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Review article

Bioaccumulation of heavy metals by aquatic macro-invertebrates of different feeding guilds: a review

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Abstract

The available literature on heavy metal bioaccumulation by freshwater macro-invertebrates has been analysed. A very uneven data distribution was found. Ephemeroptera and Diptera are the most commonly investigated orders of insect larvae, whilst many orders are not represented at all. The collector–gatherer and predator feeding guilds are more frequently investigated than other guilds. Furthermore, Zn, Cu, Pb and Cd are the most intensively researched heavy metals, and only infrequent investigations of other metals are documented. Relationships between metal concentrations in the animals and levels in sediments and waters were determined from the pooled data for three feeding guilds. No one relationship represents how each metal interacts within the feeding guilds. Each of the four metals (Zn, Cu, Pb and Cd) displays a unique relationship between metal concentrations in sediments or waters with those in individual feeding guilds of macro-invertebrates, indicating the relative importance of different sources of metals to the different feeding types. Biomagnification of Zn, Cu, Pb and Cd has been demonstrated not to occur between these guilds.

Keywords: Bioaccumulation; Heavy metals; Aquatic macro-invertebrates; Feeding guilds

1. Introduction

Bioaccumulation of heavy metals by aquatic organisms is a reasonably well documented field of research. The majority of such investigations have been undertaken since the 1970s at an increasing rate. There is, however, still a limited amount of information about the biology of trace metals in freshwater organisms (Hare, 1992, Rainbow and Dallinger, 1992), or their effects on freshwater ecosystems (Gower et al., 1994). Fur-

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thermore, it has been noted that 'to date, insects have been used to a limited extent in the study of metal contamination in freshwater' (Hare and Campbell, 1992).

Hare (1992) provided a succinct summary of many of the reasons which make insect larvae attractive as biomonitors, and other authors, including Myslinski and Ginsburg (1977), Lynch et al. (1988) and Hare and Campbell (1992) offered further reasons for their use in biomonitoring. These reasons are listed below:

1. a common and diverse group of animals which are found in freshwater of all types;
2. many taxa are fairly sedentary and thus representative of local conditions;
3. many taxa are benthic and thus are closely associated with sediments;
4. they may accumulate metals and yet tolerate low–moderate metal concentrations;
5. metal concentrations in the animals appear to be related to those in their environment;
6. a life-span of several months–years allows integration of contaminants into their bodies over a reasonable period of time, but not so long that it avoids short-term changes in the environment;
7. since most are the immature stages of the life-cycle, body concentrations are not affected by reproductive cycles or sexual differences;
8. they are near the base of foodchains, so may be vital agents of metal entry into foodchains.

Aquatic macro-invertebrates therefore appear to have the potential to be useful biomonitors in the future, despite the limited interest shown in them to date. The aim of this investigation is to review the available literature and to determine to what extent there is a good relationship between trophic types (guilds) (Root, 1973) of macro-invertebrates and the metals in their environment.

2. Methods

Previous investigations concerning freshwater contamination and macro-invertebrates are largely confined to community structure studies. Information from the literature was pooled, regardless of its nature; i.e. field or laboratory based, geographical location, metals investigated, etc. A detailed summary of these papers is presented in Appendix A.

The data were split into five categories based on feeding guild. The feeding guilds chosen are listed below, with the definitions taken from Begon et al. (1990):

1. Collector–Gatherer (C-G), animal which gathers small particles of organic material from the sediments;
2. Scraper–Grazer (S-G), animal which grazers the organic layer of algae, micro-organisms and films on stones and other substrates;
3. Predator (Pr), animal which consumes other organisms;
4. Shredder (Sh), animal which feeds on coarse particles of organic matter;
5. Filterer (Fi), animal which feeds on minute particles of suspended in water, which are strained through mucus or a meshwork of lamellae.

The animals in each of these categories are presented in Table 1. Common names are also given for the orders as most species do not have common names. The data were then investigated for relationships between metal concentrations in the animals and those in the environment for a range of metals within guilds and for each metal between guilds. Data were plotted against water and sediment heavy metal concentrations in both cases. For each relationship, the *r*-value was calculated and regression analysis performed.

3. Results

3.1. Range of data available

Visual inspection of the data revealed some relevant observations of the distribution of the data within the literature.

The metals investigated were wide ranging, but the majority of studies focused on four metals: Zn, Cu, Pb and Cd. The former two of these are

Table 1
The invertebrates in each feeding guild of the present review. Data are taken from the literature, and the references are listed in Appendix A

Collector–gatherer (C-G)	Scraper–grazer (S-G)	Predator (Pr)	Shredder (Sh)	Filterer (Fi)
Hexagenia sp.	*Campeloma* sp.	*Placobdella* sp.	*Gammarus* sp.	*Sphaerium*
Hexagenia limbata	*Gnoibasis* sp.	*Haemopsis* sp.	*Gammarus pulex*	*Orconectes* sp.
Ephemera danica	*Pleurocera* sp.	*Erpobdella* sp.		*Elliptio complanata*
Ephemera vulgata	*Limnaea* sp.	*Erpobdella octoculata*		*Fusconaia flava*
Potamanthus sp.	*Physa* sp.	Agridae		*Amblema plicata*
Ecdyonurus venosus	*Asellus* sp.	*Argia* sp.		*Quadrula quadrula*
Stenonema sp.	*Asellus aquaticus*	*Brachyptera risi*		
Rithrogena sp.	*Asellus meridanius*	*Amphinemura sulcicolis*		
Ephemerella grandis		*Leuctra* sp.		
Ephemerella ignita		*Classenia subulosa*		
Leptophlebia vespertina		*Hesperoperla pacifica*		
Baetis sp.		*Perla bipunctata*		
Baetis vernus		*Pteronarcys californica*		
Baetis rhodani		*Pteronarcella badia*		
Arctopsyche grandis		*Isognoides* sp.		
Hydropsyche sp.		*Skwala americana*		
Hydropsyche pellucidula		*Isoperla grammatica*		
Hydropsyche angustipennis		*Perloides microcephela*		
Brachycentrus sp.		*Chloroperla* sp.		
Phryganea sp.		*Sigara* sp.		
Cheumatopsyche sp.		*Sialis* sp.		
Limnephilidae		*Rhyacophila nubila*		
Limnephilus sp.		*Rhyacophila dorsalis*		
Potamophylax latipennis		*Polycentropus flavomaculatus*		
Tipula sp.		*Plectrocnemia conspersa*		
Simulium sp.		*Chaoborus punctipennis*		
Chironomidae		*Procladius* sp.		
Chironomus riparius		*Dytiscus* sp.		
Glyptotendipes sp.		*Oreodytes sanmarki*		
		Limnius volckmari		

known to be essential elements (Dadd, 1973; Bowen, 1979; Kelly, 1988; Hopkin 1989), whilst the latter two metals are not known to be essential or beneficial to living organisms (Keenan and Alikhan, 1991). A series of other metals were determined less frequently, i.e. Hg, Ni, Al, Fe, Mn, As, Cr, whilst a very sparse amount of data existed for Co, Mo, Sb, Li, Na, Ca (see Appendix A).

