The ecological effect of acid conditions and precipitation of hydrous metal oxides in a Rocky Mountain stream

Diane M. McKnight & Gerald L. Feder
U.S. Geological Survey, Water Resources Division, Denver Federal Center, Denver, Colorado, U.S.A.

Keywords: periphyton, benthic invertebrates, hydrous metal oxides, acid conditions, stream ecology

Abstract

Periphyton and benthic invertebrate assemblages were studied at the confluence of two Rocky Mountain streams, Deer Creek and the Snake River near Montezuma, Colorado. Upstream from the confluence the Snake River is acidic and enriched in dissolved trace metals, while Deer Creek is a typical Rocky Mountain stream. In the Snake River, downstream from the confluence, the pH increases and hydrous metal oxides precipitate and cover the streambed. The algal and benthic invertebrate communities in the upstream reaches of the Snake River and in Deer Creek were very different. A liverwort, *Scapania undulata* var. *undulata*, was abundant in the Snake River, and although periphyton were very sparse, there were as many benthic invertebrates as in Deer Creek. Downstream from the confluence, the precipitation of hydrous metal oxides greatly decreased the abundance of periphyton and benthic invertebrates. This study shows that in streams metal precipitates covering the streambed may have a more deleterious effect on stream communities than high metal-ion activities.

Introduction

Growth of periphytic algae and benthic invertebrates in streams can be affected by the nature of the surface available for growth and by the chemistry of the overlying aquatic medium. In streams receiving acid mine drainage or otherwise metal-stressed, two factors responsible for decreases in the abundance and diversity of periphyton communities are: (1) Toxicity resulting from acid conditions and high concentrations of dissolved trace metals; and (2) destabilization of the substrate by flocculent metal precipitates (Parsons, 1968; Warner, 1971; Lampkin & Sommerfield, 1982). Similarly, low pH and deposition of iron hydroxide have been shown to limit the abundance and species of benthic invertebrates (Hynes, 1970). Our purpose in this study was to determine which of these two factors had a more adverse effect in the Snake River, a small Rocky Mountain stream.

Study area

The confluence of the Snake River and Deer Creek in the Rocky Mountains, near Montezuma, Colorado, is at an elevation of about 3230 m above sea level. These streams are very steep and rocky and were first studied by Theobald *et al.* (1963). The watersheds of both streams are underlain by Precambrian igneous and metamorphic rocks that have been intruded by granitic rocks of Tertiary age (Theobald *et al.*, 1963). Mineralized veins containing iron, zinc, lead and silver sulfides are found scattered throughout the watersheds. There are many old mine workings, but currently there has been little mining activity (Moran & Wentz, 1974). The four sites sampled in this study are shown in Fig. 1. As indicated in the hydrograph for water years 1980 and 1981 at a Snake River site 10 km downstream from site 4 (Fig. 2), in the winter the streams are covered by snow (1 to 2 m deep) under-

Hydrobiologia 119, 129–138 (1984).

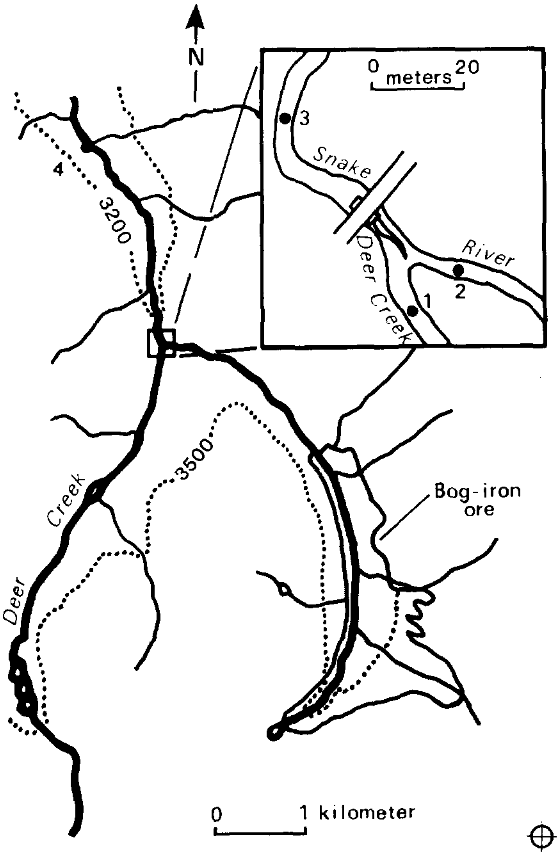


Fig. 1. Location of sampling sites in Deer Creek and the Snake River.

lain by about 0.5 m of ice. In June and July, melting of the snow pack results in large increases in stream discharge. Open water, low flow conditions occur from August through mid-October and at that time the streamflow at sites 1 and 2 is between 0.06 and 0.28 m^3s^{-1}. The peak discharge in the Snake River during June and July of 1981 was much less than usual because of the low snowfall during the previous winter.

