Mine Water and the Environment (2001) 20: 114–121 © IMWA Springer-Verlag 2001

Technical Article

Review of Benthic Invertebrate Fauna in Extremely Acidic Environments (pH ≤ 3)

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Abstract. Some benthic invertebrate species are able to colonise habitats in extremely acidic waters. We compiled a list of acid-resistant benthic invertebrates from the literature and extended it by studying extremely acidic mining lakes in eastern Germany. Acid-resistant species were registered for some habitats with pH ≤ 3, such as volcanic lakes, acid strip streams, and acidic mining lakes. Twenty nine taxa were found in waters with pH below 3. Diptera comprised 48.3% of the total number of taxa, followed by Coleoptera with 10.3%, Trichoptera 10.3%, Ephemeroptera, Megaloptera, and Plecoptera each with 6.9%, and Odonata, Hirudinea, and Acari each with 3.5%. *Chironomus* (Diptera: Chironomidae) were the most common genus in extremely acidic environments with 9 species. In Germany, *Chironomus crassimanus* was found to be the most abundant species in extremely acidic mining lakes. Generally, aquatic insects were the most common group of benthic invertebrates.

Key words: Acidic waters, acid-resistance, aquatic insects, benthic fauna, Chironomidae, Germany

Introduction

Remediation of extremely acidic environments is an important task in some parts of the world. As a consequence, the specific problems of the extremely acidic aquatic ecosystems have been studied (Smith and Frey 1971; Pietsch 1979; Klapper and Schultze 1995; Klapper et al. 1996; Schultze and Geller 1996; Geller et al. 1998). These ecosystems exhibit very different chemical and physical conditions. Highly acid water, with pH values from 2-3, can be caused by a number of different biogeochemical processes.

The flora and fauna are characterised by a very low species richness. A number of studies have investigated how acidification affects benthic fauna (e.g., Bell 1971; Koryak et al. 1972; Wiederholm and Eriksson, 1977; Økland and Økland 1986; Raddum et al. 1988; Winterbourn and McDiffett 1996), but few studies have focussed on highly acidic waters. The aim of this paper was to review the benthic invertebrate fauna occurring in extremely acid environments (with pH ≤ 3) and to add information obtained in recent studies of extremely acidic mining lakes (AML) in eastern Germany.

Study site and methods

Study site

A part of this study was performed in areas that were contaminated by mining activities in Lusatia in the eastern part of Germany. The investigation of extremely acidic mining lakes were performed around Plessa (AML 107 and 111) and Grünewalde (AML 117), which are located in the same lignite field. The investigated mining lakes AML 107, 111, and 117 are characterised by extremely low pH-values in the range of 2–3, which is caused by the oxidation of pyrite and marcasite (Herzsprung et al. 1998; Wiedermann 1994; Packroff et al. 1999).

Literature and field survey

A list of the acid-resistant benthic invertebrate fauna was compiled from the literature and extended by recent study. Qualitative and semi-quantitative samples of invertebrates were taken from May 1997 until February 1999, from all lakes with different methods: Ekman grab (400 cm^2) and hand nets with mesh of 200 µm and by colonisation experiments of benthic invertebrates on leaf packs. The leaf colonisation experiments used wire-mesh containers (20 x 20 cm) with a mesh size of 10 mm, which allowed easy access by all potential benthic invertebrate colonists. All air-dried leaves were briefly soaked in distilled water until they were pliable, before the placement into the leaf packs. Exactly 20 g of each leaf type (birch *Betula pendula*, ash *Fraxinus excelsior*, and walnut *Juglans regia*) were weighed and placed into individual leaf packs, which were placed in the littoral zone (0.5 to 1.5 m water depth) of the lakes, arranged in groups of 9 (3 replicas of each leaf type). After 1 to 6 months, the leaf packs were lifted carefully out of the water, put into plastic bags, and transported to the laboratory. In the laboratory, the leaves were sieved with 1.6 mm and > 200 µm with tap water. The leaf material (>1.6

mm) was dried and weighed to determine the leaf weight loss. The remaining material > 200 µm with the animals was kept in 70% ethanol. The benthic invertebrates were sorted at a Zeiss stereomicroscope, counted and preserved for subsequent identification.

