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INTRODUCTION

The phenomenon of acid precipitation and its destructive effects are now recognized world-wide. Acid precipitation may occur as rain, snow, sleet, dew, and fog; in addition, dry solid materials may settle to earth as dust that, when dissolved in water, result in acid conditions. Included mainly are the strong acids, sulphuric and nitric acids, derived primarily from burning fossil fuel (coal, gas, oil) in electric generating plants and internal combustion engines (automobiles), respectively.

Naturally-occurring carbon dioxide in the atmosphere, when dissolved at equilibrium in raindrops, forms carbonic acid at pH 5.6; thus, precipitation and surface waters with pH values lower than 5.6 are considered "acidified," i.e., with sulfuric and nitric acids resulting from human cultural activities.

Precipitation in approximately two-thirds of North America is now below pH 5.6, i.e., acidified (Smith, 1984). Annual averages range from 5.5 to 4.4, west to east, with the lowest values of 4.1 in southern Ontario. Only Alaska and the northern Great Plains have precipitation that is not acidified to below pH 5.6. In the upper midwest, annual pH averages range from 5.2 to 4.2, west to east (Smith, 1984), and in Minnesota, from 5.5 to 4.6, southwest to northeast (Thornton, Heiskary, Payer, and Matta, 1982). Since these are annual averages, however, more acid precipitation often occurs locally or seasonally.

Acid precipitation entering waters on the earth's surface may be neutralized or buffered by naturally occurring compounds that react with the acids, resulting in unchanged or only slightly lower pH values. Surface waters containing low concentrations of buffering compounds, usually "soft" waters, are thus most susceptible to acid precipitation, causing rapid drops in pH values. Such soft waters generally occur where bedrock near the earth's surface consists of igneous or geologically weathered rock, such as on the Precambrian Shield and the Appalachian Mountains in North America. Thus, waters most seriously affected so far have been in the eastern half of Canada, northeastern United States, and the southern Appalachians. Since the Precambrian Shield is exposed in the northern Great Lakes region, some of the waters of northern parts of Minnesota, Wisconsin, and Michigan have also been affected.

Many important aspects of human life support are affected--e.g., agriculture, forestry (Thornton et al. 1982). Public attention and research, however, have been primarily directed toward the effects of acidic precipitation on aquatic life in surface waters. Historically, northern European countries were affected first, with extinctions of fish recorded in many lakes and streams. Thousands of lakes in northern Europe and hundreds in North America have been so affected (Thornton et al., 1982). Acidification and fish extinctions in lakes and streams of North America have occurred more recently, especially in Canada and northeastern United States (Haines, 1981; Cowling, 1982).

The biological communities in acidified surface waters have been affected in many ways. The loss of entire fish populations, or individual species, has been often observed. Fish death occurs usually within a pH range of 2 to 4, depending on species; disruption of spawning and reproduction may result below pH 5 (Meyer, Molter, and Schreiber, 1984; Johnson 1980). Likewise, many benthic invertebrates are killed or otherwise affected (Singer 1980; Burton, Stanford, and Allan, 1981), as are amphibians (Tome and Pough, 1980). Algae, macrophytes, and decomposers, while not usually eliminated as entire communities, undergo drastic changes in species associations and diversity reduction (Hendrey, 1980).

In addition to the direct effects of low pH values, increased concentrations of metals, some highly toxic, result in animal mortality or other disruptions. The most important metals are aluminum, leached from sediments at low pH, and mercury, co-deposited with acid precipitation.

The distribution of acid-sensitive soft waters, associated with igneous rock exposures, is mainly in northern temperate regions of the world. The distribution of salmonid fish species, requiring low water temperatures, is mainly in these same regions. Thus, among fish species, most researchers are concerned about the salmonid group. In Minnesota, the major concern is for the native brook trout (*Salvelinus fontinalis*) and lake trout (*Salvelinus namaycush*), and the introduced rainbow trout (*Salmo gairdneri*).

North Shore streams tributary to the Minnesota portion of Lake Superior contain valuable populations of brook trout and rainbow trout, important to the state's recreational fisheries. All of these streams are of moderately soft waters and flow over Precambrian Shield rocks. These rocks, including lavas of the North Shore volcanic group resulting from formation of the Superior basin of Keweenawan age, suggest that the streams may be potentially susceptible to acidification. Precipitation in this region is acidic. The pH values of rain have varied in the North Shore areas from 5.0 to 4.6, west to east (Ely to Hovland), while pH values of snow have been observed at 4.7 to 4.3, west to east (Heiskary and Payer, 1983). Limited measurements (by the author) of pH in the spring snowpack revealed pH values as low as 3.5.

The present study has focussed on the benthos of three North Shore streams, especially the bottom invertebrates making up the principal food resource of the brook trout and rainbow trout. The objectives: (1) to determine the level of abundance of the benthos in relation to other or earlier data and whether changes attributable to acid precipitation had already taken place; and (2) to provide a bank of base data that could be used in the future for comparison and detection of effects should acid precipitation continue and intensify.

