forest streams with minimal impacts. However, high shredder abundance was also observed in GT5, which is heavily disturbed with had logging activities. It is possible that the stream gradually recovered from deforestation which occurred >30 years ago.

Friberg *et al.* (2009) studied the changes in aquatic macroinvertebrate community composition, their ecological guilds (functional feeding groups, FFGs) and the ecological functioning (leaf litter breakdown rates). They found that the aquatic macroinvertebrates' ecological functioning increased proportionately with elevation in the water temperature and negatively with stream nutrients. Similarly, Gucker *et al.* (2009), McKie and Malmqvist (2009) and Young and Collier (2009) concluded that the ecological functioning and biodiversity of aquatic organisms showed significant response to agricultural land use and disturbance of the aquatic ecosystems. In the same context, Stephenson and Morin (2009) reported that changes in canopy cover as well as the forest land use affected the distribution, ecology and production of algae, invertebrates and fish.

CONCLUSION

Nevertheless, recent development in research of biology and ecology of aquatic macroinvertebrate in tropical streams (Boyero *et al.*, 2009) and most of the studies in Malaysia investigating the aquatic macroinvertebrates were in the form of faunal surveys (see Bishop, 1973; Che Salmah *et al.*, 2001; Aweng-Eh *et al.*, 2010 but see Che Salmah *et al.*, 2013 and Al-Shami *et al.*, 2013). None have examined the influence of hydrological and physicochemical parameters on ecological and biological diversity of macroinvertebrates in tropical forest streams. In effort to investigate the ecohydrological linkages, the present study showed that disturbances due to different human activities including logging, road construction and agricultural land use affected the hydrological characters of streams, which in turn resulted in low biological and ecological diversity of aquatic macroinvertebrates. Although biodiversity of the aquatic macroinvertebrates in SE Asian tropical forests is fairly studied, little is known about their habitat requirements and ecological diversity. In addition to that, the lack of proper and complete taxonomic keys of the macroinvertebrates in the aquatic ecosystems in this region is another obstacle hindering further ecological research. In this study, 'cryptic' taxa that are restricted to tropical forest streams in SE Asia increase their potential conservation value.

On the basis of the significant contribution of tropical forest streams to the ecological integrity of the world aquatic ecosystems, it is suggested that tropical forest streams should be given more concern as biodiversity hot spots and should be considered as key zones for more effective conservation plans of the freshwater systems. Apparently, the alteration in the physical and chemical habitats (due to human disturbance) is the potential factor shaping the functional and taxonomic biodiversity patterns of aquatic macroinvertebrate assemblages in the SE Asian tropical forest streams.

Further ecohydrological studies are suggested for better understanding of the interaction between hydrological characteristics and biological components in pristine and disturbed tropical ecosystems. Thus, such research will contribute for global understanding about the adverse effect of climate change on aquatic organisms.

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CONFLICT OF INTEREST STATEMENT

We declare that we have no conflict of interest.