Results

Twenty-nine taxa of invertebrates were found in waters with pH below 3. Table 1 lists benthic invertebrates that occurred in extremely acidic waters, with the corresponding pH-value, habitat type, recorded distribution, and references. The acid-resistant species were registered from some habitats with pH ≤ 3, such as volcanic lakes, drainage from surface mines, and acidic mining lakes. Diptera comprised 48.3% of the total number of taxa, followed by Coleoptera with 10.3%, Trichoptera 10.3%, Ephemeroptera, Megaloptera, and Plecoptera each with 6.9%, and Odonata, Hirudinea and Acari each with 3.5 %. Figure 1 gives a representation of found aquatic insect groups, as well as the number of taxa recorded. In extremely acidic environments with pH below 3.0, aquatic insects were with 92 % the predominant group of the benthic fauna. Chironomidae (Diptera) had the highest number of species.

A total of 10 benthic invertebrate species were found in AML 107, 111 and 117 (Table 2). AML 117 showed the greatest number of taxa with 9, followed by AML 111 with 7 and AML 107 with 3.

Discussion

Reduced species richness and abundance of benthic macroinvertebrate assemblages have been reported from acidic waters in some countries in connection with low pH values in aquatic ecosystems. Most have pH up to 3.5 due to acid rain (e.g., Wiederholm and Eriksson 1977; Økland and Økland 1980, 1986; Schneider 1986; Hämäläinen and Huttunen 1990; Heij and Schneider 1993; Steinberg and Wright 1994; Henrikson and Brodin 1995; Reid et al. 1995; Umweltministerium Baden-Württemberg 1995).

Waters with low pH often contain a high concentration of heavy metals and ions, some of which are severely toxic to most organisms. In extremely acidic mining lakes from the Lusatian region, iron, aluminium, and sulphate are all present in high concentrations (Herzsprung et al. 1998; Wiedermann 1994; Packroff et al. 1999). All the investigated acidic mining lakes are characterised by pH values in the range of 2-3. Because of the low pH and the nature of the surrounding materials, the concentrations of dissolved substances vary considerably in the water of acidic mining lakes. The poor water quality of the acidic lakes explains the impoverishment of macroinvertebrate assemblages and also the reduction of quality and range of food sources available to benthic invertebrates.

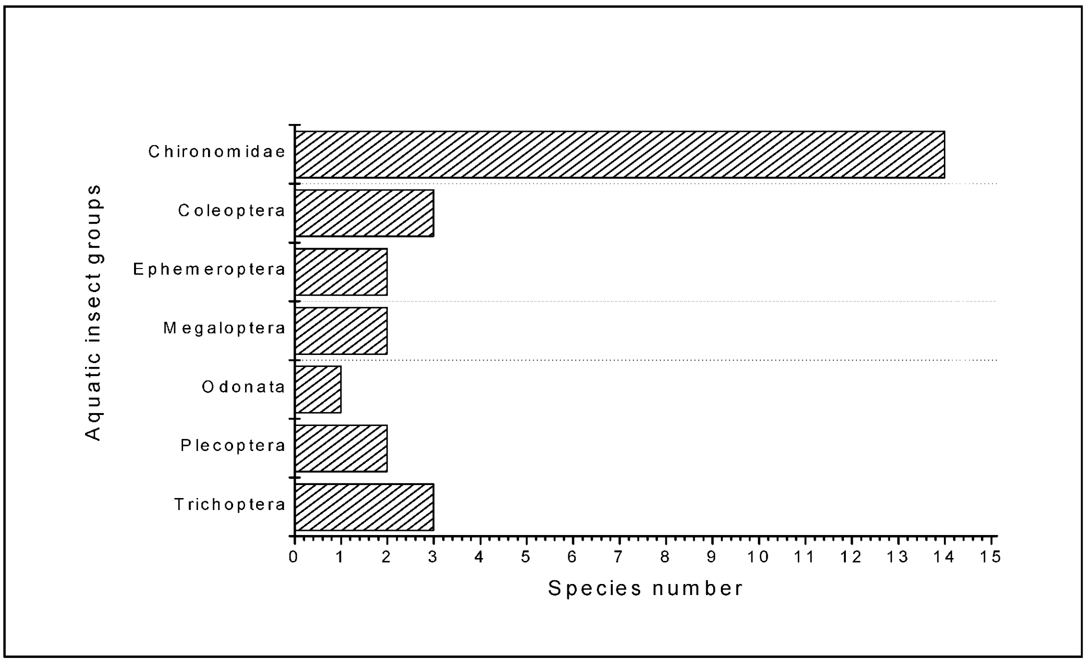

Figure 1. Number of aquatic insect taxa that occur in water with pH ≤ 3.0, according to the literature and our own studies

Table 1. List of benthic macroinvertebrate taxa occurring in extremely acidic waters