Description of Study Sites

In midsummer 1982, 19 sites in 13 streams were visited and investigated as possible study sites. The potential locations were examined for bottom type, feasibility of benthos sampling, chemical attributes, and year-round accessibility. Some limited electrofishing was conducted to detect species of salmonids present, if not already known. Since most North Shore streams have two rather distinct reaches for type of fisheries: the upper reach above waterfall barriers with brook trout, and the lower reach between barrier and mouth of stream in Lake Superior with mainly juvenile rainbow trout (steelhead), streams were sought that had suitable sampling sites in both upper and lower reaches.

Brook trout were apparently indigenous to these streams only below natural barriers and introduced to upper reaches; rainbow trout were introduced from the Pacific drainage to Lake Superior in the late 1800s and have since utilized for spawning all suitable Lake Superior streams as anadromous populations (Eddy and Underhill 1974).

Three streams having the above required attributes were selected, near Grand Marais, Minnesota, in Cook County: Devil Track River, Kimball Creek, and Kadunce Creek. The sampling sites were located as follows: Devil Track River--lower site, above highway U.S. 61 (Section 13, Township 61N, Range 1E) and upper site, above County Road 12 or Gunflint Trail (Section 34, Township 62N, Range 1E); Kimball Creek--lower site, above County Road 60 (section 28, Township 62N, Range 2E) and upper site, above County Road 60 (Section 28, Township 62N, Range 2E); Kadunce Creek--lower site, above highway U.S. 61 (Section 2, Township 61N, Range 2E), and upper site, above National Forest or Trout Lake road (Section 13, Township 62N, Range 2E).

All sampling sites were located on riffles with similar physical characteristics of depth, current velocity, and substrate primarily of cobble and gravel. All were accessible year-round, i.e., on roads plowed in winter.

METHODS

Sampling commenced in July 1982 and continued through July 1984, for a total of two years. All sampling was undertaken during daylight hours. Measurement of chemical-physical parameters were made and benthos samples collected in the months of July, August, and October of 1982, and in February, May, and July of 1983 and 1984. In addition, chemical-physical parameters only were measured during major snowmelt periods in April of each year.

Chemical-physical parameters were measured as follows: air and water temperatures, with a pocket thermometer, in degrees Celsius; pH, with a portable Orion Model 399A Analog pH meter, in standard pH units; conductivity, with a Horizon Type 1484-10 conductivity meter, in micromhos/cm; alkalinity, with both methyl orange titration and potentiometric titrations using Gran plots (Rossotti and Rossotti, 1965), in mg/L as $CoCO_3$. The Gran plot method is considered to render more precise measurements and 1 to 2 mg/L lower than the methyl orange method (Thornton et al., 1982). Water samples were collected and preserved for analysis of total aluminum, in ug/L, with analyses conducted by the Minnesota State Department of Health (Minneapolis).

During most site visits, two benthos samples were collected to estimate standing stock. Samples were taken with a D-net of 251 um-mesh Nitex, approximately 0.3 m wide. Collections were made by placing the D-net vertically on the cobble and gravel substrate and agitating the substrate in an area approximately 0.1 m^2 upstream from the net. The benthos samples collected should be regarded as only approximately quantitative; the nature of the substrate--including large, irregular cobbles--precluded the use of more precise stream bottom samplers. Materials collected in the net after ten minutes agitation were concentrated and preserved in plastic Whirl-pak bags with about 10% Formalin (40% formaldehyde). In the laboratory, all aquatic invertebrates visible without magnification were picked out and sorted into major taxonomic groups; organisms were counted and wet-weighed by taxon, after centrifuging to remove external liquids, on a Mettler balance to the nearest 0.1 mg. Standing stocks were expressed in units of g/m^2, wet weight.

RESULTS

In general, all physical/chemical parameters and levels of benthos abundance appeared to be normal and similar to what might be expected in North Shore streams. Data did not indicate any previous effects of acid precipitation.

All data obtained appear in their entirety in appendices at the end of this report, so that any future analysis and comparisons may be made in any desired detail. General narrative summaries follow, arranged by type of parameter measured.

Air and water temperature

Overall, air temperatures ranged from -3 degrees C in winter to about 25 degrees C in summer. Water temperature varied from 0 degrees C (February and April) to a maximum of around 20 degrees C (July and August) in all three streams, a range slightly less than that of air temperature, as would be expected. When differences in water temperatures occurred between upper and lower sites, temperatures were usually lower at the upper sites, by 1 to 4 degrees C (see Appendix I).

pH

The pH values in all three streams varied slightly around 7.0 or neutral. Values below 6.0 were not observed at any time. Only small differences were apparent among the three streams or between upper and lower sites. Mean pH over the study period (derived from the arithmetic average of hydrogen-ion concentrations) in the Devil Track River was 6.9 at the upper site, 6.8 at the lower site; in Kimball Creek, 7.2 at both upper and lower sites; and in Kadunce Creek, 7.0 at the upper site, 7.2 at the lower site.