APPENDIX 1. LIST OF AQUATIC MACROINVERTEBRATE TAXA AND MORPHOSPECIES COLLECTED FROM GUNUNG TEBU (GT) STREAMS, MALAYSIA

No	Order	Family	Morphospecies	GT1	GT2	GT3	GT4	GT5	No. of individuals	Relative Abundance %
1	Ephemeroptera	Baetidae	*Baetis* sp.	1	22	1	1	4	29	2·9
2			*Platybaetis* sp.	0	1	0	0	0	1	0·1
3		Caenidae	*Caenis* sp.	0	2	2	0	8	12	1·2
4		Heptageniidae	*Camsoneuria* sp.	1	22	20	12	11	**66**	**6·5**
5			*Thalerosphyrus* sp.	0	4	1	0	0	5	0·5
6			*Epeorus* sp.	0	7	0	0	0	7	0·7
7		Leptophlebiidae	*Habrophlebiodes* sp.	5	23	10	11	3	52	5·1
8		Ephemeridae	*Ephemera* sp.	6	0	0	2	1	9	0·9
9		Tricorythidae	*Tricorythus* sp.	0	6	0	0	0	6	0·6
10	Plecoptera	Perlidae	*Ectrocorema* sp.	5	22	16	0	3	46	4·5
11			*Neoperla* sp.	3	12	0	0	8	23	2·3
12			*Phanoperla* sp.	0	1	0	0	0	1	0·1
13		Peltoperlidae	*Cryptoperla sp.*	0	3	0	0	0	3	0·3
14	Trichoptera	Philopotamodae	*Chimarra* sp.	0	28	5	0	0	33	3·3
15		Hydropsychidae	*Hydropsyche* sp.	7	14	2	0	2	25	2·5
16			*Potamyia* sp.	8	31	2	0	0	41	4·1
17			*Ceratopsyche* sp.	4	0	0	0	0	4	0·4
18		Ecnomidae	*Ecnomus* sp.	0	0	1	0	0	1	0·1
19		Calamoceratidae	*Anisocentropus* sp.	0	2	0	0	0	2	0·2
20			*Ganonema* sp.	0	0	1	0	0	1	0·1
21		Helicopsychidae	*Helicopsyche* sp.	0	1	0	0	0	1	0·1
22	Odonata	Amphiterygidae	*Devadatta* sp.	0	0	0	0	1	1	0·1
23		Calopterygidae	*Vestalis* sp.	0	1	0	0	0	1	0·1
24		Gomphidae	*Heliogomphus* sp.	1	0	0	0	1	2	0·2
25			*Ophiogomphus* sp.	1	0	0	0	1	2	0·2
26			*Ictinogomphus* sp.	0	0	0	0	1	1	0·1
27		Platystictidae	*Drepanosticta* sp.	0	1	0	0	0	1	0·1
28		Euphaeidae	*Euphaeia* sp.	2	11	10	0	2	25	2·5
29		Coenagrionidae	*Agriocnemis* sp.	8	0	0	10	1	19	1·9
30		Chlorogomphidae	*Chlorogomphus* sp.	2	1	0	0	0	3	0·3
31		Macromiidae/ Corduliidae	*Macromia* sp.	6	0	0	7	0	13	1·3
32	Megaloptera	Corydalidae	*Protohermes* sp.	0	7	0	0	0	7	0·7
33	Hemiptera	Gerridae	*Ventidius* sp.	0	1	0	2	0	3	0·3
34			*Metrocoris* sp.	5	2	0	2	3	12	1·2
35			*Potamometropsis* sp.	0	1	0	1	0	2	0·2
36			*Neogerris* sp.	0	1	1	0	0	2	0·2
37			*Amemboa* sp.	2	0	0	14	8	24	2·4
38			*Rheumatogonus* sp.	0	1	0	0	0	1	0·1
39			*Ptilomera* sp.	0	2	0	0	0	2	0·2
40			*Tenagogonus* sp.	0	14	0	0	0	14	1·4
41			*Limnogonus* sp.	0	4	0	0	0	4	0·4
42			*Limnometra* sp.	0	11	1	0	0	12	1·2
43		Naucoridae	*Heleocoris* sp.	1	0	0	2	0	3	0·3
44		Veliidae	*Rhagovellia* sp.	0	39	1	0	14	**54**	**5·3**
45			*Entomovelia* sp.	0	3	0	0	0	3	0·3
46			*Perritoppus* sp.	0	0	0	5	0	5	0·5
47		Notonectidae	*Enithares* sp.	8	0	0	28	0	36	3·6
48			*Aphelonecta* sp.	0	0	0	5	0	5	0·5
49	Coleoptera	Eulichadidae	*Eulichas* sp.	0	5	0	0	1	6	0·6
50		Elmidae	*Stenelmis* sp.	0	1	0	0	0	1	0·1
51			Unknown species	0	4	1	0	0	5	0·5
52			*Grouvellinus* sp.	0	3	0	0	0	3	0·3
53		Hydrophilidae	*Berosus* sp.	2	4	0	0	1	7	0·7
54			*Helochares* sp.	8	11	0	0	0	19	1·9
55		Dryopidae	*Elmomorphus* sp.	0	0	2	0	0	2	0·2
56			Unknown species	0	2	2	0	0	4	0·4
57		Gyrinidae	*Orectochilus* sp.	26	0	0	19	1	46	4·5
58		Histeridae	Unknown species	1	0	0	0	1	2	0·2
59		Psephenidae	*Eubrianax.* sp.	3	11	13	1	0	28	2·8

(Continues)

(Continued)

No	Order	Family	Morphospecies	GT1	GT2	GT3	GT4	GT5	No. of individuals	Relative Abundance %
60		Scirtidae	Unknown species	1	11	8	0	8	28	2·8
61	Diptera	Tipulidae	Unknown species	5	2	2	2	7	18	1·8
62		Chironomidae	Unknown species	9	6	23	0	1	39	3·9
63		Arthericidae	Unknown species	2	3	0	0	1	6	0·6
64		Simuliidae	*Simulium* sp.	0	29	32	0	1	**62**	**6·1**
65		Tabanidae	Unknown species	0	0	0	0	1	1	0·1
66		Dixidae	Unknown species	0	1	2	0	0	3	0·3
67	Blattaria	Blattidae	Unknown species	11	1	0	10	2	24	2·4
68	Mollusca	Thiaridae	Unknown species	0	0	0	0	3	3	0·3
69	Crustacea	Varunidae	Unknown species	5	6	4	5	7	27	2·7
70		Palaemonidae	*Macrobrachium* sp.	0	26	2	0	24	52	5·1
71	Annelida	Hirudinea	Unknown species	0	0	0	1	0	1	0·1
		Total		**149**	**427**	**165**	**140**	**131**	**1012**	**100·0**

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