A wide range of macro-invertebrates have been used in bioaccumulation investigations (Appendix A). It is unusual that more than one investigation has studied the same species or genus of animal. Therefore to draw comparisons between data in the literature is difficult, unless broad groups of organisms are used. Several taxonomic groups have been used more frequently than others. A summary was made of the numbers of investigations undertaken on each order and family of macro-invertebrate, and is presented in Table 2. For example, the orders Diptera and Ephemeroptera have been previously investigated on many occasions (38 and 33 investigations, respectively), whilst Odonata and Decapoda have a sparse previous literature (five and one investigations, respectively).

The numbers of field- and laboratory-based investigations are not equal; the field investiga-

Table 2
The number of biogeochemical investigations which have been undertaken on various aquatic macro-invertebrate orders and families[a]

Order	Family	Number	Order	Family	Number
Amphipoda		6	Hemiptera		2
(sandhoppers)	Gammaridae	6	(bugs)	Corixidae	2
Isopoda		8	Megaloptera		3
(woodlice)	Asellidae	8	(alderflies)	Sialidae	3
Decapoda		1	Neuroptera		1
(crayfish)	Astacidae	1	(lacewings)		32
Ephemeroptera		33	Trichoptera		32
(mayflies)	Ephemeridae	12	(caddisflies)	Rhyacophilidae	3
	Potamanthidae	1		Polycentropidae	1
	Ecdyonuridae	6		Hydropsychidae	16
	Ephemerellidae	6		Bracycentridae	4
	Leptophlebidae	1		Phryganeidae	3
	Baetidae	6		Limnephelidae	4
Odonata		5		Leptoceridae	1
(dragonflies)	Aeshnidae	1	Diptera		39
	Agriidae	3	(true flies)	Tipulidae	4
Plecoptera		25		Chaoboridae	2
(stoneflies)	Taenopterygidae	1		Simulidae	4
	Nemouridae	1		Chironomidae	24
	Leuctridae	1		Phagionidae	1
	Perlidae	5	Coleoptera		4
	Pteronarcidae	8	(beetles)	Dytiscidae	2
	Perlodidae	7		Elminthidae	1
	Chloroperlidae	1			

[a] Attention is drawn to the unequal distribution between the orders and families.

tions far out numbering the laboratory ones. It is not clear why this should be so, as each type of study complements the other. Both field- and laboratory-based investigations are imperative if bioaccumulation models are to be constructed and utilised in biomonitoring or environmental impact studies. It was also noted that a smaller selection of invertebrate groups have been studied in the laboratory than in the field.

There is also an uneven distribution of investigations into the biogeochemistry of each of the five feeding guilds listed above. The guilds of collector–gatherer (C-G), scraper–grazer (S-G) and predator (Pr) have been more intensely investigated, whilst the shredder and filterer guilds have a sparse previous literature. Because of limited data availability, the remaining summaries of the pooled data concentrate on the C-G, S-G and Pr; and only for the metals Zn, Cu, Pb and Cd.

3.2. Relationships between organism and sediment / water metal concentrations

Each of the relationships between organism and environmental media has shown a characteristic scatter of points within the data. This scatter varies with each individual relationship; i.e. a broad scatter of data for all Cd relationships, and a narrow scatter in the relationships involving water Cu levels with animals of any feeding guild. Possible explanations for this are numerous and include: (i) variation in the diet of different species within a feeding guild; (ii) the metal species involved in each investigation; (iii) the geographical location the organisms were collected from; (iv) incorrect classification of feeding guilds; (v) relative ages of the individuals used in each of the feeding guilds; (vi) variations in the preparation and analysis of samples from each investigation;

(vii) accuracy of the results used, only mean values were used from each reference and no account of concentration ranges was considered; and (viii) variation in water pH, Eh, temperature, hardness, etc., between the investigations. Nevertheless, despite their co-variant factors it is obvious that overall general relationships exist linking metal concentrations in the environment to those in the animals.

3.3. Zinc

The pooled data show that relationships between Zn concentrations in sediments and in macro-invertebrates are significant for each of the feeding guilds C-G, S-G and Pr, at the 1% level and have high adjusted R^2-values (Fig. 1, Table 3). Regression analysis of the relationships between Zn concentrations in sediments and organisms illustrate that each feeding guild has a significant slope and intercept value. Zinc levels in animals appear to be taken up in direct proportion to levels in the sediments. Concentrations of Zn in animals increase along the gradient C-G > S-G > Pr, at similar sediment Zn levels.

Relationships between water Zn concentrations and those in each feeding guild have significant *r*-values (1% level), but low R^2-adjusted values

Table 3
Summary statistics describing the relationships between Zn, Cu, Pb and Cd concentrations in sediments and waters with those in aquatic macro-invertebrates[a]

		N	*R*	Regression equation	Intercept *P*	R^2-adjusted (%)
Zn sediment:	Collector/gatherer	159	0.908**	Animal Zn = $-1413 + 5.57x$	< 0.001	82.3
	Scraper/grazer	38	0.766**	Animal Zn = $707 + 0.43\ x$	< 0.001	57.6
	Predator	98	0.981**	Animal Zn = $-1139 + 2.67x$	< 0.001	75.7
Zn waters:	Collector/gatherer	158	0.231**	Animal Zn = $1222 + 0.492x$	< 0.001	4.7
	Scraper/grazer	16	0.713**	Animal Zn = $89.1x$	0.155	47.3
	Predator	90	0.411**	Animal Zn = $555 + 0.11x$	< 0.001	16.0
Cu sediment:	Collector/gatherer	121	0.810**	Animal Cu = $0.294x$	0.285	65.2
	Scraper/grazer	36	0.814**	Animal Cu = $1.73x$	0.298	65.3
	Predator	40	0.946**	Animal Cu = $26.2 + 0.114x$	< 0.001	89.2
Cu waters:	Collector/gatherer	147	0.948**	Animal Cu = $0.904x$	0.244	89.2
	Scraper/grazer	32	0.890**	Animal Cu = $107 + 0.297x$	< 0.001	78.5
	Predator	61	0.908**	Animal Cu = $87.4 + 0.209x$	0.008	82.1
Pb sediment:	Collector/gatherer	148	0.389**	Animal Pb = $0.109x$	0.085	14.5
	Scraper/grazer	46	0.365**	Animal Pb = $0.459x$	0.154	11.4
	Predator	99	0.375**	Animal Pb = $73.3 + 0.067x$	0.036	13.2
Pb waters:	Collector/gatherer	113	0.973**	Animal Pb = $11.6x$	0.826	94.6
	Scraper/grazer	20	0.672**	Animal Pb = $-405 + 107x$	0.024	42.1
	Predator	75	0.979**	Animal Pb = $99.8 + 0.401x$	< 0.001	95.7
Cd sediment:	Collector/gatherer	168	0.348**	Animal Cd = $7.19 + 0.364x$	< 0.001	11.6
	Scraper/grazer	35	0.535**	Animal Cd = $2.17x$	0.081	26.4
	Predator	99	0.247**	Animal Cd = $3.16 + 0.663x$	0.031	5.1
Cd waters:	Collector/gatherer	98	0.071	Animal Cd = 20.3	< 0.001	0.0
	Scraper/grazer	11	0.822**	Animal Cd = $0.971x$	0.290	64.0
	Predator	64	−0.011	Animal Cd = 11.9	0.040	0.0

[a] These relationships are presented in Figs. 4 and 5, and these should be used in conjunction with this table.