There was little evidence of depressed pH values at times of snow melt, in April of both 1983 and 1984. The only depression, to pH 6.0, appeared at the lower site of the Devil Track River; depression in pH values was not observed at other sites (see Appendix II.).

Alkalinity

In most cases, alkalinity, as measured by the methyl orange method, was somewhat higher than the value determined by the Gran plot method; means through the study period were higher by 1 to 5 mg/L by the methyl orange method. Gran plot results were not available, however, until the February 1983 sampling date.

Total alkalinity (expressed as mg/L $CaCO_3$) remained at moderate levels at all sites throughout the study period, ranging overall from 14 to 52 (methyl orange) or 13 to 48 mg/L (Gran plot).

Among the three streams, alkalinity was highest in Kimball Creek, mid-level in Kadunce Creek, and lowest in the Devil Track River. Little difference was observed between upper and lower sites, although minor increases were apparent at the lower sites in the Devil Track River and Kadunce Creek, suggesting some accretion in lower reaches of groundwater, frequently of higher alkalinity than surface water.

Study period means were as follows: Devil Track River, upper site 20 (methyl orange) and 16 mg/L(Gran plot)--lower site, 24 (methyl orange) and 20 mg/L (Gran plot); Kimball Creek--both sites 36 (methyl orange) and 31 mg/L (Gran plot); Kadunce Creek, upper site 26 (methyl orange) and 25 mg/L (Gran plot) and lower site, 32 (methyl orange) and 28 mg/L (Gran plot).

Alkalinity varied seasonally, with the highest levels observed in late summer (August, both years), due to low water levels at this time and the greatest relative contributions from groundwater. Alkalinity generally was lowest in winter in all three streams. The lowest pH values were observed during snow melt (April) in all three streams in 1983 (but not in 1984), apparently due to dilution by melting snow (see Appendix III).

Conductivity

Conductivity varied similarly to alkalinity at almost all times and sites. Conductivity was highest in Kimball Creek, lowest in the Devil Track River. Values were somewhat higher at lower sites than at upper sites.

Study period means were as follows: Devil Track River--upper site, 60 umho/cm and lower site 66; Kimball Creek--upper site, 93 and lower site, 97; Kadunce Creek--upper site 60, and lower site, 85.

Seasonally, conductivity varied in a pattern similar to alkalinity, with the highest values in the summer and the lowest values in the winter, probably for the same reasons. Conductivity was apparently slightly depressed at the time of snow melt in 1983, but not in 1984 (see Appendix IV).

Aluminum

Total aluminum varied greatly in all three streams, depending on water conditions. Values were consistently higher under conditions of greater turbidity.

Since aluminum is a basic constituent of clay, waters turbid with clay should show high values of total aluminum. Unfortunately, the presence and significance of clay turbidity was not foreseen; consequently, most data reported herein are not meaningful in terms of their effect on benthos or fish. The high values reported here are thus not to be construed as accurately representing values potentially detrimental to living organisms nor as indicative of aluminum concentrations resulting from low pH values.

All three streams were similar in total aluminum content, but in all three streams study period means were much higher at downstream sites: Devil Track River--upper site, 165 ug/L and lower site 1378; Kimball Creek--upper site, 148 and lower site, 1340; Kadunce Creek--upper site, 158 and lower site, 1073.

In all cases, the higher means at the lower sites appeared to be the result of extremely high values during periods of high water and snow melt, reflecting the higher clay turbidity at the lower sites. In all three streams, clay turbidity was visible to the eye at the lower sites during these times but not at the upper sites.

Excluding the data from the sampling dates when either high water was obvious due to rains (October 6, 1982, and October 24-25, 1983) or during snow melt (April 25-26, 1983, and April 3-4, 1984), the study period means are as follows: Devil Track River--upper site, 43 ug/L and lower site, 96; Kimball Creek--upper site, 50 and lower site, 104; Kadunce Creek--upper site, 125 and lower site, 141. This latter group of means would probably be more biologically meaningful than total means that included data from turbid waters (see Appendix V).

Benthos

Qualitatively, the benthos of all three streams appeared to include an acceptable diversity of aquatic invertebrates, mainly immature insects. Caddisflies (Trichoptera), mayflies (Ephemeroptera), and stoneflies (Plecoptera) were all well represented and together usually made up the major components in abundance. Among the Diptera, black flies (Simuliidae) and midges (Chironomidae) were well represented in numbers though small in size. The orders Megaloptera and Odonata were represented by fewer but larger organisms. Aquatic worms (Annelida) were frequently present, with Oligochaeta common, and leeches (Hirudinea) less so.

Quantitatively, the standing stocks of insects Trichoptera, Ephemeroptera, and Plecoptera together constituted the major portions of biomass. Single or few specimens of large Pteronarcys (Plecoptera) frequently added substantially to standing stock totals. Variation among samples, as expected, was high.