The water chemistry at sites 1–4 on August 18, 1980 is shown in Table 1. These values are representative of low flow during the late summer and autumn. Upstream from the confluence with Deer Creek, the Snake River has a low pH (3.5–4.3) and high concentrations of filtrable trace metals (Al = 4.0 mg l^{-1} and Fe = 0.7 mg l^{-1}). The low pH and high Fe concentration result from the weathering of pyrite disseminated in the rocks of the watershed; the high Al concentration is a result of solution of aluminous minerals by the acidic waters. Chemical equilibrium calculations using MINEQL, a compu-

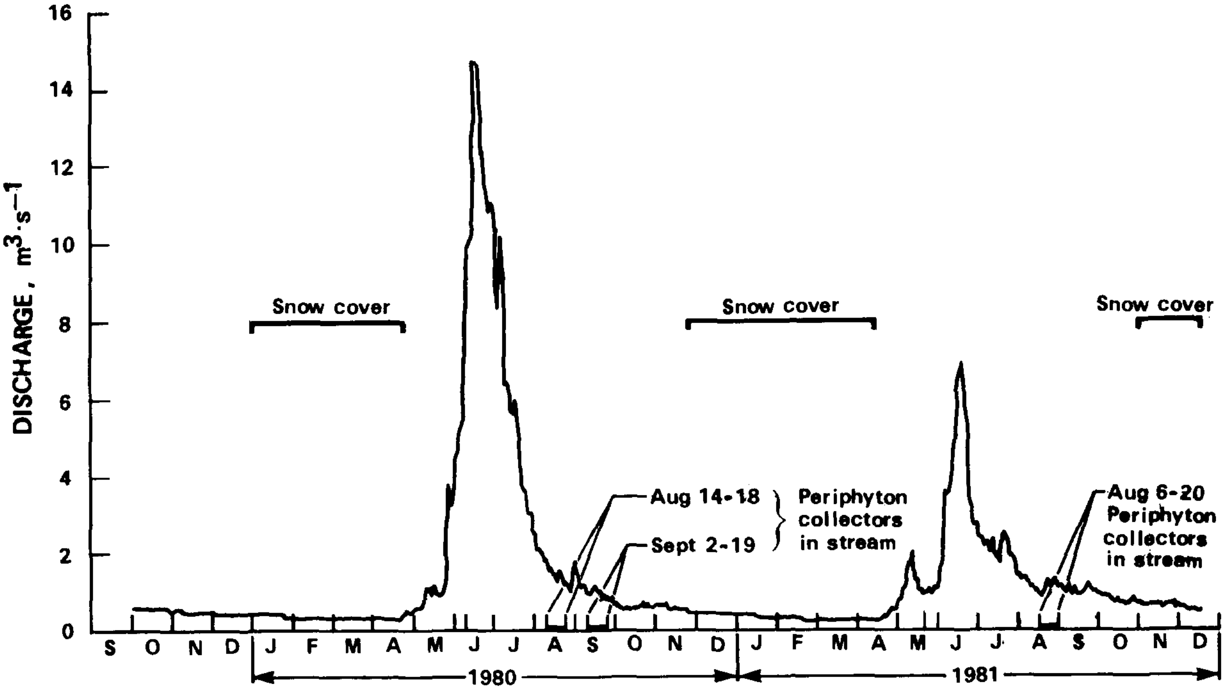


Fig. 2. Stream discharge for water years 1980 and 1981 in the Snake River 10 km downstream from the confluence with Deer Creek (Colorado Water Resources District, U.S. Geological Survey, written communication, 1982).

Table 1. Chemical characteristics of water at sampling sites on the Snake River and Deer Creek on August 18, 1980 (ion concentrations in mg/L).

Property or constituent	Deer Creek (Site 1)	Snake River		
		Site 2	Site 3	Site 4
pH	7.3	3.75	5.2	6.4
T (°C)	6	4	5	4
Ca	10.6	8.7	10.5	13.2
Mg	1.8	4.35	3.3	3.4
Na	–	3.2	2.6	2.6
SO_4	10.4	70.6	42.2	43.5
Cl	.9	.34	.25	.32
*Al	.04	2.36	.22	.095
Fe	.06	.66	.29	.19
Zn	.003	.45	.27	.28
Mn	.005	.93	.53	.38
Cu	.002	.018	.012	.004
NO_3	.01	.005	.01	.005
**PO_4	.002	.002	.005	.011
DOC mgC/L	.9	.6	.2	.4

* August 4, 1980.