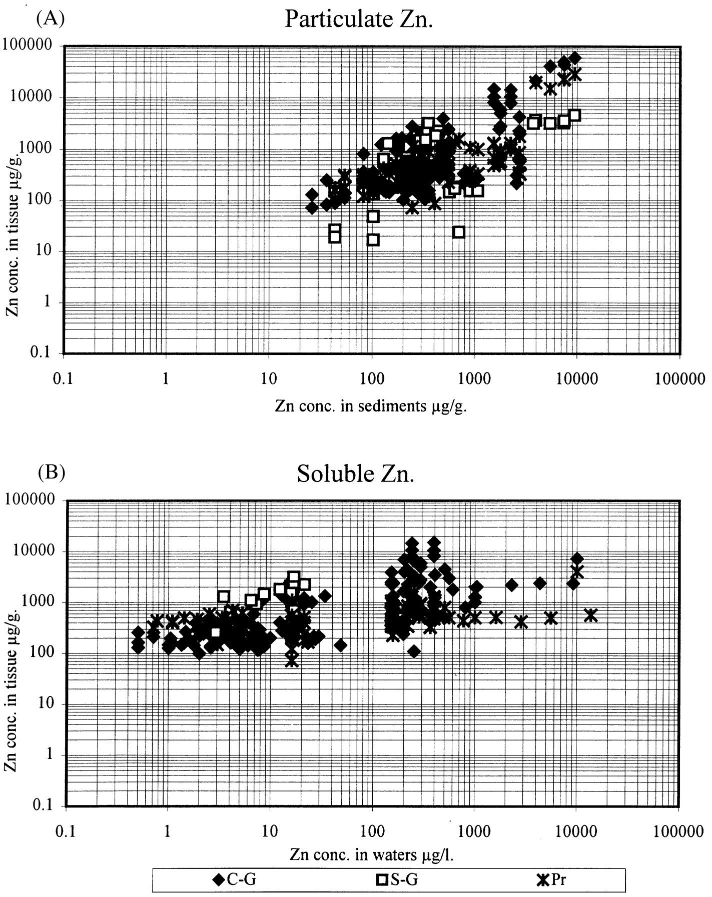

Fig. 1. Relationships between Zn concentrations in macro-invertebrates of different feeding guilds with those in (A) sediments or (B) waters. Figure should be used in conjunction with Table 3.

(C-G, 4.7%; S-G, 47.3%; and Pr, 16%; Table 3). Concentrations of Zn in the animals appear to be more or less regulated regardless of concentrations in the waters; regression equations confirming these relationships. It appears that Zn concentrations in C-G are higher than in Pr at lower water Zn concentrations, but are lower than Pr at higher water Zn concentrations (Fig. 1). Significant positive relationships between Zn concentrations in waters and in insect larvae have been documented previously, e.g. Vuori (1993) found relationships for *Hydropsyche angustipennis* and *H. pellucidula* (Trichoptera) (C-G), and Timmermans et al. (1992) for *Mystacides* sp. (Trichoptera) (C-G). Therefore when considering Zn bioaccumulation in aquatic macro-invertebrates it is important to know whether the Zn is in a particulate or soluble phase, and to which feeding guild the animal belongs. Furthermore, Zn biomagnification does not seem to be occurring between these groups of animals, as Zn concentrations in animals taken from similar environmental concentrations do not significantly increase in animals of a higher trophic level.

3.4. Copper

Each of the feeding guilds of macro-invertebrate, C-G, S-G and Pr, have body Cu concentrations in similar relationships with sediment Cu concentrations (Fig. 2), whereby body concentrations increase as sediment concentrations in-

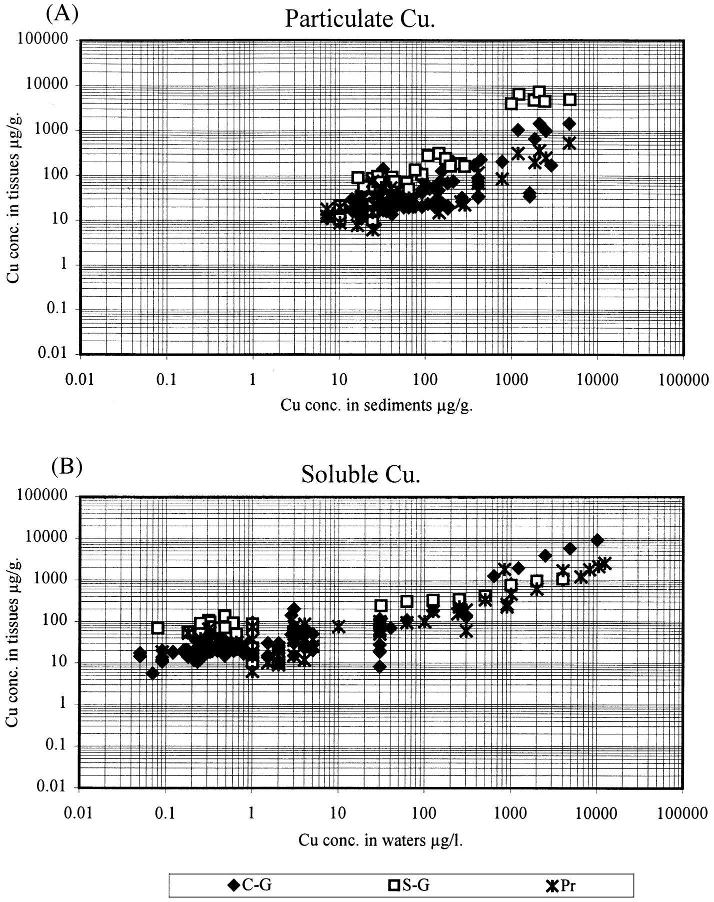

Fig. 2. Relationships between Cu concentrations in macro-invertebrates of different feeding guilds with those in (A) sediments or (B) waters. Figure should be used in conjunction with Table 3.

crease. Significant r-values and high R^2-adjusted values for each relationship confirm the visually-obvious relationships. Regression analyses of the relationships give significant slope and intercept values (Table 3). Copper concentrations in the these feeding guilds follow the gradient S-G > C-G > Pr.