The study period means for the standing stock in biomass (g/m^2, wet weight) were remarkably similar among all three streams, when both upper and lower sites were combined: Devil Track River, 10.7 g/m^2; Kimball Creek, 11.2; and Kadunce Creek, 12.3. Substantial differences were apparent, however, between upper and lower sites, with standing stock at the upper sites higher than at the lower sites, especially in the Devil Track River and Kadunce Creek. Study period means were as follows: Devil Track River--upper site, 15.5 g/m^2 and lower site, 5.9; Kimball Creek--upper site, 12.5 and lower site, 9.9; and Kadunce Creek--upper site, 16.6 and lower site, 7.9 (see Appendix VI).

Standing stock summaries by major taxa are presented in Appendixes VII, VIII, and IX.

DISCUSSION

The major objective of the present study was to obtain information on chemical/physical conditions and benthos abundance, as a base of data for making comparisons at a later date. A necessary assumption was that the data were obtained prior to acidification when the conditions could be considered "normal." Since conditions in the Devil Track River and Kimball and Kadunce creeks were similar to previous conditions in these streams, and also to other similar streams, the assumption appears to be valid.

The main source of historical information on these streams is the classic work of Smith and Moyle (1944), who investigated many aspects of the streams on the Minnesota portion of the North Shore of Lake Superior in the early 1940s. While their data are sketchy for individual streams, having visited most streams infrequently, overall their results give an excellent summary of general conditions prevailing 40 years ago, prior to occurrence of acid precipitation in the region.

Thornton et al. (1982) provided a classification of alkalinities indicating the sensitivity of surface waters as follows: alkalinity of 0, acidified; 1 to 5 mg/L, extremely sensitive; 6 to 10 mg/L, moderately sensitive; 10 to 20 mg/L, potentially sensitive; and higher than 20 mg/L, non-sensitive. In the present study, alkalinity values suggest that Kimball and Kadunce creeks, with alkalinities higher than 20 mg/L, fall into the non-sensitive category. The Devil Track River, however, would be classed as potentially sensitive for at least part of the year.

The pH values observed in all three streams were above those which would be expected to cause stress in either fish or invertebrates--a pH of about 5 to 6, depending on fish or invertebrate species (Thornton et al., 1982). During snow melt, despite acid conditions in the accumulated snow pack, the observed pH values of stream water were insignificantly affected due to the buffering capacity of the stream water. Brousseau (1981) observed similar effects in several Ontario North Shore streams.

A special problem exists in streams, however, as compared with lakes, related to snow melt and other short-term episodic events such as spates or floods. Short-term depressions of pH values to toxic levels during these episodes may be just as damaging as low pH values that persist longer, especially if mortality or high drift occurs. Low pH and alkalinity may occur at toxic levels during snow melt, though only non-toxic levels are observed at all other times of the year (Jeffries, Cox, and Dillon, 1979). Thornton et al. (1982) have summarized data from the literature indicating that conditions during the first of spring snow melt may be damaging only for a short time and therefore go undetected by routine surveys. It is probable that conditions during the first snow melt were not observed in the present study, even though attempts were made to obtain samples during the major snow melts. Those conditions remain unknown. However, in view of what appears to be normal levels of benthos abundance, toxic levels apparently were not reached (see below).

Mean levels of pH in the present study were not much different from those observed by Smith and Moyle (1944). A range of pH from 6.8 to 7.6 (all three streams) reported by Smith and Moyle may be compared to a range in mean values from 6.8 to 7.2 for the same three streams in the present study. Smith and Moyle reported ranges in alkalinity about 15 to 38 mg/L; in the present study ranges in mean values were 16 to 36 mg/L. Smith and Moyle did not report conductivity values. Even taking into account the possibility of differences due to improved instrumentation, differences between the two studies would probably not be great. The pH and alkalinity values observed in the present study did not approach stress levels for either fish or invertebrates.

Concentrations of total aluminum reached toxic levels during snow melt and high water. Levels above 200 ug/L appear to be toxic for many species (Burton, Stanford, and Allan 1981). Concentrations of total aluminum reached above this level on several occasions, to a maximum of 9800 ug/L in the Devil Track River (lower site) and Kimball Creek (lower site) during the April 1983 snow melt. Heiskary and Payer (1983) also found levels of total aluminum of 2000 ug/L or higher in these three streams during snow melt.

However, total aluminum from unfiltered samples may not be the best parameter to use for diagnostic purposes, since aluminum may be present in high quantities as an inherent component of clay and soil particles, as well as in complexed form with organic particles. In the present study, high values during snow melt at lower sites (with clay turbidity) but not at upper sites (without turbidity) suggest that the aluminum was in the mineral particles. Furthermore, high values of total aluminum in turbid, high waters in October, especially at the lower sites, suggest the clay and soil particles as the source of aluminum, rather than from leaching by acid conditions of melting snow. Lower values of less than 100 ug/L, occurring during low flow conditions in both winter and summer are probably more representative of aluminum concentrations experienced by the invertebrates.

