IMPACTS ON WATER QUALITY AND BIOTA FROM NATURAL ACID ROCK DRAINAGE IN COLORADO'S LAKE CREEK WATERSHED[1]

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Abstract. Colorado's Lake Creek watershed hosts natural acid rock drainage that significantly impacts surface water, streambed sediment, and aquatic life. The source of the ARD is a group of iron-rich springs that emerge from intensely hydrothermally altered, unexploited, low-grade porphyry copper mineralization in the Grizzly Peak Caldera. Source water chemistry includes pH of 2.5 and dissolved metal concentrations of up to 277 mg/L aluminum, 498 mg/L iron, and 10 mg/L copper. From the hydrothermally altered area downstream for 27 kilometers to Twin Lakes Reservoir, metal concentrations in streambed sediment are elevated and the watershed experiences locally severe adverse impacts to aquatic life due to the acidic, metal-laden water. The water and sediment quality of Twin Lakes Reservoir is sufficiently improved that the reservoir supports a trout fishery, and remnants of upstream ARD are negligible.

Additional Key Words: Grizzly, Lake, Chaffee, Twin Lakes, Arkansas River, trout, invertebrates

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Introduction

Colorado's Lake Creek watershed hosts severe natural acid rock drainage (ARD) with no visible or measurable contributions from anthropogenic sources. Lake Creek is a tributary to the upper Arkansas River, located about 150 km southwest of Denver and about 25 km southwest of Leadville (Fig. 1). Elevations in the study area range from about 2,804 m (9,200 ft) at the lowermost sample site on Lake Creek just above the confluence with the Arkansas River, to about 4,023 m (13,200 ft) on Red Mountain above Peekaboo Gulch.

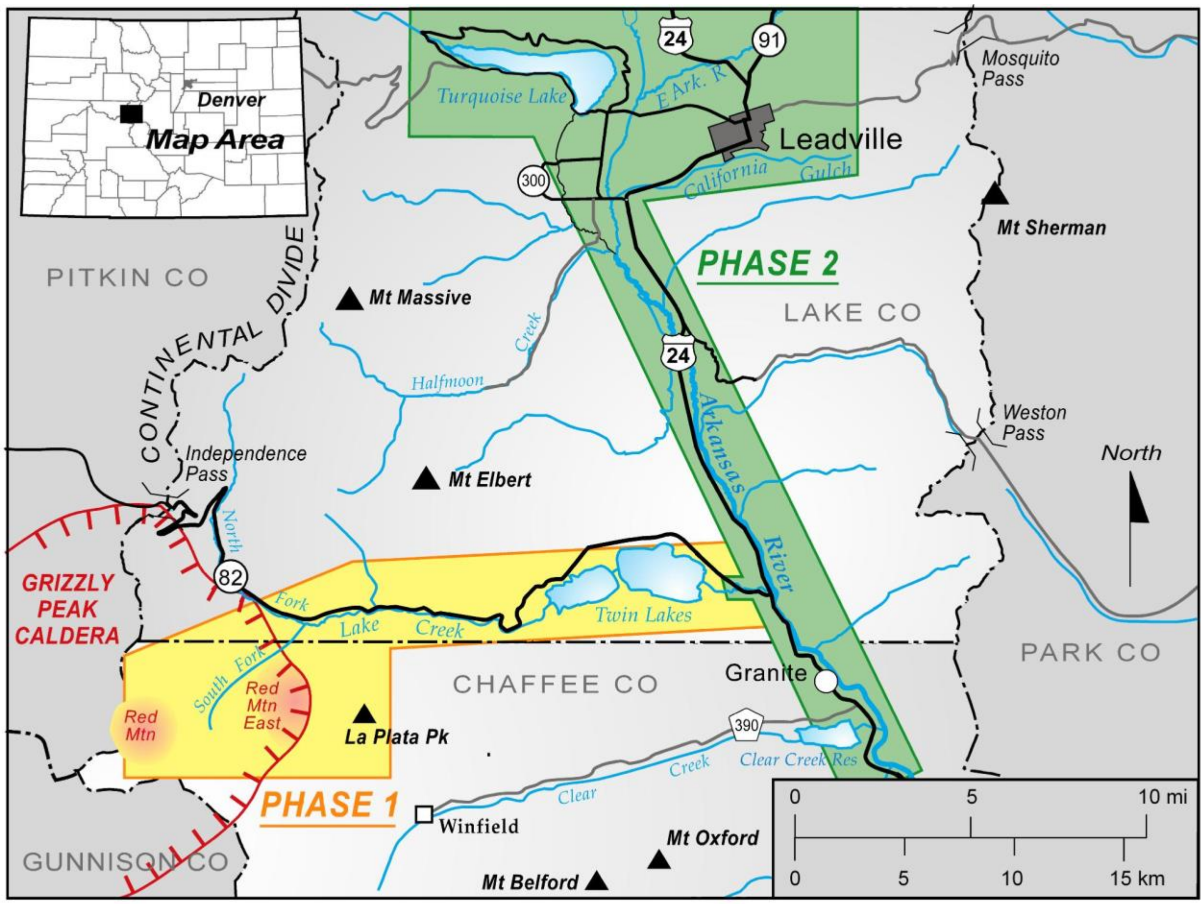

Figure 1. Location of project area.

This study was conducted by the Colorado Geological Survey (CGS) and several partners as part of a larger NASA-funded project with the objective of using hyperspectral imagery to map acid-generating minerals that indicate or affect water quality. Additional water, sediment, and biological data were provided by the U.S. Geological Survey funded Central Colorado Assessment Project. The Lake Creek component of the project was designated as Phase 1. Phase 2, which is not discussed in this paper, focuses on the mainstem of the Arkansas River. Greater detail on interpretation of the geochemistry and imagery of both phases of the project is presented in Bird et al. (2005), Hauff et al. (2003a, 2003b) and Peters et al. (2004).