Significant relationships between animal Cu concentrations and those in water are highlighted by the r-values, high R^2-adjusted values and the significant slope and intercept values for each regression equation (Fig. 2, Table 3). It is not possible to determine a Cu concentration gradient between the feeding guilds as the cloud of points for each guild overlaps with the others. Previously, Nehring (1976) illustrated that *Ephemerella grandis* (Ephemeroptera) (C-G) and *Pteronarcys californica* (Plecoptera) (Pr) accumulated Cu in proportion to concentrations in waters. It appears that macro-invertebrates bioaccumulate Cu, and that they do so from both particulate and soluble sources. Because there is no significant difference in the intercept values between guilds, there appears to be no biomagnification of Cu.

3.5. Lead

The relationships between Pb concentrations in sediments and in C-G and Pr feeding guilds of macro-invertebrates are significant at the 1% level. These two feeding guilds have significant regression lines and intercept values, but low R^2-adjusted values (Fig. 3, Table 3). Conversely, the relationship involving S-G animals is not significant and does not have a significant intercept value. This suggests that the S-G is interacting in a different manner with sediments than the C-G or Pr guilds. No Pb concentration gradient between the feeding guilds can be established, as data for all guilds fall within one cloud of points. Eyres and Pugh-Thomas (1978) and Timmermans et al. (1989) both found that Pb concentrations were lower in carnivorous species than those of other guilds, but the data here suggest the opposite, with the Pr guild having greater amounts than the S-G.

All relationships between Pb concentrations in macro-invertebrates and in waters are significant (Table 3). The guilds S-G and Pr have both significant slopes and intercepts, while the C-G only has a significant slope (Fig. 3). A broad concentration gradient between the guilds is suggested to be C-G = S-G < Pr. Positive significant relationships between Pb concentrations in waters and in *Ephemerella grandis* (Ephemeroptera) (C-G), *Pteronarcys californica* (Plecoptera) (Pr) (Nehring 1976), *Hexagenia limbata* (Ephemeroptera) (C-G) (Besser and Rabeni 1987) and *Ecdyonurus venosus* (Ephemeroptera) (C-G)

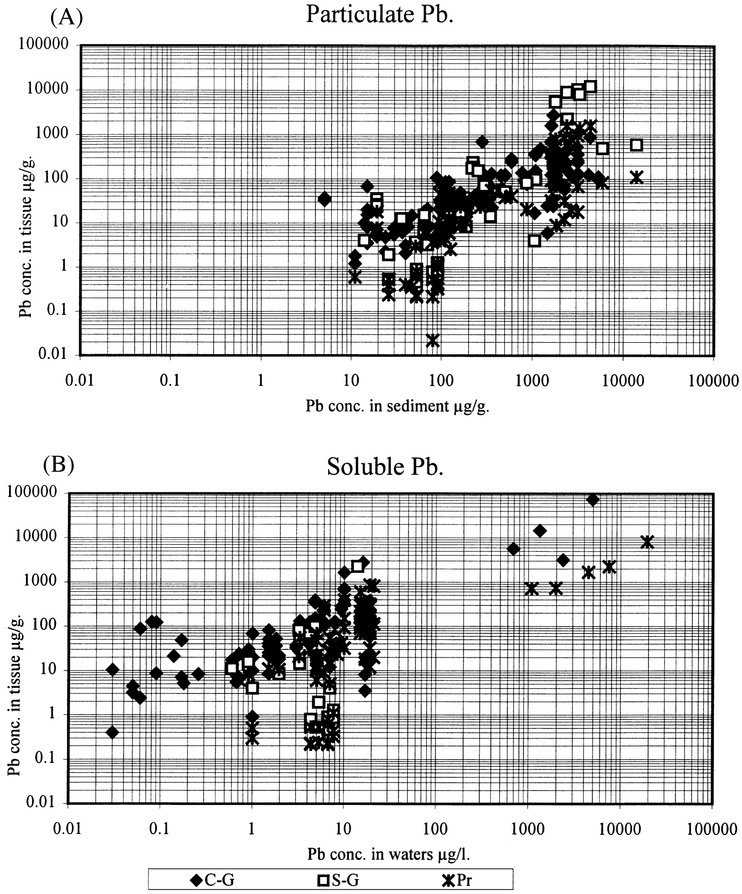

Fig. 3. Relationships between Pb concentrationd in macro-invertebrates of different feeding guilds with those in (A) sediments or (B) waters. Figure should be used in conjunction with Table 3.

(Burrows and Whitton 1983) have previously been documented. The individual feeding guilds of macro-invertebrates are therefore not interacting similarly with Pb in the particulate and soluble phases, and Pb biomagnification may be occurring.

3.6. Cadmium

Relationships involving Cd concentrations in the sediments and waters are more difficult to interpret, as concentrations are always low, nearing the detection limit of the instrumentation on which they were made. For this reason, the summary offered below is at best a suggestion of possible relationships between the media.

Only the feeding guilds C-G and S-G have possible relationships with sediment Cd concentrations. Furthermore, the C-G are the only guild to have a significant regression equation (Table 3). All guilds have data which plot within one widely-scattered cloud. Relationships involving water and animal Cd concentrations fail to produce any significant relationships. This is probably the result of poor data precision.

Many authors have suggested there are good relationships between Cd and Zn concentrations in waters and organisms, and that relationships involving Zn may be used as tracers for Cd relationships, e.g. Clubb et al. (1975a,b), Carter and Nicholas (1978), Dressing et al. (1982), Burrows and Whitton (1983), Memmert (1987) and Barak and Mason (1989). This may be so but the present data for Cd are too poor to show whether this is generally the case or not.

3.7. Relationships between concentrations of different heavy metals within feeding guilds

3.7.1. Collector–gatherer

Fig. 4a and Fig. 5a illustrate relationships between heavy metal concentrations in organisms of the C-G feeding guild and sediments or waters, respectively. Levels of Zn, Cu, Pb, Cd in organisms are found in direct proportion to those in sediments, suggesting that the organisms metal concentrations are heavily influenced by the sediment metal levels (Fig. 4a). The same relationship is found between organism and water metal concentrations, although water metal concentrations are very much less than those in organisms (Fig. 5a). The concentration gradient between metal levels in organisms and sediments or waters is the same, Cd $<$ Pb $\leq$ Cu $\leq$ Zn. In turn this suggests that the sediment and water metal concentrations are in close association, and that the organisms are interacting with both sources of the metals, as might be expected with animals that burrow through the sediment. Significant relationships between metal levels in sediments and C-G were found by Jop (1991) [*Ephemera danica* and *E. vulgata* (Ephemeroptera)] and Hare et al. (1991a,b) [*Hexagenia rigida* (Ephemeroptera)].