Total benthos abundance, expressed as standing stock in g/m^2, appeared similar both to the observations of Smith and Moyle (1944) and to the limited available data on similar streams. The overall mean (three streams, upper and lower sites, both years) was about 10 to 12 g/m^2, wet weight. Data among the three streams were remarkably similar, but with greater standing stock at upper sites than at lower sites: overall means were about 12 to 16 g/m^2 at upper sites and 8 to 10 g/m^2 at lower sites. It may be postulated that the smaller abundance of benthos at the lower sites was due to the larger substrate size, higher current velocities, and greater occurrence of floods or high water with consequent turbidity and silt.

The observations of Smith and Moyle included one sample from the Devil Track River, 17 g/m^2; one sample from Kimball Creek, 19 g/m^2; and two samples from Kadunce Creek, 4 and 28 g/m^2, a sketchy sample set, but as a whole not much different from the results of the present study.

Smith and Moyle concluded that, in general, the benthos of North Shore streams (total of about 100 samples from 27 stream systems) was low in abundance and rated poor relative to general stream benthos abundance. They reported that usual standing stocks in larger, warmer North Shore streams ranged from 10 to 20 g/m^2 and in smaller, colder streams from 2 to 5 g/m^2. Most of the data from the present study falls within or between these ranges, suggesting no significant changes in benthos abundance since the time of their earlier work.

In a similar North Shore stream, Caribou River (total alkalinity 34 mg/L, pH 6.8), Krueger (1979) found an annual mean standing stock of 8 g/m^2, similar to means in the present study. In a soft-water (total alkalinity 8.4 mg/L) but non-acidified (pH 6.8) Pennsylvania stream, Arnold et al. (1981) reported a mean benthos standing stock of 3.5 g/m^2 (insects only).

The species distribution in the three streams of the present study appeared normal, with mayflies making up a substantial proportion. Mayflies are among the stream invertebrate taxa most sensitive to acid conditions, disappearing first among benthos upon acidification (Burton et al., 1981; Mackay and Kersey, 1985). The mayfly group in the present study was well represented in apparently viable populations, adding further support to the conclusion that these three streams have not yet been subjected to acidification.

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APPENDICES

Appendix I. Air and water temperature (^{o}C) in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984.

Date	Devil Track				Kimball				Kadunce			
	Upper		Lower		Upper		Lower		Upper		Lower	
	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water	Air	Water
7-14-82	19	18	10	15	19	16	13	12	19	17	16	13
8-18,19-82	19	15	19	14	19	9	17	11	17	13	14	12
10-6-82	3	6	4	4	2	4	4	4	4	4	4	4
2-12-83	-3	0	0	0	-3	0	0	0	-3	0	-2	0
4-25,26-83	2	1	3	0	12	0	4	0	12	0	8	0
5-21,23-83	11	9	12	9	11	8	16	8	10	6	11	7
7-12,13-83	27	21	16	17	25	19	20	17	24	18	17	17
8-29,30-83	21	18	19	17	22	16	22	17	20	18	20	18
10-24,25-83	8	7	9	6	8	4	3	4	7	3	7	4
2-8,9-84	-1	0	-2	0	-2	0	0	0	-3	0	-1	0
4-3,4-84	5	0	7	0	6	0	6	0	6	0	3	0
5-30,31-84	20	13	17	10	18	12	18	10	18	11	11	11
7-12-84	22	19	16	18	22	18	17	16	17	16	15	16

Appendix II. pH values in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984.

Date	Devil Track		Kimball		Kadunce	
	Upper	Lower	Upper	Lower	Upper	Lower
7-14-82	7.2	7.6	7.3	7.7	7.3	7.7
8-18,19-82	6.4	7.7	7.9	7.8	7.3	7.6
10-6-82	8.0	7.5	7.9	7.6	7.4	8.2
2-12-83	6.9	7.1	7.1	7.0	6.8	6.9
4-25,26-83	7.8	6.0	7.4	8.1	7.5	6.9
5-21,23-83	7.4	7.4	7.4	7.4	7.1	7.0
7-12,13-83	7.1	7.2	7.5	7.3	7.3	7.6
8-29,30-83	7.2	7.3	7.7	7.6	7.2	7.9
10-24,25-83	6.9	7.2	6.8	7.2	6.9	7.0
2-8,9-84	6.7	6.9	6.8	7.6	6.7	7.1
4-3,4-84	6.7	6.9	7.8	6.7	7.4	7.6
5-30,31-84	6.5	6.7	6.9	6.8	7.0	7.0
7-12-84	6.9	7.0	7.4	7.3	7.2	7.4
Mean pH *	6.9	6.8	7.2	7.2	7.0	7.2

*Calculated from average hydrogen-ion concentration.

Appendix III. Total alkalinity (as mg/L $caCO_3$) by methyl orange (MO) and Gran plot (GP) in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984.