The Lake Creek watershed lies partially within the Grizzly Peak Caldera, which contains widespread hydrothermal alteration, low-grade, uneconomic, porphyry Cu-Mo deposits, and

Au-bearing quartz-pyrite veins (Cruson, 1973; Fridrich et al., 1991, 1998) with abundant sulfides and other minerals that produce ARD when weathered. Historical mining production in the study area has been limited to exploitation of small veins (Howell, 1919).

Water Quality

CGS and its cooperators sampled the Lake Creek watershed under both high (July) and low (September) flow conditions in 2001. Sample locations are shown on Figs. 2a through 2c.

The data reveal that the Lake Creek watershed is severely impacted by natural acid rock drainage and metal loadings from weathering of hydrothermally altered and mineralized rock associated with the Grizzly Peak Caldera. Source water chemistry includes pH of 2.5, dissolved metal concentrations of up to 277 mg/L Al, 498 mg/L Fe, and 10 mg/L Cu, and SO_4^{-2} as high as 3,400 mg/L (Table 1). The profile of total dissolved solids (TDS) (Fig. 3) illustrates the magnitude of the impact along the 36 kms of stream in the study area from the headwaters in Peekaboo Gulch downstream to Lake Creek's confluence with the Arkansas River.

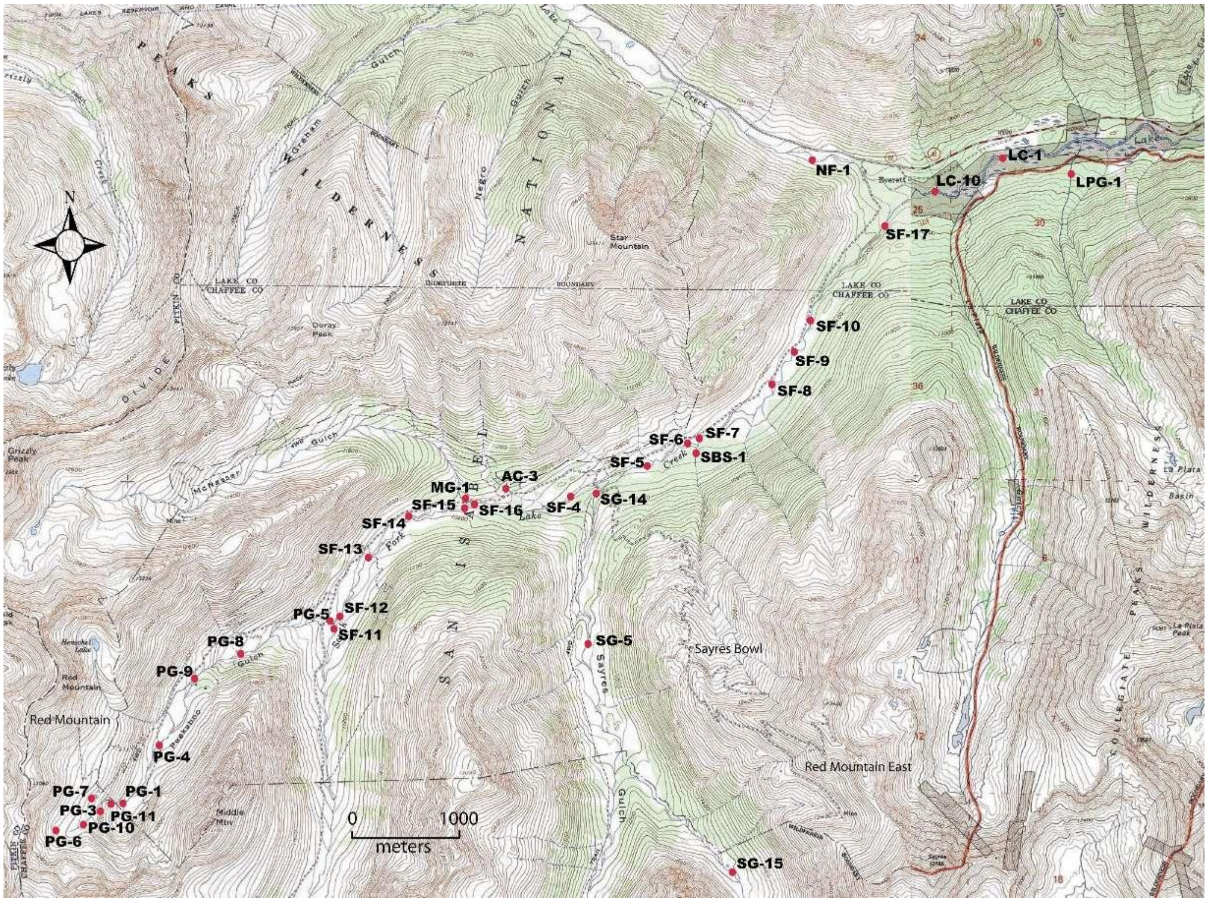

Figure 2a. Water sample locations from Peekaboo Gulch to South Fork Lake Creek.