Taxon	pH	Habitat	Recorded Distribution	Reference
INSECT-DIPTERA				
Chironomidae				
Ablabesmyia longistyla	2.6-2.9	Acidic mining lake	Eastern Germany	(present study)
Chironomus acerbiphilus	1.4	Volcanic lake	Japan	Yamamoto (1986)
C. decorus group	2.3	Acid strip-mine	Central USA	Harp & Campbell (1967)
C. fusciceps	• 3.0	Sulphur waters	Japan	Yamamoto (1990)
C. crassimanus	2.1-3.0	Acidic mining lakes	Eastern Germany	(present study)
C. near maturus	2.3-3.8	Acid strip-mine lake	Illinois, USA	Zullo & Stahl (1988)
C. plumosus group	2.3-2.8	AMD stream; strip-mine lakes	USA	Warner (1971); Harp & Campbell (1967)
C. riparius	2.8	Pond	North West Canada	Havas & Hutchison (1983)
C. sulfurosus	• 3.0	Sulphur waters	Japan	Yamamoto (1990)
C. zealandicus	2.1	Acid thermal lake	New Zealand	Forsyth & McColl (1974); Forsyth (1977)
Corynoneura lobata	2.6-2.9	Acidic mining lakes	Eastern Germany	(present study)
Limnophyes minimus	2.1-3.0	Acidic mining lakes	Eastern Germany	(present study)
Orthocladiinae spp.	2.8-3.3	AMD stream	New Zealand	Winterbourn & McDiffett (1996)
Tanytarsus dendyi	2.3-3.8	Acid strip-mine lake	Illinois, USA	Zullo & Stahl (1988)
INSECT NON-DIPTERA				
Coleoptera				
Gyrinidae				
Gyrinus aeratus	2.8	Mining lake	Eastern Germany	(present study)
Orectochilus villosus	3.0	Mining lake	Eastern Germany	(present study)
Ilybius fenestratus	3.0	Mining lake	Eastern Germany	(present study)
Ephemeroptera				
Zephlebia sp.	2.9-6.1	AMD stream	New Zealand	Winterbourn & McDiffett (1996)
Leptophlebiidae				
Deleatidium sp.	2.9-3.9	AMD stream	New Zealand	Winterbourn & McDiffett (1996)
Megaloptera				
Sialidae				
Sialis lutaria	3.0	Mining lake	Eastern Germany	(present study)
Sialis sp.	2.8	AMD stream	USA	Warner (1971); Tomkiewicz & Duson (1977)
Odonata				
Coenagrionidae				
Coenagrion mercuriale	3.0	Mining lake	Eastern Germany	(present study)
Plecoptera				
Notonemouridae	2.8-3.3	AMD stream	New Zealand	Winterbourn & McDiffett (1996)
Perlidae				
Acroneuria carolinensis	2.8-3.3	AMD stream	North America	Whipple & Duncan (1993)
Trichoptera				
Limnephlidae				
Hesperophylax sp.	2.97	Mining lake	USA	Nelson (1994).
Kokiriidae				
Kokiria miharo	2.9	AMD stream	New Zealand	Winterbourn & McDiffett (1996)
Ptilostomatidae				
Ptilostomis sp.	2.6-3.0	AMD stream	North America	Koryak et al. (1972)
OTHER INVERTEBRATES				
Acari				
Hydrozetidae				
Hydrozetes lacustris	2.1-3.0	Acidic mining lakes	Eastern Germany	(present study)
Hirudinea				
Glossifonidae				
Helobdella sp.	2.1	Acid thermal lake	New Zealand	Forsyth (1977)

Table 2. Occurrence of benthic invertebrates on leaves from AML 107, 111, and 117. Frequency classes of benthic invertebrates were according to leaf colonisation experiment (ind. g leaf^{-1}). + = 1 ind. g leaf^{-1}; ++ = 2-10 ind. g leaf^{-1}; +++ = 11-100 ind. g leaf^{-1}; ++++ = > 101 ind. g leaf^{-1}

Taxa	AML 107 pH 2.3	AML 111 pH 2.6	AML 117 pH 3
Diptera			
Chironomidae			
Ch. crassimanus Strenzke, 1959	++	+++	+++
Ablabesmyia longistyla Fittkau, 1962		+	
Limnophyes minimus (Meigen 1818)		++	++
Corynoneura lobata (Edwards, 1924)		+	
Coleoptera			
Gyrinidae			
Orectochilus villosus (Müller, 1776)			+
Odonata			
Coenagrionidae			
Coenagrion mercuriale (Charpentier, 1840)			+
Trichoptera			
Phryganeidae			+
Hemiptera-Heteroptera			
Corixidae			
Sigara nigrolineata (Fieber, 1848)	+	+	++
Megaloptera			
Sialidae			
Sialis lutaria L.			++
Acari			
Hydrozetidae			
Hydrozetes lacustris (Michael, 1882)	+	++	++++
Nematoda		+	+
Total number of taxa	**3**	**7**	**9**

concerning haemolymph, sodium and chloride balance (Jernelöv et al. 1981).