	Devil Track				Kimball				Kadunce			
Date	Upper		Lower		Upper		Lower		Upper		Lower	
	MO		GP		MO		GP		MO		GP	
7-14-82	17	--	22	--	34	--	25	--	26	--	37	--
8-18,19-82	24	--	36	--	52	--	52	--	32	--	44	--
10-6-82	20	--	30	--	*	--	40	--	22	--	34	--
2-12-83	16	16	18	21	35	36	32	37	21	22	24	32
4-25,26-83	14	14	18	16	17	14	17	13	17	*	18	13
5-21,23-83	19	13	17	14	20	18	24	19	22	15	26	22
7-12,13-83	21	18	27	18	35	33	39	34	35	32	26	22
8-29,30-83	26	22	34	30	48	46	50	48	33	27	48	44
10-24,25-83	20	16	20	15	30	25	31	26	23	20	31	30
2-8,9-84	20	18	26	21	43	38	45	38	26	21	37	34
4-3,4-84	21	16	27	23	39	35	32	29	26	23	27	23
5-30,31-84	18	13	19	17	31	27	33	29	23	30	31	27
7-12-84	19	16	22	21	45	41	44	41	26	34	39	36
Mean	20	16	24	20	36	31	36	31	26	25	32	28

*Sample missed

Appendix IV. Conductivity (μ mho/cm) in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984.

	Devil Track		Kimball		Kadunce	
Date	Upper	Lower	Upper	Lower	Upper	Lower
10-6-82	60	80	80	114	72	89
2-12-83	72	69	114	119	69	105
4-25,26-83	51	52	52	47	55	47
5-21,23-83	81	59	70	86	64	64
7-12,13-83	54	55	85	98	65	87
8-29,30-83	67	90	128	128	77	123
10-25,26-83	55	57	83	83	64	87
2-8,9-84	57	71	108	107	65	92
4-3,4-84	60	80	116	93	68	73
5-30,31-84	50	54	78	85	62	79
7-12-84	55	64	109	110	65	92
Mean	60	66	93	97	60	85

Appendix V. Total aluminum (µg/L) in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984.

	Devil Track		Kimball		Kadunce	
Date	Upper	Lower	Upper	Lower	Upper	Lower
10-6-82	1100	3200	660	3200	360	3400
2-12-83	39	71	50	130	42	62
4-25,26-83	210	9800	370	9800	310	5900
5-21,23-83	45	160	91	210	370	280
7-12,13-83	*	170	*	110	*	160
8-29,30-83	56	98	32	65	80	67
10-24,25-83	29	710	74	220	61	310
2-8,9-84	36	38	27	58	170	160
4-3,4-84	53	880	78	800	95	1200
5-30,31-84	34	82	55	88	45	150
7-12-84	47	54	45	68	45	110
Mean	165	1388	148	1341	158	1073
Mean**	43	96	50	104	125	141

* Sample missed

** Mean calculated without data in high water (10-6-82, 10-24,25-83) and snow melt (4-25,26-83, 4-3,4-83).

Appendix VI. Standing stock of benthos (g/m^2, wet weight) in Devil Track River, Kimball Creek, and Kadunce Creek, Minnesota, 1982-1984. Two samples per date. All taxa combined.

	Devil Track				Kimball				Kadunce			
Date	Upper		Lower		Upper		Lower		Upper		Lower	
	1	2	1	2	1	2	1	2	1	2	1	2
7-14-82	10.0	19.0	11.0	14.4	16.6	6.4	15.2	14.0	15.6	2.3	4.7	5.7
8-18,19-82	14.3	27.7	6.4	5.3	10.0	15.8	3.7	10.3	7.7	19.5	6.4	4.6
10-6-82	0.6	13.6	*	*	*	*	*	*	18.7	15.7	*	*
2-12-83	14.2	11.5	3.0	6.6	8.8	11.5	1.9	3.4	9.7	8.6	5.4	5.1
5-21,23-83	23.4	36.6	7.2	6.8	13.2	18.3	10.3	15.2	17.7	30.1	8.6	11.0
7-12,13-83	11.9	10.5	2.5	2.5	5.5	8.5	10.4	6.5	12.6	9.8	6.9	2.4
8-29,30-83	12.7	14.7	7.7	13.6	24.2	9.7	24.1	3.4	19.4	9.0	6.2	15.1
10-24,25-83	15.9	1.1	1.6	2.9	21.4	7.7	7.5	25.5	31.3	21.6	11.7	9.9
2-8,9-84	18.6	42.1	5.0	2.9	17.0	11.6	1.9	2.2	9.7	21.0	11.7	4.6
5-30,31-84	12.6	17.6	6.6	4.1	19.0	8.7	6.5	10.5	42.4	21.5	15.7	7.9
7-12-84	6.3	6.7	2.5	5.0	12.0	5.1	18.9	7.0	16.4	5.6	7.6	6.3
Site mean	15.5		5.9		12.5		9.9		16.6		7.9	
Stream mean	10.7				11.2				12.3			

*Samples precluded due to high water

Appendix VII. Benthos samples (mg/0.1 m^2, wet weight) in the Devil Track River, by taxon, 1982-1984. Two samples per site, per date.