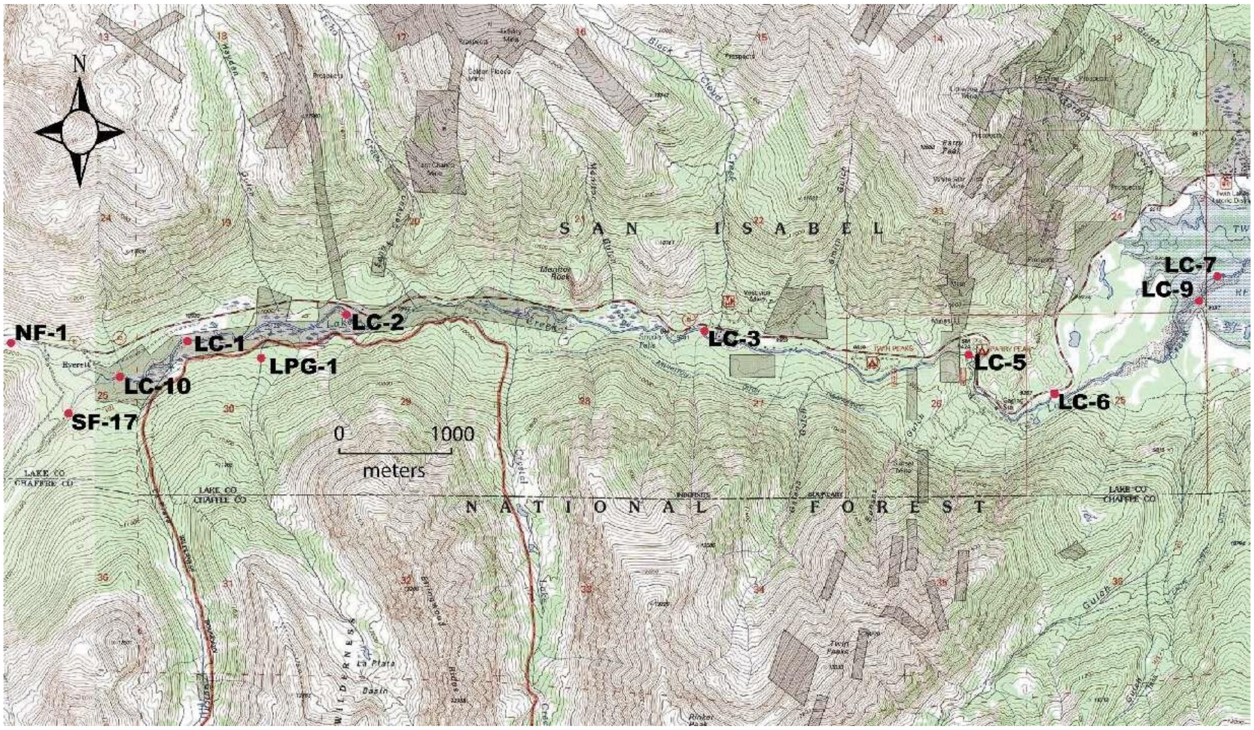

Figure 2b. Water sample locations in mainstem Lake Creek above Twin Lakes Reservoir.

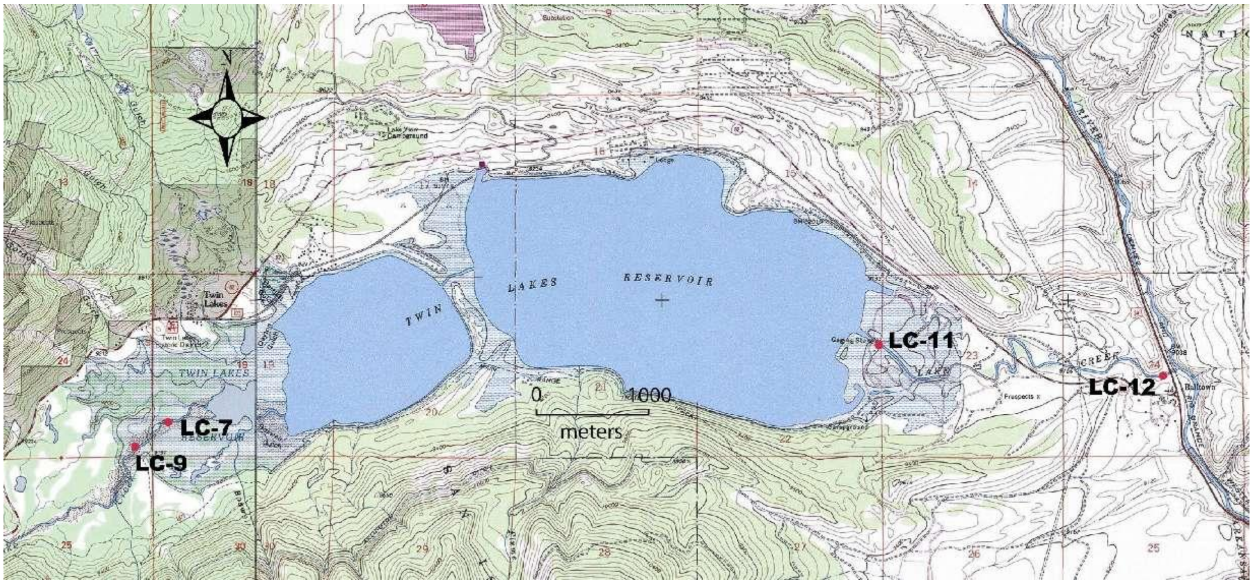

Figure 2c. Water sample locations in lower Lake Creek.

Table 1. Chemical compositions of source areas of natural acid rock drainage from Red Mountain and Red Mountain East.

Analyte	**Red Spring**	**White Spring**	**Sayres Gulch**	**Sayres Bowl**
pH	2.74	4.97	2.52	3.27
TDS (mg/L)	4,236	74	1,787	1,847
Al-total recoverable (mg/L)	284	3.2	101	101
Al-dissolved (mg/L)	277	1.6	101	103
Fe-total recoverable (mg/L)	486	169	114	152
Fe-dissolved (mg/L)	498	<50	105	146
SO_4 (mg/L)	3,400	59	1,500	1,500
Cu (µg/L)	10,000	160	7,730	6,520
Mn (µg/L)	446	63	1,230	1,580
Ni (µg/L)	75.4	1.9	323	327
Pb (µg/L)	<0.1	0.2	0.38	0.52
Zn (µg/L)	1,180	32	809	972