In general, taxonomical information about benthic invertebrates in highly acidic environments is limited. Just one key to the species of *Chironomus* living in the extremely acidic water in Japan was found (Yamamoto 1990). Three acid-resistant species have been reported from volcanic regions of Japan: *Ch. acerbiphilus* Tokunaga, 1938 (Fujimatsu 1938; Tokunaga 1938) from Lake Katanuma with pH 1.4 (Yoshimura 1933), *Ch. fusciceps* Yamamoto, 1990 and *Ch. sulfurosus* Yamamoto, 1990 from hot sulphurous springs with pH 2.9-4.3 (Uéno 1932, 1933, Itô 1937; cited in Yamamoto 1986) (Table 1).

Chironomus crassimanus is a pioneer species in extremely acidic mining lakes with pH-value 2-3 in eastern Germany. *Ch. crassimanus* was described by Strenzke (1959) from a clay pool near Reinbek, in northern Germany with a pH of 3.05.

Another acid-resistant chironomid, *Limnophyes minimus* (Meigen 1818, inhabited extremely acidic lakes from the Lusatian region with pH 2-3. The rare *Corynoneura lobata* (Edwards 1924) and *Ablabesmyia longistyla* (Fittkau 1962) were also recorded for the Lusatian mining lakes with pH 2.6-2.9 (AML 111) in eastern Germany (Table 2), but with lower numbers compared to *Chironomus crassimanus* and *L. minimus*.

In different parts of the world, different acid-resistant chironomids can be found (Table 1). It seems that some of them prefer an acid environment. *Chironomus crassimanus*, for example, was found only in extremely acid waters. It is known only from artificial lakes, the clay pond near Reinbek, from where the species was described for the first time (Strenzke 1959) and from the mining lakes in Lusatia (Rodrigues, in press). Where did this species live before the formation of these man-made waters? We do not have an answer to this question.

Aquatic insects: non-Diptera

Some others aquatic insects that do not belong to Diptera also occurred in extremely acidic waters. *Sialis lutaria* (Megaloptera, Sialidae) is an abundant acid-resistant species found at pH 3.0 in Lusatian lakes (AML 117). Megaloptera species were also reported in aquatic ecosystems in Canada with a pH 3.6 (Kerekes et al. 1984). *S. lutaria* is a fairly widespread species through the whole of Europe, except the southeast (Vanhara 1970). They are often numerous in the benthos, especially in humic, acid lakes and ponds (Matthey 1971; McLachlan and McLachlan 1975).

Larvae of *Orectochilus vilosus* (Coleoptera: Gyrinidae) were also found in AML 117. This species has been registered for still waters and slow flowing waters (Klausnitzer 1996). Kerekes et al. (1984) reported the occurrence of Coleoptera species in aquatic ecosystems in Canada with pH 3.6. Some species in these extremely acidic environments do not depend on free acidity, but the increase of these potential predators may be due to the availability of food resource and the decrease of competition.

Henrikson and Oscarson (1981) reported the occurrence of species of pleustonic corixids (Hemiptera-Heteroptera) as top-predators in acidic waters. Nymphs of the pleustonic *Sigara nigrolineata* (Heteroptera: Corixidae) were found in all acidic mining lakes investigated. Wollmann (1998) supplied further data on Corixidae of acidic eastern German mining lakes and focussed on species composition in lakes with different pH values. This author found 6 species of corixids for AML 117 and 8 species for AML 111.