	Site	Sample No.	7-14-1982	8-18,19-1982	10-6-1982	2-12-1983	5-21,23-1983	7-12,13-1983	8-29,30-1983	10-24,25-1983	2-8,9-1984	5-30,31-1984	7-12-1984
Ephemeroptera	Upper	1	271.3	104.7	6.4	158.3	312.4	73.6	51.4	164.8	232.8	88.2	132.6
		2	161.9	54.8	34.3	326.2	521.2	91.9	120.4	13.5	509.6	390.1	114.4
	Lower	1	355.1	190.5	*	265.5	280.0	56.6	190.4	106.6	404.8	111.3	69.0
		2	307.7	149.8	*	515.6	207.6	103.7	158.7	97.7	207.6	115.7	162.9
Trichoptera	Upper	1	352.6	31.5	14.1	178.4	148.3	28.1	15.2	290.7	587.1	283.2	212.7
		2	244.5	125.1	65.5	99.4	230.8	225.0	237.7	30.2	232.1	322.6	141.3
	Lower	1	551.2	145.2	*	18.7	150.4	105.1	498.9	36.2	54.8	276.3	69.9
		2	998.7	211.8	*	9.8	93.1	10.2	958.2	58.3	52.2	68.4	67.4
Plecoptera	Upper	1	344.1	875.2	0.2	747.1	1562.8	227.0	1086.3	757.9	598.4	547.8	259.1
		2	1437.0	2398.0	1117.3	653.8	1213.5	149.3	470.1	9.3	2889.1	906.4	76.7
	Lower	1	0.0	67.5	*	14.7	250.2	3.9	24.5	10.8	33.2	100.9	0.8
		2	1.6	99.2	*	125.3	37.7	1.0	138.1	24.0	33.4	19.8	0.0
Diptera	Upper	1	28.0	12.8	0.0	61.8	92.7	177.1	1.9	16.1	437.4	270.3	29.2
		2	59.5	62.0	35.9	72.8	178.0	116.3	63.8	0.0	60.2	35.1	58.7
	Lower	1	54.8	34.2	*	0.3	24.4	47.8	10.4	0.7	7.3	60.2	38.3
		2	87.4	26.4	*	2.5	76.5	26.4	25.7	0.3	0.8	148.1	46.6
Annelida	Upper	1	0.0	51.6	0.0	131.5	67.7	279.0	20.6	240.4	1.7	73.6	0.0
		2	0.0	0.0	92.8	0.2	406.1	334.8	93.0	34.3	200.3	73.1	0.0
	Lower	1	138.8	195.9	*	3.6	16.8	34.4	45.8	3.2	0.0	115.6	72.6
		2	44.1	44.3	*	3.9	255.7	107.4	79.8	109.5	0.0	62.8	223.1
Others	Upper	1	0.0	349.6	42.0	142.3	159.8	402.5	92.3	118.8	0.0	0.0	0.0
		2	0.0	125.3	9.7	0.0	1107.4	130.8	487.6	27.3	314.4	31.4	280.2
	Lower	1	0.0	1.8	*	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0
		2	0.0	0.0	*	0.0	13.4	1.1	4.0	0.0	0.0	0.0	2.2

* Samples precluded due to high water

Appendix VIII. Benthos samples (mg/0.1 m^2, wet weight) in Kimball Creek, by taxon, 1982-1984. Two samples per site, per date.

	Site	Sample No.	7-14-1982	8-18,19-1982	10-6-1982	2-12-1983	5-21,23-1983	7-12,13-1983	8-29,30-1983	10-24,25-1983	2-8,9-1984	5-30,31-1984	7-12-1984
Ephemeroptera	Upper	1	181.6	46.6	*	116.9	613.4	125.5	177.9	327.4	315.9	211.3	139.6
		2	72.3	96.9	*	361.3	353.3	67.2	94.7	124.7	568.6	191.7	114.2
	Lower	1	279.9	87.9	*	111.9	453.8	482.1	125.8	68.8	59.9	219.2	233.0
		2	213.8	144.6	*	226.3	298.4	104.6	30.5	158.2	26.7	524.5	157.9
Trichoptera	Upper	1	384.1	195.6	*	3.4	99.1	232.2	1688.7	841.4	191.7	315.7	326.9
		2	174.4	745.7	*	59.1	95.0	13.9	423.9	2.9	187.1	116.2	193.1
	Lower	1	1014.7	229.0	*	40.2	291.7	254.0	1640.8	405.1	16.1	0.3	314.6
		2	704.7	471.3	*	47.3	111.0	374.6	222.3	712.1	118.4	182.0	418.3
Plecoptera	Upper	1	1035.4	493.7	*	70.4	175.8	3.1	131.5	77.4	50.5	142.8	103.8
		2	171.6	578.1	*	216.3	7.2	0.9	45.2	75.1	137.5	247.9	5.6
	Lower	1	4.4	6.3	*	7.7	35.4	6.8	411.2	178.6	87.8	128.6	1039.8
		2	315.8	215.1	*	17.0	1079.9	1.3	40.7	1275.8	30.8	19.6	1.8
Diptera	Upper	1	57.8	58.4	*	680.7	165.0	75.8	114.9	580.4	1067.7	37.2	165.8
		2	212.7	33.3	*	61.7	855.3	101.1	111.6	10.8	97.2	23.9	51.7
	Lower	1	88.0	7.3	*	25.9	121.2	34.4	5.9	11.0	17.5	34.5	79.8
		2	10.9	17.2	*	4.5	30.8	47.0	19.1	36.3	26.0	101.3	30.0
Annelida	Upper	1	1.4	199.5	*	8.0	261.1	114.9	98.5	229.2	77.2	1192.9	301.8
		2	0.0	99.8	*	443.1	469.3	482.2	211.0	556.8	168.5	290.7	87.3
	Lower	1	134.5	35.8	*	2.5	128.6	259.8	172.8	24.1	0.0	263.2	184.0
		2	152.8	80.6	*	44.5	2.3	118.6	22.2	363.9	20.8	204.5	67.2
Others	Upper	1	0.8	7.0	*	0.0	0.9	0.4	209.7	81.9	0.0	0.0	161.3
		2	4.3	28.4	*	3.6	54.3	184.4	85.7	0.0	0.0	1.7	60.7
	Lower	1	0.0	1.2	*	0.0	1.6	1.1	53.8	63.5	3.9	0.0	36.8
		2	1.1	101.8	*	1.9	0.9	0.0	2.2	0.0	0.0	20.0	21.8