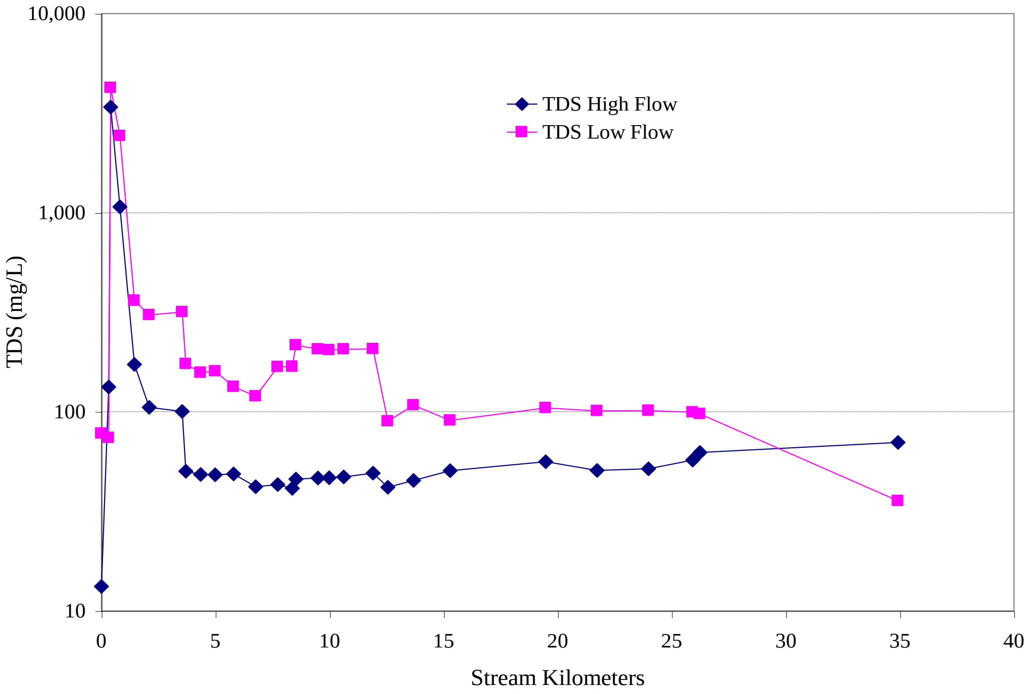

Figure 3. Profile of total dissolved solids in Lake Creek at high and low flow from Peekaboo Gulch to confluence with Arkansas River.

The highest concentration of TDS (4,236 mg/L at low flow) occurs just below the headwaters of the watershed in Peekaboo Gulch, where the impacts of the hydrothermal alteration are first seen. From that point downstream to the confluence with the Arkansas River, TDS decreases by a factor of about 100 due to the inflows from numerous dilute, circum-neutral, freshwater tributaries that cause the stream flow to increase from <1 cfs at the headwaters to 54 cfs at the confluence during low flow, and from 8 cfs at the headwaters to over 400 cfs at the confluence during high flow (Bird et al., 2005). The abundance of mineral precipitates coating the streambeds indicates that removal of constituents by precipitation also contributes to the reduction of TDS in the watershed.

Red Mountain (Fig. 4) and Red Mountain East (Fig. 5), two strongly mineralized and hydrothermally altered areas of the Grizzly Peak Caldera, are the primary sources of ARD and metals to Lake Creek. On Red Mountain, two springs informally named the Red Spring and the White Spring (Fig. 4), due to the colors of the associated mineral precipitates, are the dominant surface sources of ARD released to the watershed. The primary sources of ARD on Red Mountain East are an active ferrosinter bog in Sayres Gulch (Fig. 6), and springs emerging from altered bedrock, colluvium, and talus in Sayres Bowl (Fig. 7). None of the ARD originating anywhere within the study area is associated with anthropogenic disturbances such as mine shafts, waste rock piles, or tailings deposits.

The impacts to pH and TDS due to the inflows to Lake Creek from Red Mountain, Sayres Gulch, and Sayres Bowl are shown on Figs. 8a and 8b. With the lone, unexplained exception of Sayres Bowl at high flow, the impacts of ARD under low flow conditions are more pronounced at all confluences, resulting in pH decreases and TDS increases. Most notably, the Red Mountain discharge causes a TDS increases by more than a factor of three and a pH drops of nearly two units.

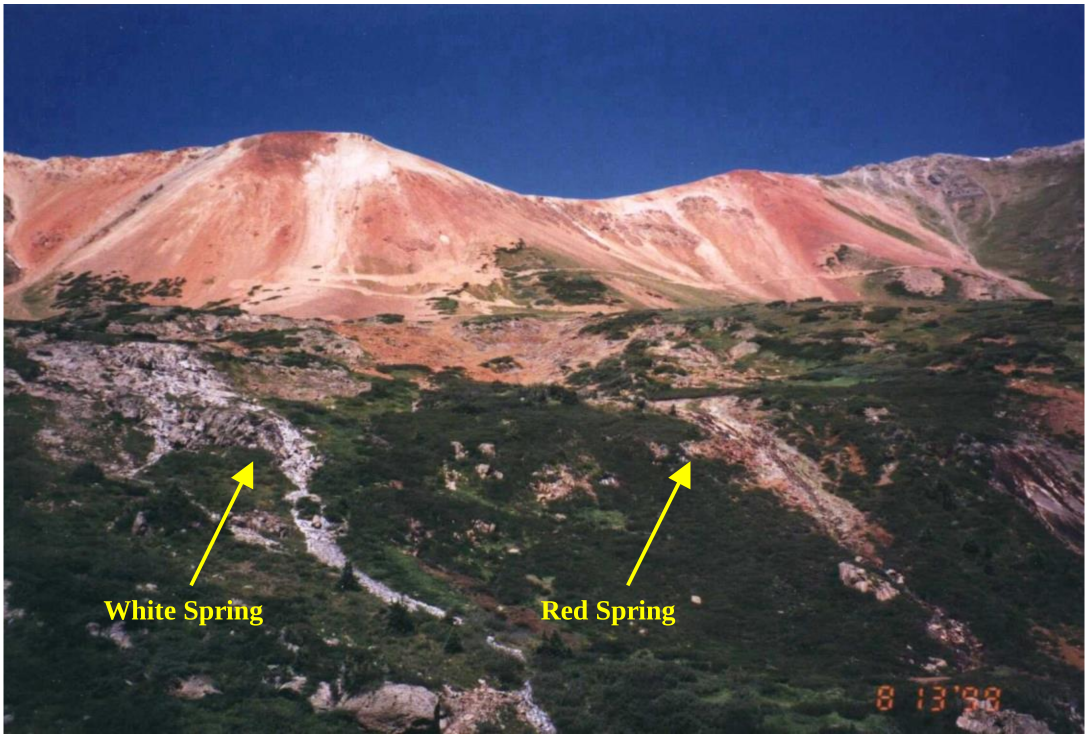

Figure 4. Red Mountain, looking west, showing White Spring and Red Spring.