3.7.2. Scraper–grazers

Fig. 4b and Fig. 5b illustrate relationships between metal concentrations in organisms of the S-G feeding guild and sediments or waters, respectively. In both relationships data points are few in number. It would appear that concentrations of Zn, Cu and Cd in sediments and organisms are equable, but that Pb concentrations in organisms are less than sediments (Fig. 4b). The relationship between metal concentrations in S-G and sediments follows a simple gradient: Cd $<$ Pb $=$ Cu $=$ Zn. No further explanation of this relationship may be made with the available data. Too few data are available to assess concentration gradients of heavy metals in organisms with relation to water concentrations (Fig. 5b). It may be that Cu is accumulated to low levels by the S-G, but more data are needed to verify this relationship.

3.7.3. Predator

Fig. 4c and Fig. 5c illustrate relationships between metal concentrations in organisms of the Pr feeding guild and sediments or waters, respectively. The Pr appear to accumulate Cd and Zn in direct proportion to those levels in the sediments, with Zn $>$ Cd. Copper and Pb are also accumulated by the organisms, but at levels below those found in sediments. Only a very generalised concentration gradient of metal concentrations in the Pr can be made, and that is Cd $<$ Pb $=$ Cu $=$ Zn (Fig. 4c), following that for the S-G. Linear rela-

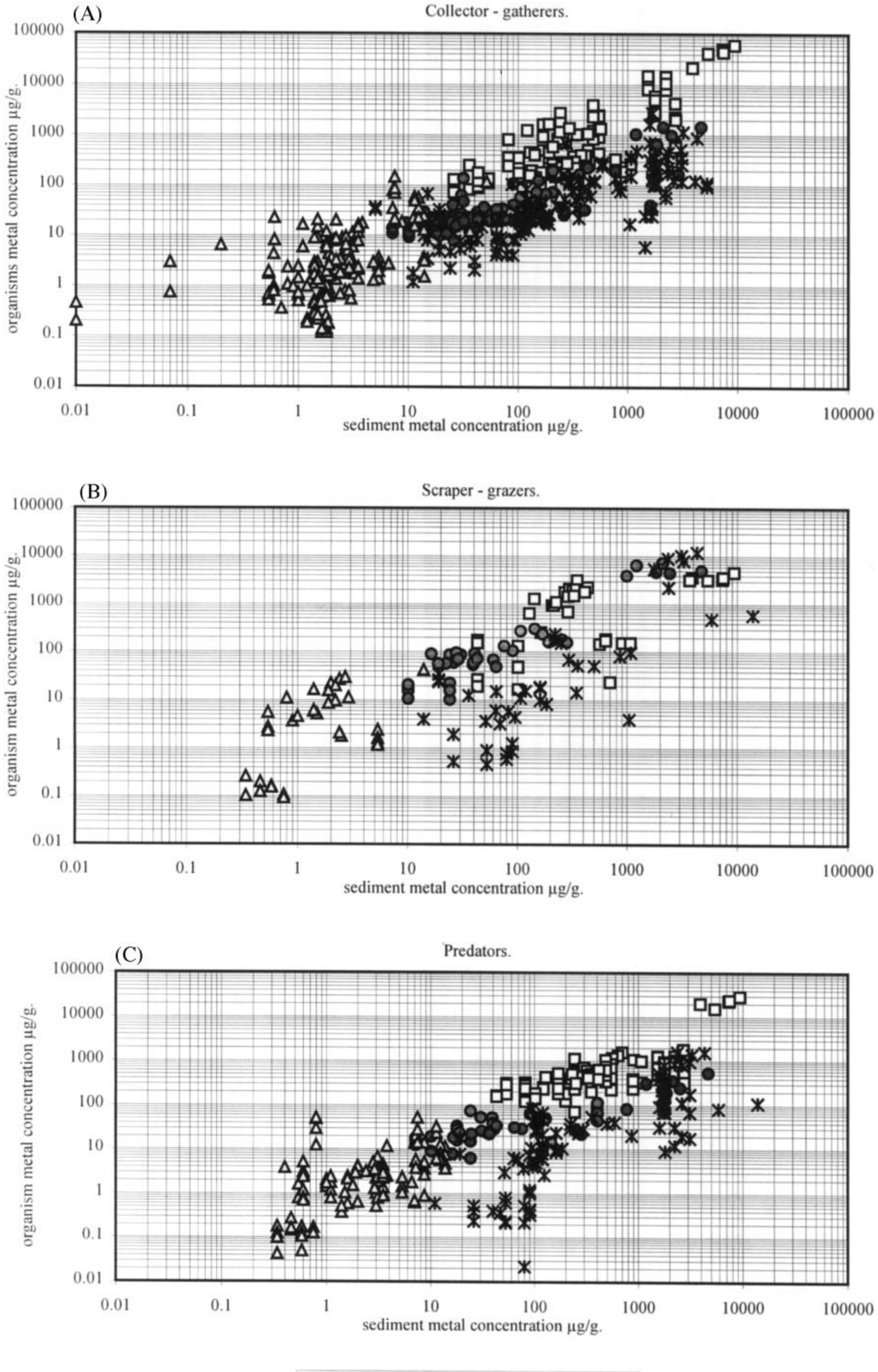

Fig. 4. Relationships between Zn, Cu, Pb and Cd concentrations in sediments with those in macro-invertebrates of different feeding guilds. Attention is drawn to the unequal distribution of data between the guilds, and the differences in concentrations of each metal in the individual guilds.