Odonata are moderately to very tolerant to waters with a low pH value (e.g., Bell 1971; Mossberg and Nyberg 1979; Kerekes et al. 1984; Schell and Kerekes 1989), but only one study was found that described the effects of pH at species or genus level (Lonergan and Rassmussen 1996). In Germany, Baltes (2000) found *Cordulegaster boltonii* (Odonata: Cordulegastridae) in acid streams in south Germany with a pH 4.5 and Braukmann (1995) emphasised that this species has been considered as an acid-tolerant taxon. Furthermore, *Coenagrion mercuriale* were also found in AML 117 with pH-value of 3.0, but in low numbers. This species has a preference for small streams, rich in calcium and in vegetation (Lehmann and Nüß 1998). Corbet (1955) reported that *C. mercuriale* occurs typically in small streams draining acid peat-bogs in Britain. The number of the dragon fly *Coenagrion* sp. increased in acidified Swedish Lake Stora Härsjön after liming (Appelberg 1995). *C. mercuriale* is largely distributed in Upper Rhine Valley region in Germany, and rarely occurs in the German Alps, near Osnabrück (eastern part of Lower Saxonia), Thuringia and Magdeburg (Saxonia-Anhalt) (Lehmann and Nüß 1998).

Phryganeidae (Trichoptera) were rarely found in AML 117. In Middle Europe, 10 species are known (Botosaneanu and Malicky 1978; Tobias and Tobias 1981). They are large caddis flies, have a wide distribution and colonise principally aquatic lakes (Pitsch 1993). Also, the occurrence of a rarely recorded *Kokiria miharo* (Trichoptera, Kokiriidae) in acidic habitats from New Zealand where the pH-value was 2.9 (see Table 1) adds more information about the extreme environmental tolerance of some members of the Trichoptera. A very low pH and high concentration of many ions, including aluminium, were tolerated in the field by larvae of *Ptilostomis* (Trichoptera, Ptilostomatidae) (Koryak et al. 1972) and of *Hesperophylax* (Trichoptera, Limnephilidae) in North American streams (Nelson 1994) (see Table 1). In Germany, *Odontocerum albicorne* (Trichoptera: Odontoceridae) has been reported by Baltes (2000) at pH 3.7 in acid streams from the Black Forest.

In general, the species richness of Trichoptera, Plecoptera and Ephemeroptera decreases when the pH is lowered (e.g. Økland and Økland 1986). However, Whipple and Ducan (1993) reported that both iron and aluminium are indispensable for the larvae of *Acroneuria carolinensis* (Perlidae, Plecoptera) at pH of 2.8-3.3 in acid mine drainage streams in North America (Table 1). *Leuctra inermis* (Plecoptera: Leuctridae) occurred in acid streams in south Germany with pH 3.7 (Baltes 2000). In addition, Winterbourn and McDiffett (1996) recorded the occurrence of *Deleatidium* (Ephemeroptera: Leptophlebiidae) at pH values between 2.9 and 3.9, and also the occurrence of *Zephlebia* sp. at pH-values between 2.9 and 6.1 (see Table 1). Although Ephemeroptera have been reported as extremely sensitive to low pH, *Baetes vernus* (Baetidae) and *Ecdyonurus venosus* (Heptageniidae) were found by Baltes (2000) in acid streams in Germany with a pH value of 4.5. Also, *Ameletus inospionatus,* a frequent species from ML B, is considered as acid-tolerant species, was found in acid rain streams in south Germany (Braukmann 1995) and in acidic lakes with pH 4.4 in Sweden (Engblom and Lingdell 1984), but did not colonise the studied extremely acidic mining lakes in Lusatia.

Aquatic benthic invertebrates: non-insects

Beside the aquatic insects, other aquatic invertebrates, like *Hydrozetes lacustris* (Acari, Hydrozetidae) were also found in Lusatian mining lakes with pH-values in the range 2.1-3.0 (Table 2). Previous studies have suggested a strong relationship between the occurrence of leeches and water pH. Økland and Økland (1986) reported that in Norway, leeches are a potentially valuable indicator for pH above 5.0. However, the leech *Helobdella* sp. occurred in acid mine drainage with pH 2.1 in Lake Rotokawa in New Zealand (Forsyth 1977). Probably, the presence or absence of carnivorous leeches depends not only on the physiological characteristics of the leeches but also on the presence of available food. Leeches like to feed on gastropods that disappear below pH of about 5.5. Probably the leeches in Lake Rotokawa take other food than gastropods.

Conclusions

(a) Twenty-nine acid-resistant taxa occurred in extremely acidic waters with pH ≤ 3 from diverse aquatic ecosystems, including acid mine drainage and volcanic lakes.

(b) Aquatic insects are widely spread in extremely acidic waters.

(c) *Chironomus* species (Chironomidae, Diptera) is the most common group in waters with pH ≤ 3.

(d) Aquatic insects that do not belong to Diptera and other invertebrates (leeches and mites) occurred in extremely acidic waters (pH ≤ 3) and may not depend on free acidity, but on the availability of food resources.

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