** Filtrable ionic phosphate.

ter program (Westall *et al.*, 1979), show that at the pH and Al and Fe concentrations in the Snake River upstream from the confluence (site 2), the two major chemical species for Al should be Al^{3+} (45%) and $AlSO_4$ (aq) (48%) and for Fe the major chemical species should be, $Fe(OH)_2^+$ (49%) and $Fe(OH)^{2+}$ (12%), and precipitated iron hydroxide, $Fe(OH)_3$ (s) (37%). This result indicates that some of the Fe passing through the 0.4-μm Nuclepore* membrane is actually colloidal and not truly dissolved. Deer Creek, which has approximately the same discharge as the Snake River upstream from the confluence, has a pH between 6.5 and 8.0, with lower pH values occurring during spring snowmelt. Deer Creek also has low concentrations of filtrable trace metals. The rocky streambed in the Snake River has a hard, red, iron oxide coating and in Deer Creek the rocks have a hard, black, iron and manganese oxide coating (Theobald *et al.*, 1963). Downstream from the confluence the pH is between 5.5 and 6.5 and the streambed is covered with a thick (up to 1 cm), flocculent, brownish-white precipitate of hydrous Al and Fe oxides coprecipitated with aquatic humic substances (Theobald *et al.*, 1963). The covering of the rocks with a hydrous metal oxide precipitate extends several kilometers downstream, even though the concentrations of filtrable Al and Fe decrease rapidly. There does not appear to be significant accumulation of this flocculent precipitate from year to year; this is probably a result of the scouring action of the moving bed load (gravel to large rocks) during the high flow conditions in June and July.

Methods

Moran & Wentz (1974) found that the harsh climatic conditions in the Colorado Rocky Mountains prevented reliable collection of periphyton and benthic invertebrates during the winter and snowmelt period, which includes about nine months of the year. For this reason, in this study, biological samples were obtained during low-flow, open water conditions, in August and September of 1980, and August of 1981 (Fig. 2). These samples are satisfactory for indicatig major differences in the stream biota at the four sites, but are not representative for all seasons.

Initial reconnaissance of the sites showed that natural periphyton on the rocks at sites 2, 3, & 4 were extremely sparse, or impossible to collect. Therefore, artificial substrates for periphyton colonization were used to obtain data that could be compared quantitatively. The artificial substrates used in this study were 5 × 20 cm opaque Mylar plastic strips suspended in the stream, with nylon rope anchored to a rock in a design similar to that described by Chessman & McCallum (1981). Moran & Wentz (1974) found that glass or brick artificial substrates generally were unsuccessful in rapidly flowing Rocky Mountain streams because of breakage by saltating rocks; however, they found Mylar strips were satisfactory. At each site three Mylar strips were left in riffles for about two weeks, as shown in Fig. 2. The only Mylar strip not recovered was one at site 3 in September, 1980. Upon removal from the stream, each strip was cut in half and one half was preserved with Lugol's solution for algal identification and counting and the other half was frozen for chlorophyll analysis. The periphyton scraped from the three strips at each site were combined before analysis. Benthic invertebrates were collected by using a 929 cm^2

---

* The use of trade names in this report is for identification purposes only and does not constitute endorsement by the U.S. Geological Survey.

(1-ft^2) Surber stream-bottom sampler with a 210-μm mesh size (Greeson *et al.*, 1977). In 1980 and in 1981, three Surber samples were collected near the center of the streams at each site, and after sorting, the organisms from the three samples were preserved with alcohol in a jar. The replication of the composite periphyton and benthic invertebrate samples was not tested. Samples of *Scapania undulata* var. *undulata*, a liverwort, were collected from several places upstream on the Snake River.

Chlorophyll *a* concentrations were determined by high-pressure liquid chromatography, with an Aminco-Bowman spectrofluorometer following the method described by Lium & Shoaf (1979). Identification and counting of periphyton were done by first scraping the strips into the original streamwater and diluting to 80 or 100 ml; placing the entire sample or a subsample in an Uhteromöhl settling chamber; and after allowing 24 hrs for settling, examining the sample with a Wild M-40 inverted microscope (Greeson *et al.*, 1977). Identification of algal species was done at 1000 × magnification with oil immersion and counting was done at 400 × magnification. The amount of sample placed in the settling chambers varied because of the extreme range in the abundance of periphyton on the artificial substrates, and because the artificial substrates at site 3 were covered with hydrous metal oxide precipitate. At site 1 the periphyton were abundant and a 17 ml subsample of each 80 ml sample was placed in a settling chamber. For sites 2 and 4, where the periphyton were scarce and precipitate was not a problem, the entire 80 ml of each sample was used. For site 3, each sample was diluted to 100 ml and several 12 or 15 ml subsamples were placed in a settling chamber and examined microscopically. For site 1 a minimum of 10 fields were counted, for the other sites the entire area of the settling chamber was counted because of the scarcity of the periphyton. Periphyton abundance in cells per unit area was calculated using the measured area of the plastic strips as described by Greeson *et al.* (1977). Benthic invertebrates were counted and identified using a stereoscopic microscope as described by Greeson *et al.* (1977).