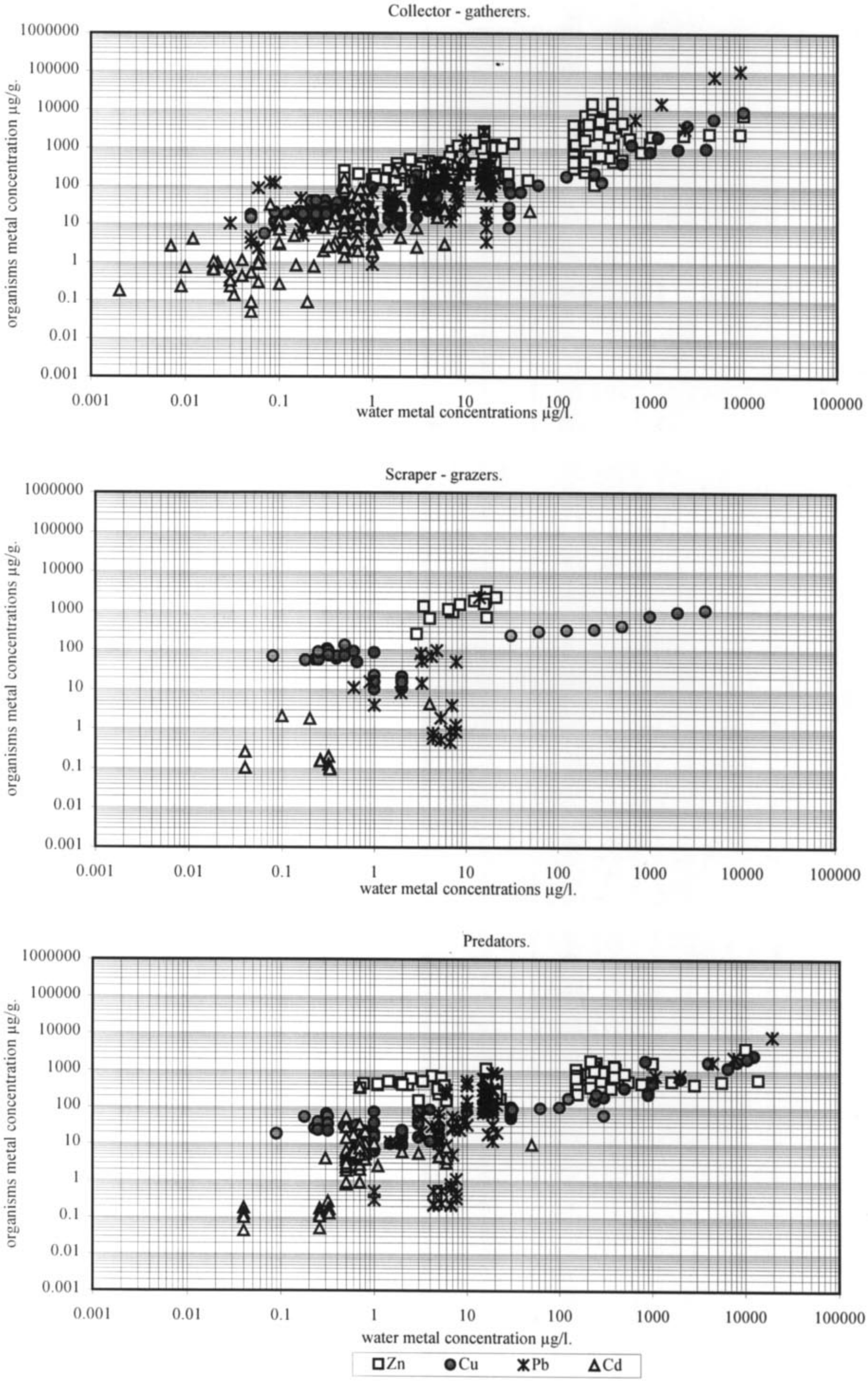

Fig. 5. Relationships between Zn, Cu, Pb and Cd concentrations in waters with those in macro-invertebrates of different feeding guilds. Attention is drawn to the unequal distribution of data between the guilds, and the differences in concentrations of each metal in the individual guilds.

tionships between Zn and Cu concentrations in waters and Pr are found, with Zn being regulated at approximately 1000 mg/g and Cu being accumulated to levels equal to those found in sediments (Fig. 5c). There are no clear relationships between levels of Pb and Cd in animals and waters, probably because the low concentrations of metals found in the Pr, and often waters, are hard to determine with any accuracy. Data for Pb and Cd appear to cluster and little interpretation about their bioaccumulation can be made from the available literature. A generalised concentration gradient of metal concentrations in predators follows thus: Cd < Pb < Cu ≤ Zn.

4. Discussion and conclusion

Statistical analyses of the relationships between Zn concentrations in macro-invertebrates and sediments or waters suggests that they are significant. There appear to be no differences in the relationships between the feeding guilds. The graphical representation of the data shows there is regulation or restriction of Zn uptake from the aqueous sources. The relationship involving sediments on the other hand, suggests that the animals accumulate Zn in direct proportion to sediment levels. The source of Zn, either aqueous or particulate, is therefore an important aspect of the concentrations found in macro-invertebrates.

Copper and Pb concentrations in organisms of each feeding guild significantly correlate with those in sediments and waters. Concentrations in animals are always more than in waters, but are usually less than in sediments, irrespective of feeding type. Levels of Cu and Pb in the environment appear therefore to greatly affect the whole-animal metal concentrations, as Cu and Pb concentrations increase in proportion to those in the environment with no signs of biological limitation. Biomagnification of Cu does not seem to be occurring between guilds as the levels of this metal do not appear to be higher at higher trophic levels. Biomagnification of Pb may occur, as concentrations in Pr are often significantly higher than S-G at many environmental concentrations.

Relationships between Cd concentrations in insect larvae and waters or sediments are hard to interpret, as many Cd concentrations are close to the detection limit of the instrumentation used. There appear to be no significant relationships between water and animal Cd concentrations, but there are significant relationships between sediment and animal Cd concentrations. These latter relationships do not produce convincing bivariate plots.

Biomagnification is a phenomenon which is to date not fully understood. It is imperative to understand biomagnification if the protection of organisms of all trophic levels is to be considered. An understanding of the metal content of food sources of higher trophic levels, and the environment in which they live, must be assessed (Timmermans et al., 1992). Several previous investigations, e.g. Memmert (1987) and Prosi (1989), have shown that biomagnification of Pb and Cd do not take place, but Timmermans et al. (1989) suggested that Zn biomagnification did occur, in their investigation of food-web chemistry. The work presented above would suggest that Zn and Cu are not biomagnified by freshwater macro-invertebrates, Pb may be in some circumstances, and it is impossible to determine if Cd is biomagnified with this dataset.

To date, there is a lack of available data about metal bioaccumulation by freshwater macro-invertebrates. As a result, relationships between environmental metal concentrations and those in organisms are not well understood. Kelly (1988) notes that the small number of organisms used in many relationships between metal concentrations in waters and organisms may account for the relatively few significant correlations found. He suggests that ‘more extensive sampling of particular groups may reveal better correlations’. The purpose of this investigation has been to increase the number of data points available and to try to establish clearer general relationships between metal levels in various groups of macro-invertebrates and environmental media. Further investigations of more species, for more metals, and over greater concentration ranges are needed to develop the understanding of bioaccumulation and biomagnification in freshwater macro-invertebrates.

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Appendix A

Summary of the available literature on heavy metal bioaccumulation by aquatic macro-invertebrates. Attention should be paid to the variety of species used and the lack of studies investigating the same species. Full references are given in the reference list.