Samples precluded due to high water.

Appendix IX. Benthos samples (mg/0.1 m^2, wet weight) in Kadunce Creek, by taxon, 1982-1984. Two samples per site, per date.

	Site	Sample No.	7-14-1982	8-18,19-1982	10-6-1982	2-12-1983	5-21,23-1983	7-12,13-1983	8-29,30-1983	10-24,25-1983	2-8,9-1984	5-30,31-1984	7-12-1984
Ephemeroptera	Upper	1	55.3	25.7	538.0	266.6	343.3	46.9	25.2	607.2	386.7	1338.7	36.1
		2	2.5	29.7	205.6	389.1	185.2	45.4	30.3	269.6	520.5	974.6	17.0
	Lower	1	62.9	74.9	*	107.8	430.5	121.1	65.7	204.1	150.8	303.5	117.1
		2	102.8	60.1	*	169.0	391.4	18.5	102.2	73.1	121.4	114.0	32.8
Trichoptera	Upper	1	826.0	287.2	446.5	106.1	153.1	267.3	102.7	767.2	15.2	662.0	697.7
		2	138.9	632.5	127.7	82.0	630.3	167.5	57.9	108.2	184.4	440.1	224.4
	Lower	1	280.2	338.6	*	14.7	26.3	221.4	168.2	260.6	491.4	497.5	331.5
		2	364.4	199.1	*	2.7	52.8	48.0	632.3	257.0	155.9	205.5	469.0
Plecoptera	Upper	1	50.5	10.1	40.2	83.5	204.4	57.3	4.1	169.5	131.0	97.9	22.1
		2	0.8	11.0	16.5	122.0	58.6	8.8	17.2	48.2	735.1	64.6	2.7
	Lower	1	85.9	35.8	*	42.8	25.4	8.0	161.2	465.6	203.2	48.3	3.2
		2	9.5	22.6	*	123.1	41.5	1.6	526.3	229.5	50.6	16.4	0.0
Diptera	Upper	1	67.6	15.1	6.9	286.2	512.7	299.6	170.1	876.2	8.4	445.4	251.9
		2	3.5	19.4	42.8	189.0	387.1	125.0	178.7	615.0	365.4	35.7	44.8
	Lower	1	34.4	20.0	*	26.0	21.5	17.9	20.7	7.3	15.9	57.1	44.7
		2	26.5	4.4	*	11.3	26.6	14.4	17.9	15.2	24.5	16.5	10.0
Annelida	Upper	1	227.5	310.6	343.5	45.8	546.9	371.9	359.3	687.6	418.7	1030.5	419.0
		2	3.5	372.8	58.9	60.9	707.8	580.4	207.2	552.5	71.4	143.4	245.7
	Lower	1	0.0	164.8	*	170.9	358.9	322.5	197.6	236.6	245.4	663.2	260.5
		2	66.8	169.7	*	208.9	582.6	156.5	230.4	6.4	99.6	425.7	115.2
Others	Upper	1	337.6	125.8	495.5	181.2	6.7	215.4	1282.6	25.4	7.1	662.9	214.2
		2	82.1	883.6	1123.1	15.4	1044.8	50.0	407.2	571.1	224.7	487.8	28.5
	Lower	1	3.7	10.7	*	178.9	0.0	0.1	2.0	0.0	59.9	0.0	0.0
		2	4.7	1.8	*	0.0	1.9	4.7	3.0	406.1	3.9	0.6	0.4

Samples precluded due to high water.

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