Figure 5. Red Mountain East, looking southeast.

Figure 6. Ferrosinter bog in Sayres Gulch on Red Mountain East.

Figure 7. Springs emerging from hydrothermally altered bedrock and talus in Sayres Bowl on Red Mountain East.

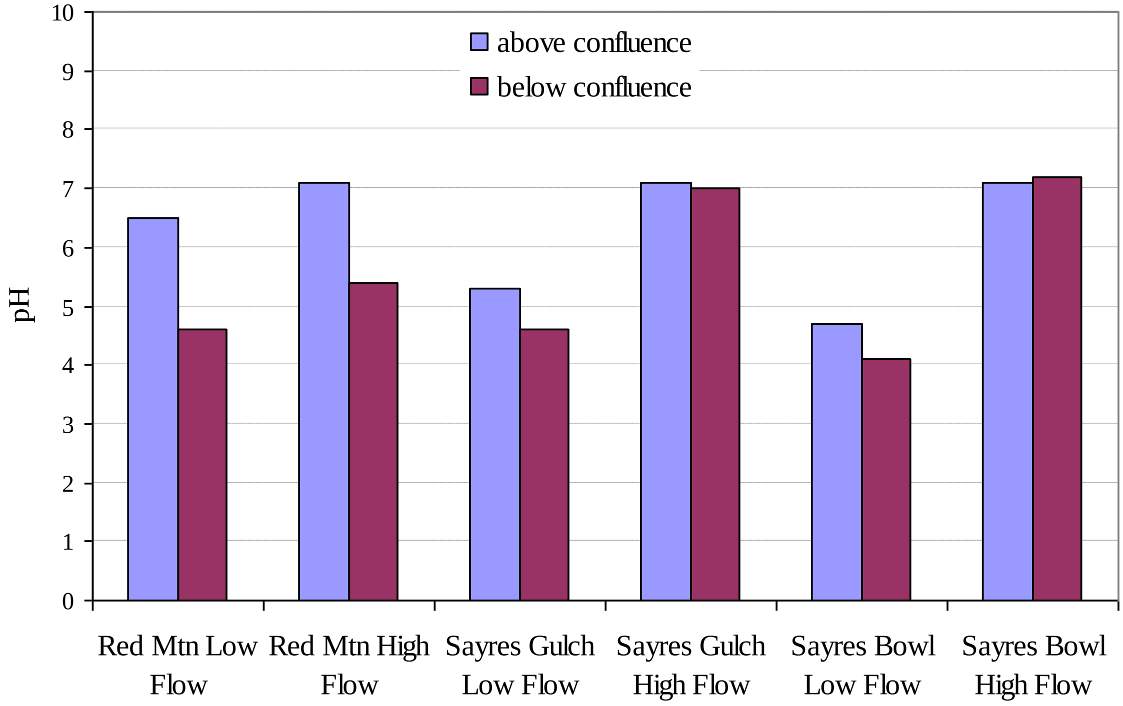

Figure 8a. Change in pH at confluences in Lake Creek watershed.

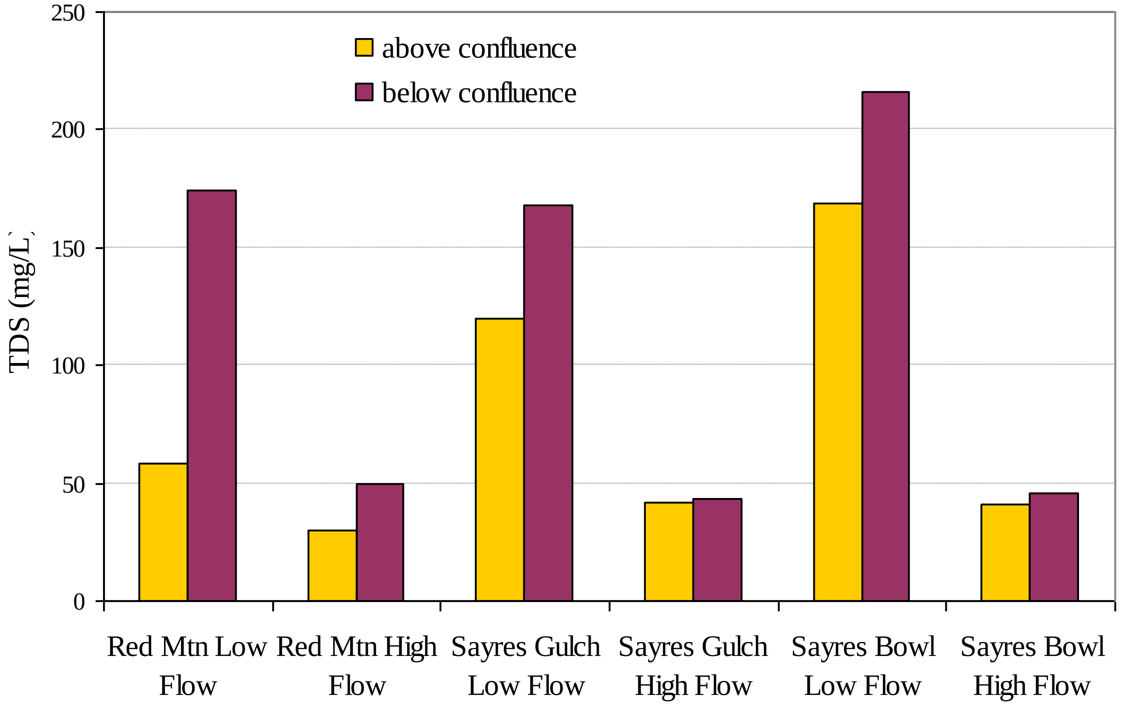

Figure 8b. Change in total dissolved solids (TDS) at confluences in Lake Creek watershed.