Samples for chemical analysis were collected in 250-mL acid-washed plastic bottles that had been rinsed three times with streamwater; samples for inorganic analysis were filtered through 0.4-μm Nuclepore filters with a Millipore syringe filtration unit; samples for cation and trace metal analysis were acidified with 0.5 mL of Ultrex nitric acid. Samples for dissolved organic carbon (DOC) analysis were filtered through 0.45-μm Selas silver membranes and stored at 4 °C. Anion concentrations were determined with a Dionex ion chromatograph, cation and trace-metal concentrations were measured with a Jarrel-Ash inductively-coupled plasma spectrometer, DOC concentrations were measured with a Technicon auto analyzer and pH was measured with an Orion combination pH electrode.

Results

Periphyton

The abundance and diversity of the periphyton assemblage colonizing the artificial substrates in the Snake River and Deer Creek are listed in Table 2. The periphyton assemblage on the artificial substrates may have been different from the periphyton actually present on the rocks at each site; however, the data can be compared quantitatively and indicate the extreme differences among the sites. The most abundant diatom species identified at each site are listed in Table 3, and the occurrence of all identified species at the four sites are compared in Table 4. The major species at each site are presented diagramatically in Fig. 3.

Periphyton in Deer Creek were much more abundant than in any of the Snake River sites. The dominant diatom species in Deer Creek was *Hannea arcus* Kützing, which is commonly found in Rocky Mountain streams (L. J. Britton, U.S. Geological Survey, written commun. 1980). In August 1981, several species of the genus *Synedra* and several chlorophytes also were abundant. Upstream in the Snake River (site 2) the chlorophyll and algal-cell concentrations were two or three orders of magnitude less than in Deer Creek. The dominant diatom species at site 2 were *Eunotia exigua* (Brêb.) Grunow in 1980, and *Eunotia tenella* (Grun.) Hustedt and *Melosira italica* (Ehrenberg) Kützing in 1981. On all three sampling occasions, *Hannea arcus*, the dominant species in Deer Creek, also was found in the Snake River, but was much less abundant; however, in September, 1980, it was the

Table 2. Characteristics of stream communities in the Snake River and Deer Creek (NS = no sample, N = no intact cells on artificial substrate).

	Periphyton			Benthic-invertebrates
	Chlorophyll *a* (mg m^{-2})	Abundance (cells cm^{-2})	Diversity H[a]	Abundance Organisms m^{-2}
August 1980				
Sites				
1	0.598	NS	NS	242
2	.005	49	0.305	280
3	.001	100	.613	145
4	.001	NS	NS	11
September 1980				
Sites				
1	.593	14 481	.311	NS
2	.001	32	.450	NS
3	.001	N	N	NS
4	.001	N	N	NS
August 1981				
Sites				
1	.238	24 294[b]	0.76[b]	344
2	.003	289	.46	406
3	.001	N	N	43
4	.001	24	.78	79

[a] Calculated from the formula $H' = \sum_{i=1}^{s} p_i \log p_i$ where s = total number of species and p_i = relative abundance of species in the area.

[b] Includes three green-algal species.

second most abundant species in the Snake River.

The differences in total primary productivity between Deer Creek and the Snake River upstream from the confluence may not be as great as indicated by comparison of periphyton abundance, because of the abundant growth of a liverwort, *Scapania undulata* var. *undulata*, in the entire upstream reach of the Snake River. This species of liverwort also was found by Say & Whitton (1980) in Gillgill Burn, England. *Scapania* appears to be growing in iron-oxide precipitate accumulated between rocks of the streambed in the Snake River. Neither *Scapania*, nor any other aquatic bryophytes, were found in Deer Creek or in the downstream reaches of the Snake River.

Although a great difference in periphyton abundance occurs between Deer Creek and the Snake River, there is no consistent difference in diversity (Table 2). A total of 15 species were identified at each site and 7 species occurred at both sites. Although the dominant species in Deer Creek, *Hannea arcus*, also was present in the Snake River, none of the major species in the Snake River, *Eunotia exigua*, *E. tenella* and *Melosira italica*, were found in Deer Creek, indicating that these species are adapted to the acidic, metal-enriched conditions of the Snake River.

For all three sampling periods, after two weeks in the stream the plastic strips for periphyton colonization at the two sites downstream from the confluence (sites 3 & 4) were covered with hydrous metal oxide precipitate. The precipitate covering the strips was much thicker at site 3 than at site 4. Chlorophyll *a* and cell-count data for the artificial substrates at sites 3 & 4 generally show an even lesser abundance of periphyton than in the upstream reach of the Snake River (site 2). There were only diatom fragments and no intact diatom cells in two of three samples from site 3, and in one of the two samples from site 4.

In August, 1980, there was a significant periphytic population at site 3 and the dominant species was *Hannea arcus* from Deer Creek. Of the 12 species identified at that time, 4 were found at both upstream sites, 5 were found only at the upstream Snake River site, 1 was found only in Deer Creek,

Table 3. Composition of diatom assemblages on artificial substrates in the Snake River and Deer Creek (NS = no sample, n = no intact cells on artificial substrate, NF = not found).