Macro-invertebrate	Authors	Metals				Other	Environ-ment.	Feeding guild
		Cd	Pb	Cu	Zn			
ARTHROPODA								
Crustacea								
Malacostraca								
Amphipoda (sandhoppers)								
Gammaridae	Zauke, 1982	/					Stream	Sh
Gammarus pulex	Jop and Wojtan, 1982	/	/				Stream	Sh
Gammarus pulex	Khan, 1995			/			Lab.	Sh
Gammarus pulex	Xu and Pascoe, 1994				/		Lab.	Sh
Gammarus pseudolimnaeus	Spehar et al., 1978	/	/				Lab.	Sh
Gammarus sp.	Barak and Mason, 1989	/	/			Hg	Stream	Sh
Isopoda (woodlice)								
Asellidae								
Asellus aquaticus	Jop and Wojtan, 1982	/	/				Stream	Sh/Gr
Asellus aquaticus	Eyres and Pugh-Thomas, 1978		/	/	/		Stream	Sh/Gr
Asellus aquaticus	van Hattum et al., 1989	/					Lab.	Sh/Gr
Asellus meridianus Rac	Brown, 1977b		/	/			Lab.	Sh/Gr
Asellus communis	Lewis and McIntosh, 1986		/		/		Lab.	Sh/Gr
Asellus sp.	Anderson et al., 1978	/	/	/	/		Stream	Sh/Gr
Asellus sp.	Dixit and Witcomb, 1983		/	/	/		Stream	Sh/Gr
Asellus sp.	Barak and Mason, 1989	/	/			Hg	Stream	Sh/Gr
Decapoda (crayfish)								
Astacidae.								
Orconectes sp.	Anderson et al., 1978	/	/	/	/		Stream	Fi
Uniramia (insects)								
Pterygota								
Ephemeroptera (mayflies)	Barak and Mason, 1989	/	/			Hg	Stream	
Ephemeridae								
Hexagenia bilineata	Dukerschein et al., 1992	/				Hg	Stream	C-G
Hexagenia limbata	Hare et al., 1989	/		/	/	As	Stream	C-G
Hexagenia limbata	Hare and Campbell, 1992	/		/	/		Lake	C-G
Hexagenia limbata	Besser and Rabeni, 1987		/				Lab.	C-G
Hexagenia rigida	Hare et al., 1991b	/	/		/		Lake	C-G
Hexagenia sp.	Anderson et al., 1978	/	/	/	/		Stream	C-G
Hexagenia sp.	Beauvais et al., 1995	/				Hg	Stream	C-G
Hexagenia sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Ephemera danica	Jop, 1991	/	/	/	/		Stream	C-G

(*Continued*)

Macro-invertebrate	Authors	Metals				Other	Environ-ment.	Feeding guild
		Cd	Pb	Cu	Zn			
Ephemera danica	Jop and Wojtan, 1982	/	/				Stream	C-G
Ephemera danica	Goodyear, 1997	/	/	/		Fe, Mn	Stream	C-G
Ephemera vulgata	Jop, 1991	/	/	/	/		Stream	C-G
Potamanthidae								
Potamanthus sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Ecdyonuridae								
Ecdyonurus venosus	Burrows and Whitton, 1983	/	/		/		Stream	
Ecdyonurus venosus	Goodyear, 1997	/	/	/	/	Fe, Mn	Stream	
Stenonema modestum	Smock, 1983					Co, Cr, Fe, Mn, Sb, Sc	Lab.	C-G
Stenacron interpunctatum	Smock, 1983					Co, Cr, Fe Mn, Sb, Sc	Lab.	C-G
Stenonema sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Rithrogena sp.	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Ephemerellidae								
Drunella doddsi	Colborn, 1982					Mo	Stream	C-G
Drunella grandis	Colborn, 1982					Mo	Stream	C-G
Ephemerella ignita	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Ephemerella grandis	Nehring, 1976		/	/	/	Ag	Lab.	C-G
Ephemerella grandis	Clubb et al., 1975a	/					Lab.	C-G
Ephemerella grandis	Clubb et al., 1975b	/					Lab.	C-G
Leptophlebidae								
Leptophlebia vespertina	Jop, 1991	/	/	/	/		Stream	C-G
Baetidae	Saiki et al., 1995	/		/	/		Stream	C-G
Baetis rhodani	Rehfeldt and Söchtig, 1991	/	/	/	/		Stream	C-G
Baetis vernus	Jop, 1991	/	/	/	/		Stream	C-G
Baetis sp.	Kiffney and Clements, 1993	/		/	/		Stream	C-G
Baetis sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Baetis sp.	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Odonata (dragonflies)	Brown, 1977a			/	/	Fe	Stream	Pr
Aeshnidae								
Anax sp.	Anderson, 1977	/	/	/	/		Stream	Pr
Agriidae	Barak and Mason, 1989	/	/			Hg	Stream	Pr
Argia sp.	Anderson, 1977	/	/	/	/		Stream	Pr
Amphiagrion sp.	Anderson, 1977	/	/	/	/		Stream	Pr
Plecoptera (stoneflies)	Brown, 1977a			/	/	Fe	Stream	
Taenopterygidae								
Brachyptera risi	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Nemouridae								
Amphinemura sulcicollis	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Leuctridae								
Leuctra sp.	Burrows and Whitton, 1983	/	/		/		Stream	Pr

(*Continued*)

Macro-invertebrate	Authors	Metals				Other	Environment.	Feeding guild
		Cd	Pb	Cu	Zn			
Perlidae								
Classenia sabulosa	Cain et al., 1992	/	/	/	/		Stream	Pr
Classenia sabulosa	Moore et al., 1991	/		/	/	As, Ni	Stream	Pr
Hesperoperla pacifica	Cain et al., 1992	/	/	/	/		Stream	Pr
Hesperoperla pacifica	Moore et al., 1991	/		/	/	As, Ni	Stream	Pr
Perla bipunctata	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Pteronarcidae								
Pteronarcys californica	Cain et al., 1992	/	/	/	/		Stream	Pr
Pteronarcys californica	Nehring, 1976		/	/	/	Ag	Lab.	Pr
Pteronarcys californica	Clubb et al., 1975b	/					Lab.	Pr
Pteronarcys dorsata	Spehar et al., 1978	/	/				Lab.	Pr
Pteronarcella badia	Kiffney and Clements, 1993	/		/	/		Stream	Pr
Pteronarcella badia	Clubb et al., 1975a	/					Lab.	Pr
Pteronarcella badia	Clubb et al., 1975b	/					Lab.	Pr
Acroneuria pacifica	Clubb et al., 1975a	/					Lab.	Pr
Perlodidae								
Megarcys signata	Colborn, 1982					Mo	Stream	Pr
Skwala americana	Kiffney and Clements, 1993	/		/	/		Stream	Pr
Isoperla grammatica	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Isoperla grammatica	Goodyear, 1997	/	/	/	/	Fe, Mn	Stream	Pr
Perloides microcephala	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Arcynopteryx signata	Clubb et al., 1975b	/					Lab.	Pr
Isogenoides sp.	Cain et al., 1992	/	/	/	/		Stream	Pr
Chloroperlidae								
Chloroperla sp.	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Hemiptera (bugs)								
Corixidae								
Sigara sp.	Barak and Mason, 1989	/	/			Hg	Stream	Pr
Sigara sp.	Anderson et al., 1978	/	/	/	/		Stream	Pr
Megaloptera (alderflies)								
Sialidae								
Sialis sp.	Hare and Campbell, 1992	/		/	/		Lake	Pr
Sialis sp.	Barak and Mason, 1989	/	/			Hg	Stream	Pr
Sialis sp.	Hare et al., 1991a	/	/	/	/	As	Lake	Pr
Neuroptera (lacewings)	Brown, 1977a			/	/	Fe	Stream	
Trichoptera (caddisflies)								
Rhyacophilidae								
Rhyacophilla nubila	Vuori, 1993	/	/	/	/	Al, Fe	Stream	Pr
Rhyacophilla dorsalis	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Rhyacophilla sp.	Kiffney and Clements, 1993	/		/	/		Stream	Pr
Polycentropidae								
Polycentropus flavomaculatus	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Hydropsychidae								
Plectrocnemia conspersa	Darlington et al., 1987			/			Stream	Pr
Plectrocnemia conspersa	Gower and Darlington, 1990			/			Stream	Pr