The pH of the Lake Creek watershed behaves quite differently depending on flow conditions (Fig. 9). Under both high and low flow, the pH at the headwater source is near neutral, but plummets sharply to below 3 under both flow regimes due to the discharge from Red Mountain. At high flow, the influence of snowmelt causes dilution and neutralization of the pH to 6.7 immediately downstream from the confluence of Peekaboo Gulch with South Fork Lake Creek, and the pH stays neutral over the entire remainder of the Lake Creek reach. However, at low flow, the lack of snowmelt allows the creek to remain acidic for a much greater reach of over 11 kms, until the inflow from North Fork Lake Creek (site LC-10) raises the pH to 6.9 (note: the aberration in pH at LC-10 is explained in Bird et al., 2005).

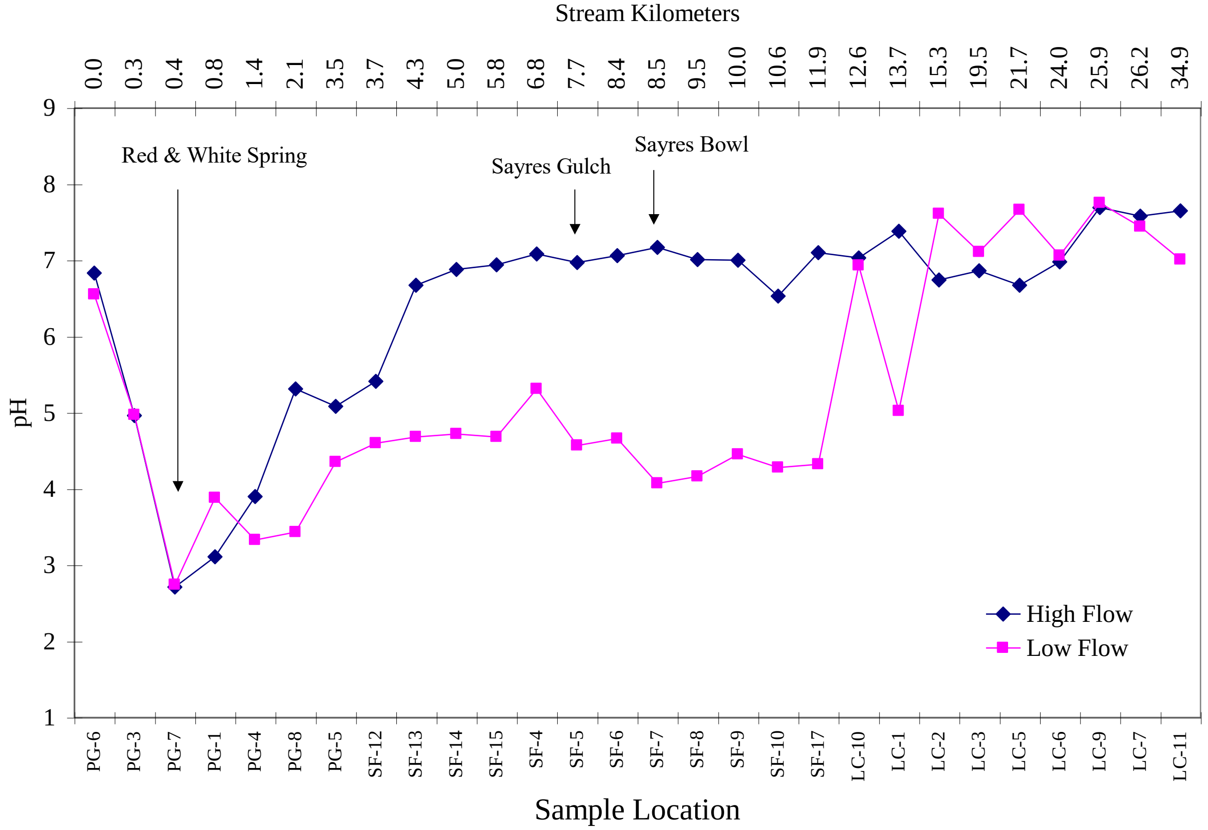

Figure 9. Profile of pH in Lake Creek at high and low flow from Peekaboo Gulch to confluence with Arkansas River.

Trace-Metal Concentrations

The Lake Creek watershed carries relatively high concentrations of dissolved trace metals over significant lengths of stream reach (Fig. 10), and the impact of the primary ARD sources is apparent. Above Red Mountain, the stream is pristine with neutral pH and largely undetectable trace metal concentrations. Discharge from Red Mountain causes a marked increase in the concentrations of several trace metals, by two or more orders of magnitude for all metals shown on Fig. 10 with the exception of cadmium. From Red Mountain downstream to the inflow to Twin Lakes Reservoir, the stream is visibly impaired with the effects of ARD, including voluminous mineral precipitates (Fig. 11).