Species	August 1980		September 1980		August 1981	
	cells cm ^{2}	%	cells cm ^{2}	%	cells cm ^{2}	%
Deer Creek (site 1)						
Achnanthes minutissima Kütz	NS	NS	538	3.7	239	1.1
Cymbella minuta Hilse *ex* Rabh.	NS	NS	641	4.4	611	2.8
Gomphonema clevei Cleve	NS	NS	513	3.5	478	2.2
Hannea arcus Kütz.	NS	NS	12 102	83.4	11 031	50.3
Synedra famelica Kütz.	NS	NS	282	2.0	NF	NF
Synedra rumpens Kütz.	NS	NS	NF	NF	4 333	19.8
Synedra ulna (Nitz) Ehr.	NS	NS	385	2.6	4 492	20.5
Synedra sp. Ehr.	NS	NS	Trace	Trace	744	3.4
Snake River (site 2)						
Eunotia exigua (Brėb.) Grun.	42	87.3	2.2	71.0	NF	NF
Eunotia tenella (Grun.) Hust.	NF	NF	NF	NF	145	52.9
Hannea arcus	1	2.0	6	19.0	4	1.5
Melosira italica (Ehr.) Kütz.[a]	3	6.2	0.6	2.0	117	42.7
Snake River (site 3)						
Achnanthes minutissima	5	5.6	N	N	N	N
Cymbella minuta	8	8.9	N	N	N	N
Hannea arcus	61	68	N	N	N	N
Nitzschia sp. (Hass.)	3	3.3	N	N	N	N
Pinnularia braunii (Grun.) Cleve	11	12.2	N	N	N	N
Snake River (site 4)						
Cymbella minuta	N	N	N	N	3	12.5
Hannea arcus	N	N	N	N	3	12.5
Melosira granulata (Ehr.) Ralfs	N	N	N	N	8	33.3
Melosira italica	N	N	N	N	3	12.5
Navicula sp. Bory	N	N	N	N	3	12.5
Nitzschia sp.	N	N	N	N	3	12.5

[a] Number of cells in colonies.

and 3 were not found at any of the other sites. Given the much greater abundance of periphyton in Deer Creek, one might expect more algal species from Deer Creek than the Snake River at the confluence. The observed poor representation of algal species found only in Deer Creek illustrates the extreme effect of the hydrous metal oxide precipitate.

In August, 1981, when intact algal cells were found at site 4, the farthest downstream site, 4 of the 7 identified algal species, including the most abundant species, *Melosira granulata* (Ehrenberg) Ralfs, were only found at that site. Two of the other species were found at all upstream sites; one species was found at all sites in the Snake River. The results from the two downstream sites show that the covering of the artificial substrates with hydrous-metal oxide severely limits periphyton colonization. The failure to collect periphyton from the rocks during the initial reconnaissance of sites 3 & 4 indicates that the precipitate also limits periphyton growth on the rocks in the streambed.

Benthic invertebrates

In many aspects, the benthic-invertebrate distribution shows the same pattern as the periphyton distribution. There were two distinct benthic-invertebrate assemblages in the upstream reach of the Snake River (site 2) and in Deer Creek (site 1); and there was a much lesser abundance of benthic invertebrates in the downstream reaches of the Snake River (sites 3 & 4). In Deer Creek, a total of 12 species were identified in 1980 and 1981, and during both summers the community was dominated by mayfly nymphs, *Baetis* sp., *Cinygmula* sp., and *Epeorus grandis*, and by a stonefly of the family Chloroperlidae. Merrit & Cummins (1978) describe all these benthic invertebrates as collectors-gather-

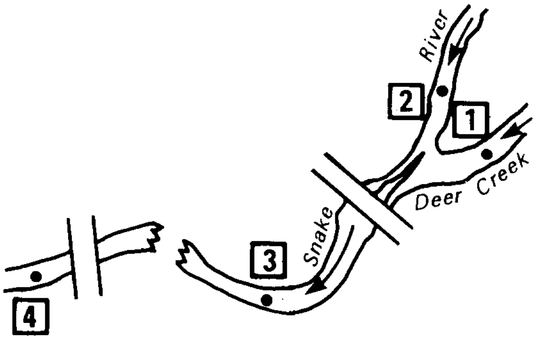
Table 4. Distribution of algal species on artificial substrates in the Snake River and Deer Creek (+ = present, - = not found).