(*Continued*)

Macro-invertebrate	Authors	Metals				Other	Environ-ment.	Feeding guild
		Cd	Pb	Cu	Zn			
Arctopsyche grandis	Cain et al., 1992	/	/	/	/		Stream	C-G
Arctopsyche grandis	Moore et al., 1991	/		/	/	As, Ni	Stream	C-G
Arctopsyche grandis	Kiffney and Clements, 1993	/		/	/		Stream	C-G
Hydropsyche pellucidula	Vuori, 1993	/	/	/	/	Al, Fe	Stream	C-G
Hydropsyche pellucidula	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Hydropsyche angustipennis	Vuori, 1993	/	/	/	/	Al, Fe	Stream	C-G
Hydropsyche angustipennis	Khan, 1995			/			Lab.	C-G
Hydropsyche siltalai	Goodyear, 1997	/	/	/	/	Fe, Mn	Stream	C-G
Hydropsyche instabilis	Goodyear, 1997	/	/	/		Fe, Mn	Stream	C-G
Hydropsyche sp.	Cain et al., 1992	/	/	/	/		Stream	C-G
Hydropsyche sp.	Anderson et al., 1978	/	/	/	/		Stream	C-G
Hydropsyche sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Hydropsyche sp.	Colborn, 1982					Mo	Stream	C-G
Hydropsyche sp.	Dressing et al., 1982	/					Lab.	C-G
Bracycentridae								
Brachycentrus americanus	Clubb et al., 1975a	/					Lab.	C-G
Brachycentrus americanus	Clubb et al., 1975b	/					Lab.	C-G
Brachycentrus sp.	Moore et al., 1991	/		/	/	As, Ni	Stream	C-G
Brachycentrus sp.	Spehar et al., 1978	/	/				Lab.	C-G
Phryganeidae								
Phryganea sp.	Iivonen et al., 1992	/	/	/	/	Ni	Lake	C-G
Cheumatopsyche sp.	Anderson, 1977	/	/	/	/		Stream	C-G
Cheumatopsyche sp.	Anderson et al., 1978	/	/	/	/		Stream	C-G
Limnephilidae	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Potamophylax latipennis	Vuori, 1993	/	/	/	/	Al, Fe	Stream	C-G
Limnephilus sp.	Iivonen et al., 1992	/	/	/	/	Ni	Lake	C-G
Limnephilus sp.	Moore et al., 1991	/		/	/	As, Ni	Stream	C-G
Leptoceridae								
Mystacides sp.	Timmermans et al., 1992	/			/		Lab.	C-G
Diptera (true flies)								
Nematocera								
Tipulidae								
Tipula sp.	Burrows and Whitton, 1983							
Dicranota sp.	Clubb et al., 1975b	/	/		/		Stream	C-G
Hexatoma sp.	Clubb et al., 1975b	/					Lab.	Pr
Holorusia sp.	Burrows and Whitton, 1983	/					Lab.	Pr
Chaoboridae		/	/		/		Stream	Pr
Chaoborus punctipennis	Hare and Campbell, 1992							
Chaoborus sp.	Groulx and Lasenby, 1992	/		/	/		Lake	Pr
Simulidae		/					Lake	Pr
Simulium sp.	Carter and Nicholas, 1978							
Simulium ornatipes	Anderson et al., 1978				/		Lab.	Fi
Simulium sp.	Burrows and Whitton, 1983	/	/	/	/		Stream	Fi

(*Continued*)

Macro-invertebrate	Authors	Metals				Other	Environ-ment.	Feeding guild
		Cd	Pb	Cu	Zn			
Simulium sp.	Anderson, 1977	/	/		/		Stream	Fi
Chironomidae	Anderson, 1977	/	/	/	/		Stream	Fi
	Saiki et al., 1995	/	/	/	/		Stream	
		/		/	/		Stream	
Chironomus riparius	Besser and Rabeni, 1987		/				Lab.	C-G
Chironomus riparius	Williams et al., 1986	/					Lab.	C-G
Chironomus riparius	Timmermans and Walker, 1989	/			/		Lab.	C-G
Chironomus thummi	Seidman et al., 1986	/					Lab.	C-G
Chironomus tetans	Gauss et al., 1985				/		Lab.	C-G
Chironomus tentans	Phipps et al., 1995	/	/	/	/	Ni	Lab.	C-G
Chironomus sp.	Anderson et al., 1978	/	/	/	/		Stream	C-G
Chironomus sp.	Hare and Campbell, 1992	/		/	/		Lake	C-G
Chironomus sp.	Hare et al., 1991a	/	/	/	/	As	Lake	C-G
Chironomus sp.	Krantzberg and Stokes, 1988	/		/	/	Al, Mn, Ni	Stream	C-G
Chironomus sp.	Burrows and Whitton, 1983	/	/		/		Stream	C-G
Chironomus sp.	Krantzberg, 1989	/		/		Mn, Ni, Fe	Lab.	C-G
Chironomus sp.	Krantzberg and Stokes, 1989	/	/	/	/	Ni, Mn	Lab./lakes	C-G
Chironomids	Krantzberg and Stokes, 1989	/	/	/	/	Ni Mn	Lakes/lab.	C-G
Chironomids	Chapman, 1985		/	/	/	Fe, Mn, Ni, Co	Stream	C-G
Chironomids	Dixit and Witcomb, 1983		/	/	/		Stream	C-G
Stictochironomus histrio	Timmermans and Walker, 1989	/			/		Lab.	C-G
Glyptotendipes sp.	St. Louis, 1993			/	/	Al, Fe, Mg, Mn	Lake	C-G
Clinotanypus sp.	Hare and Campbell, 1992	/		/	/		Lake	C-G
Procladius sp.	Hare et al., 1991a	/	/	/	/	As	Lake	Pr
Procladius sp.	Hare and Campbell, 1992	/		/	/		Lake	Pr
Brachycera								
Rhagionidae								
Atherix variegata	Clubb et al., 1975b	/					Lab.	Pr
Coleoptera (beetles)	Hare et al., 1991a	/	/	/	/	As	Lake	Pr
Dytiscidae								
Dytiscus sp.	Barak and Mason, 1989	/	/			Hg	Stream	Pr
Oreodytes sanmarki	Burrows and Whitton, 1983	/	/		/		Stream	Pr
Elminthidae								
Limnius volckmari	Burrows and Whitton, 1983	/	/		/		Stream	Pr

Sh, shredder; S-G, scraper–grazer; C-G, collector–gatherer; Fi, filterer; Pr, predator.

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