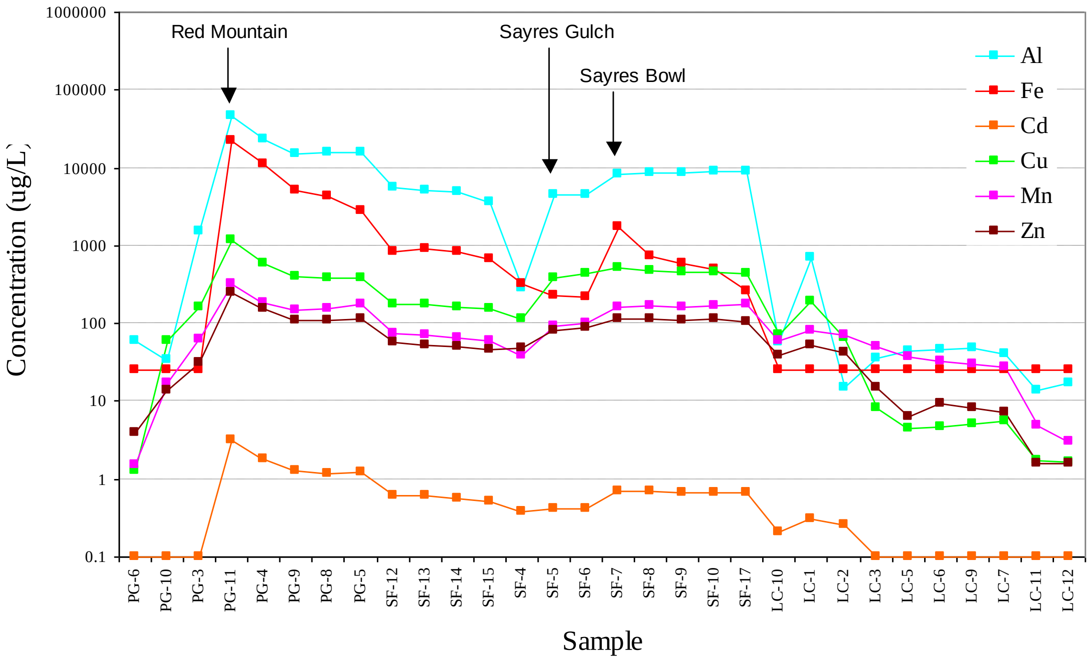

Figure 10. Profile of selected dissolved trace-element concentrations in Lake Creek watershed at low flow from Peekaboo Gulch to confluence with Arkansas River.

Upward concentration spikes occur at the inflows from Sayres Gulch (SF-5) and Sayres Bowl (SF-7), due to the releases from Red Mountain East. Between the inflows from the primary source areas of Red Mountain, Sayres Gulch, and Sayres Bowl, the stream shows the capability to naturally attenuate, due to the numerous freshwater tributary inflows from unmineralized areas, and possibly ground-water inflow. Downstream from the confluence with North Fork Lake Creek, pH trends toward neutral at both high and low flow (Fig. 9), the dissolved metals are gradually attenuated (Fig. 10), and the most visible impact to the watershed is the volume of mineral precipitates coating the streambed (Fig. 11). Along the Lake Creek reach, all dissolved trace-element concentrations are greatly reduced, and several drop to undetectable concentrations, coincident with the onset of sustained neutral pH conditions.

Water Quality Standards

Bird et al. (2005) briefly discuss the concentrations of various constituents in the context of aquatic life criteria and how the chronic toxicity threshold is influenced by metals concentrations. Until recently however, no biological data were available to relate the water- and sediment-quality data to biotic communities. As would be expected, dilution improves water quality, reduces the impact of ARD, and decreases the frequency and magnitude to which various constituents exceed water quality standards. Under low flow conditions, some constituents exceeded the Colorado state water quality standards for aquatic life (available online at http://www.cdphe.state.co.us/regulate.asp) over a greater reach than during high flow. Examples are presented for dissolved Al (Fig. 12), dissolved Fe (Fig. 13), and dissolved Zn (Fig. 14); other constituents display similar patterns.

Figure 11. Mineral precipitates coating streambed and banks of Lake Creek (photo taken near water sample site SF-7, just downstream from Sayres Bowl inflow).

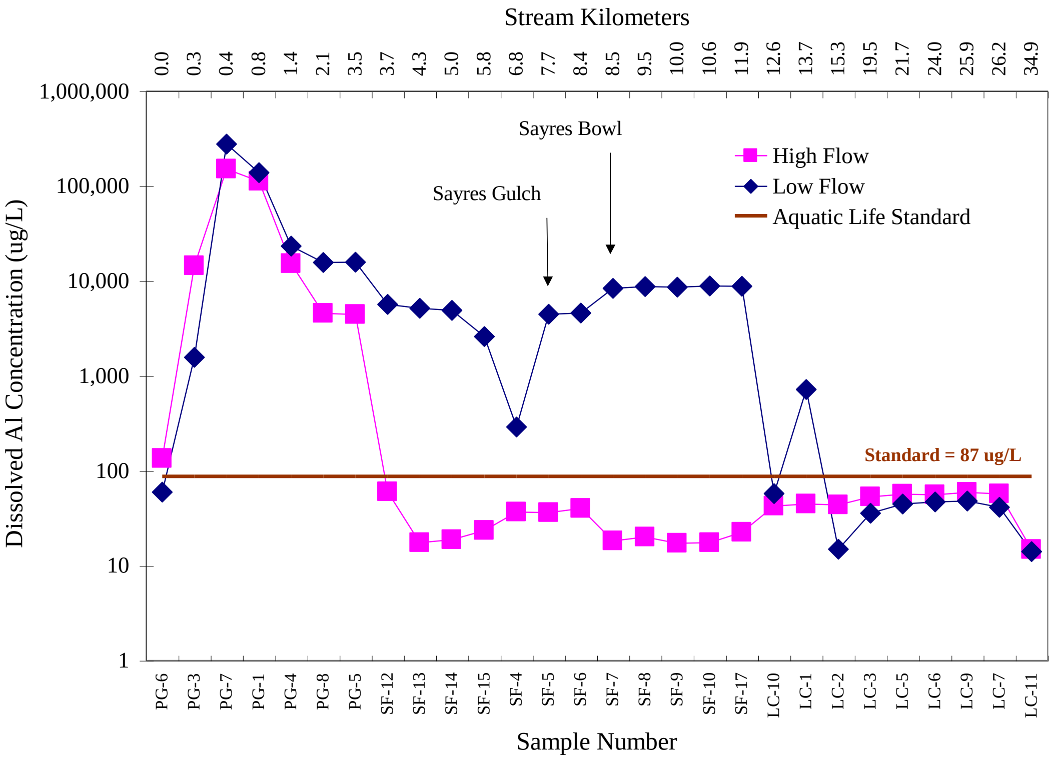

Figure 12. Profile of dissolved aluminum in Lake Creek watershedat high and low flow versus water quality standard of 87 µg/L.