Species	Deer Creek (site 1)	Snake River (site 2)	Snake River (site 3)	Snake River (site 4)
BACILLARIOPHYTA				
Achnanthes lanceolata Bréb.	+	+	-	
Achnanthes minutissima Kütz.	+	+	+	-
Anomoeneis serians (Bréb.) Cleve	+	-	-	
Cymbella minuta Hilse *ex* Rabh.	+	+	+	+
Diatoma hiemale (Lyngb.) Heib	-	+	+	-
Eunotia exigua (Bréb.) Grun	-	+	+	-
Eunotia tenella (Grun.) Hust.		+	+	-
Fragilaria construens (Ehr.) Grun.	-	-	+	-
Gomphonema sp. 1 Agardh	-	+	+	-
Gomphonema sp. 2 Agardh	+	-	-	-
Gomphonema clevei Cleve	+	-	-	-
Gomphonema truncatum Ehr.	-	-	+	-
Hannea arcus Kütz.	+	+	+	+
Melosira granulata (Ehr.) Ralfs	-	-	-	+
Melosira italica (Ehr.) Kütz.	-	+	+	+
Meridian circulare Agardh	+	+	+	-
Navicula cryptocephala Kütz.	+	-	-	-
Navicula halophila (Grun.) Cleve	-	+	-	-
Navicula radiosa Kütz.	-	-	-	+
Navicula sp. Bory	-	-	-	+
Nitzschia sp. Bory	+	-	+	-
Pinnularia braunii (Grun.) Cleve	-	+	+	-
Rhopalodia gibba (Ehr.) O.Müll.	-	-	-	+
Surirella ovata Kütz.	-	+	-	-
Synedra famelica Kütz.	+	-	-	-
Synedra rumpens Kütz.	+	-	-	-
Synedra ulna (Nitz.) Ehr.	+	+	-	-
Synedra ulna var. *oxyrhynchus* Kütz.	+	-	-	-
Synedra sp. 1 Ehr.	-	+	-	-
Synedra sp. 2 Ehr.	+	-	-	-
Tabellaria flocculosa (Roth) Kütz.	+	+	-	-

ers or scrapers. The numbers of benthic invertebrates per unit area in Deer Creek were similar to numbers found by Pennak and van Gerpen (1947) in another Colorado Rocky Mountain stream. More individuals were found in the Surber samples in August 1981 than in August 1980, which may be due to the lower flow conditions in 1981.

In the upstream reach of the Snake River the same three species were found in the summers of 1980 and 1981. The most abundant species was a stonefly, *Zapada frigida*, and the other two species were chironomids, *Diamesa latitarsis* and *Eukiefferiella bavarica*. The genus *Zapada* is described as shredders-detritivores, whereas the two chironomids are described as collectors-gatherers (Merrit & Cummins, 1978). The stonefly *Zapada frigida* was not unique to the upstream reach of the Snake River; in both years a few individuals also were found in Deer Creek. As in Deer Creek, more benthic invertebrates were found in 1981 than in 1980. However, in contrast to the much lesser abundance of periphyton in the Snake River than in Deer Creek, the abundance of benthic invertebrates was about the same in the Snake River and in Deer Creek. The abundant and distinctive benthic invertebrate assemblage at site 2 suggests that these species are well-adapted to acidic, metal-enriched streamwater, and that the liverwort *Scapania undulata* may provide a food source or habitat that compensates for the scarcity of periphyton.

For both years of the study, there were fewer benthic-invertebrates at the downstream sites than at the upstream sites (Table 2). The deposition of iron hydroxide has been found to restrict benthic



EXPLANATION

1 Water chemistry: pH 6.5-8.0
filtrable trace metals:<0.1 mgL^{-1}
Aquatic community:
Diatoms (abundant): Hannea arcus
Mayflies: Baetis sp.

2 Water chemistry: pH 3.5-4.0
filtrable trace metals;
Al≈4.0, Fe≈0.7, Mn≈1.0, Zn≈0.5 mgL^{-1}
Aquatic community:
Liverwort (abundant): Scapania undulata
Diatoms (sparse): Eunotia exigua or E. tenella
Stonefly: Zapada frigida; and chironomids

3 Water chemistry: pH 5.0-6.3
Precipitated hydrous Al and Fe oxides
filtrable trace metals;
Al≈0.4, Fe≈0.3, Mn≈0.5, Zn≈0.25 mgL^{-1}
Aquatic community: extremely sparse

4 Water chemistry: pH 5.5-7.0
Precipitated hydrous Al and Fe oxides
filtrable trace metals;
Al≈0.1, Fe≈0.2, Mn≈0.5, Zn≈0.2 mgL^{-1}
Aquatic community: extremely sparse

Fig. 3. Summary of the water chemistry and major aquatic organisms at the four sampling sites.

invertebrate assemblages in other stream environments (Thorup, 1966; Hynes, 1970). Throughout both summers, most of the individuals found at the confluence (site 3) were from the same species as individuals found at one or the other of the upstream sites. These may have represented drift, rather than individuals actually inhabiting the confluence. However, in both years there were a few individuals from species not found upstream. In August, 1980, only one stonefly, *Zapada frigida* and one chironomid, *Eukiefferiella bavarica*, were found at site 4 farthest downstream from the confluence, and these may have drifted from upstream in the Snake River. In 1980, there also were no intact algal cells found on the periphyton collectors. However, in 1981, when there was a significant and distinct periphyton assemblage at site 4, there were also more benthic invertebrates and the dominant species, a chironomid *Eukiefferiella claripennis*, was only found at this site. Differences in the benthic invertebrates between 1980 and 1981 were probably caused by the differences in hydrologic conditions.

Discussion

A significant advance in understanding the toxicity of trace metals to aquatic organisms was the demonstration by laboratory experiments that the toxicity of trace metals is a function of the activity of the free metal ion rather than the total metal concentration (Sunda & Guillard, 1976; Anderson & Morel, 1978). In a study of the $CuSO_4$ treatment of Mill Pond, a reservoir used for drinking water supplies, McKnight (1981) found that there was good agreement between laboratory results and actual changes in algal populations when compared on the basis of the measured cupric ion activity. However, it can be argued that because of the importance of the streambed surface, stream environments are inherently more complex than laboratory flasks or the epilimnion of a lake. Therefore, the effect of trace-metal stress on stream communities may not be a simple function of the free metal-ion activity in streamwater. In the study presented here, we see that the periphyton and benthic-invertebrate community is more adversely effected in the downstream reach of the Snake River, where hydrous metal oxide precipitate covers the rocks of the streambed, than in the upstream reach where the ion activities of Al, Fe, and Zn are much higher. In the upstream reach, there is a stable community, comprising a liverwort, several algal species, a stonefly, and two chironomids species, that has adapted to the acidic, metal-enriched stream-water. However, in the downstream reach of the Snake River the continuous thick covering of the rock substrate by metal precipitate appears to have prevented the development of a stable stream community. An example of the adverse effect of the metal precipitate is absence of any intact algal cells on the majority of the artificial substrates at the downstream sites.

Most of the algal species and the liverwort found at the upstream Snake River site have also been found in other acidic environments, which supports the conclusion that these species are adapted to these conditions. The taxonomy and ecology of *Eunotia exigua* and *E. tenella* are discussed in detail by van Dam *et al.* (1981). These diatom species are commonly found in many acid habitats, including acid mine drainage, and van Dam *et al.* (1981) suggest that *E. exigua* may be the most metal-tolerant diatom. For example, *Eunotia exigua* was found by Say & Whitton (1980) in Gillgill Burn, England, a stream contaminated with high concentrations of Zn from a nearby abandoned lead mine; by Hargreaves *et al.* (1975), in several acidic English streams; and by Warner (1971) in an acid mine-drainage-contaminated stream in West Virginia, U.S.A. *Eunotia tenella* was the dominant algal species in the reach of Lynx Creek adjacent to an abandoned copper mine in Arizona, U.S.A. (Lampkin & Sommerfield, 1982). Bennett (1969) found *Eunotia tenella* was abundant in mine-contaminated streams in West Virginia, U.S.A.

The chemistry of the Snake River upstream from the confluence with Deer Creek is similar in several ways to the chemistry of streams in the northeastern United States and Canada that are becoming acidified from the atmospheric transport of fossil fuel and mining pollutants. The two major similarities are the low pH, an excess of SO_4 ions, and high concentrations of dissolved Al and Fe from weathering of rocks under acid conditions (Cronan, 1980). Cronan & Schofield (1979) reported average dissolved-Al concentrations of 54 and 67 eq/L in soil water and springs in the Adirondack Mountains. As acid streams join streams draining terrain with a greater ability to buffer strong acids in rainfall, the pH eventually will increase to a value where many dissolved metals from the acid streams are no longer soluble. Results of the study presented here suggest that in addition to changes in stream communities in the acid streams, there may be changes in stream communities where Al and Fe precipitate as hydrous metal oxides, because of changes in stream chemistry, or because of mixing of stream waters of dissimilar chemistry downstream from confluences.

Summary and conclusions

The data presented here illustrate the major differences in the stream biota at the four sites of the study; however, the data are limited by the restricted sampling schedule and the use of artificial substrates for periphyton colonization. In the headwaters of the Snake River, a small naturally acidic, metal-enriched stream in the Rocky Mountains, the stream community is composed of one liverwort species, *Scapania undulata* var. *undulata*, a sparse periphyton assemblage dominated by diatoms of the genus *Eunotia*, abundant populations of the stonefly, *Zapada frigida*, and the chironomids, *Eukiefferiella bavaria* and *Diamesa latitarsis*. In Deer Creek, a small stream of neutral pH that joins the Snake River, the abundant periphyton assemblage is dominated by a common Rocky Mountain diatom, *Hannea arcus*, and the most important benthic invertebrates are several mayflies, *Baetis* sp., *Cinygmula* sp., and *Epeorus grandis*. Downstream from the confluence of the Snake River and Deer Creek, the concentrations of dissolved metals are much lower than upstream in the Snake River and hydrous Al and Fe oxides cover the rocks of the streambed, which greatly decreases the periphyton and benthic-invertebrate assemblages. Some of the few species of periphyton and benthic invertebrates found downstream from the confluence also were found upstream from the confluence and others only were found in the reach where the bed material was covered with metal precipitate. This study shows that destabilization of the rock surface in a stream by hydrous metal-oxide precipitation can have a more adverse effect on stream communities than low pH and high concentrations of free metal ions.

Acknowledgements

We thank L. Gough and Won Shic Hong for identification of liverwort species, and J. Brocksen for identification of algae and benthic invertebrates. We also thank E. Stiles for field assistance and for measurements of chlorophyll *a* concentrations.

References

Anderson, D. M. & F. M. M. Morel, 1978. Copper sensitivity of *Gonyaulax tamarensis*. Limnol. Oceanogr. 23: 283–295.

Bennet, H. D., 1969. Algae in relation to mine water. Castanea 34: 306–328.

Chessman, B. C. & S. D. McCallum, 1981. A simple and inexpensive artificial-substrate unit for obtaining periphyton collections from streams. Wat. Res. Research. 15: 351-352.

Cronan, C. S., 1980. Solution chemistry of a New Hampshire subalpine ecosystem: a biogeochemical analysis. Oikos 34: 272-281.

Cronan, C. S. & C. L. Schofield, 1979. Aluminum leaching response to acid precipitation: Effects on high-elevation watersheds in the northeast. Science 204: 304-306.

Greeson, P. E., T. A. Ehlke, G. A. Irwin, B. W. Lium & K. V. Slack, 1977. Methods for collection and analysis of aquatic biological and microbiological samples. U.S. Geol. Surv. Tech. Wat. Resour. Invest. Book 5, chapter A4.

Hargreaves, J. W., E. J. H. Lloyd & B. A. Whitton, 1975. Chemistry and vegetation of highly acidic streams. Freshwat. Biol. 5: 563-576.

Hynes, H. B. N., 1970. The Ecology of Running Waters. Univ. Toronto Press, Toronto, 555 pp.

Lampkin, A. J., III & M. R. Sommerfeld, 1982. Algal distribution in a small intermittent stream receiving acid mine-drainage. J. Phycol. 18: 196-199.

Lium, B. W. & W. T. Shoaf, 1979. Cellular contents, in a supplement of Methods for collection and analysis of aquatic biological and microbiological samples. In P. E. Greeson (ed.), U.S. Geological Survey Open-File Report 79-1279.

McKnight, D. M., 1981. Chemical and biological processes controlling the response of a freshwater ecosystem to copper stress: A field study of the $CuSO_4$ treatment of Mill Pond Reservoir, Burlington, Massachusetts. Limnol. Oceanogr. 26: 518-531.

Merrit, R. W. & K. W. Cummins, 1978. An Introduction to the Aquatic Insects of North America. Kendall Hunt Publishing Company, Dubuque, Iowa.

Moran, R. E. & D. A. Wentz, 1974. Effects of metal-mine drainage on water quality in selected areas of Colorado, 1972-73. U.S. Geol. Surv., Colorado Wat. Resour. Circ. 25, 250 pp.

Parsons, J. D., 1968. Effects of acid strip mine pollution on the ecology of a central Missouri stream. Arch. Hydrobiol. 65: 25-50.

Pennak, R. W. & E. D. Van Gerpen, 1947. Bottom fauna production and physical nature of the substrata in a northern Colorado trout stream. Ecol. 28: 42-48.

Say, P. S. & B. A. Whitton, 1980. Changes in flora down a stream showing a zinc gradient. Hydrobiologia 76: 255-262.

Sunda, W. G. & R. R. Guillard, 1976. Relationship between cupric ion activity and the toxicity of copper to phytoplankton. J. Mar. Res. 34: 511-529.

Theobald, P. K., H. W. Lakin & D. B. Hawkins, 1963. The precipitation of aluminum, iron and manganese at the junction of Deer Creek with the Snake River in Summit County, Colorado. Geochim. Cosmochim. Acta 27: 121-132.

Thorup, J., 1966. Substrate type and its value as a basis for the delimitation of bottom fauna communities in running waters. Spec. Publs, Pymatuning Lab. Fld. Biol. 4: 59-74.

van Dam, H., G. Suurmond & C. J. F. ter Braak, 1981. Impact of acidification on diatoms and chemistry of Dutch moorland pools. Hydrobiologia 83: 425-459.

Warner, R. W., 1971. Distribution of biota in a stream polluted by acid-mine drainage. Ohio J. Sci. 71: 202-215.

Westall, J. C., J. L. Zachary & F. M. Morel, 1979. MINEQL, a computer program for the calculation of chemical equilibrium composition of aqueous systems. Ralph M. Parsons Wat. Qual. Lab., Tech. Note 18, Mass. Inst. Tech., Cambridge.

Received 28 February 1983; in revised form 2 March 1984; accepted 2 March 1984.