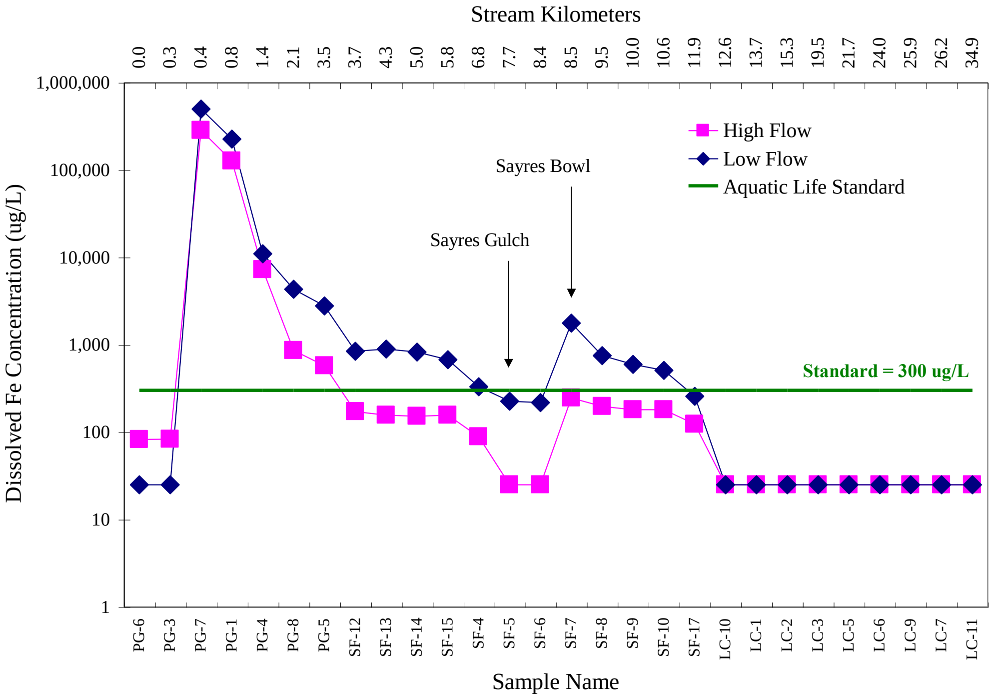

Figure 13. Profile of dissolved iron in Lake Creek watershed at high and low flow versus water quality standard of 300 µg/L.

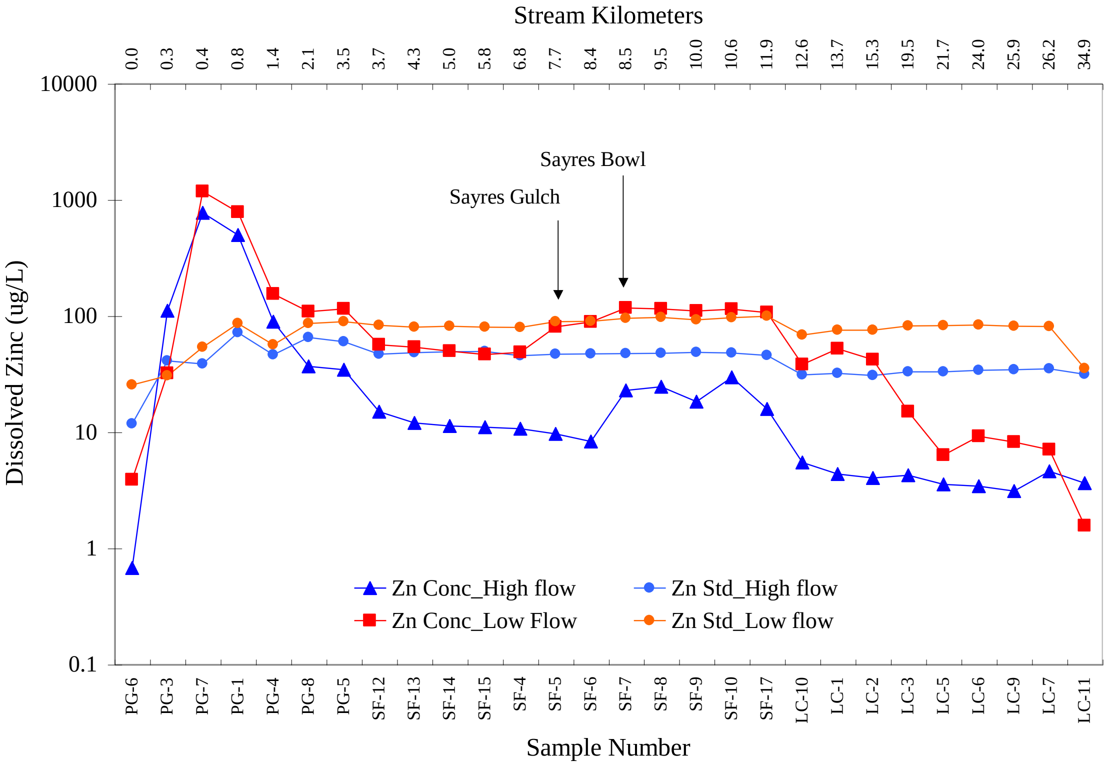

Figure 14. Profile of dissolved Zn in Lake Creek watershed versus **h**ardness-dependent water quality standards.

As Fig. 12 shows, dissolved Al exceeds the standard of 87 µg/L at low flow over the entire reach above the North Fork Lake Creek confluence. At high flow, dilution lowers the concentration such that the standard for dissolved Al was exceeded only in Peekaboo Gulch. Similar patterns exist for dissolved iron (Fig. 13) and dissolved zinc (Fig. 14). At high flow, Fe and Zn exceeded their respective water-quality standards only in Peekaboo Gulch, whereas at low flow they exceeded the quality standards well into South Fork Lake Creek.

Streambed Sediment Geochemistry

The U.S. Geological Survey collected sediment, water and biological data in 2004 (Table 2). Additional sediment data collected in 1994 (Church et al, 1994) are included to show that there has been little or no change in metal concentrations over either the period of low flow sampled in 2004, or the decade spanned by the data sets. Streambed sediment samples were collected over a 10-m reach of streambed; samples were composited from a minimum of five separate localities along the reach. Samples were sieved to <2mm in the field, dried and split in the laboratory, and sieved to minus 80 mesh. ICP-AES analyses were completed on total digestions (HCl, HNO_3. $HClO_4$, and HF; Briggs, 1996) of 0.2g of material. The data from Lake Creek and tributaries thereto are plotted against downstream distance in Fig. 15. Concentrations of metals in sediment from acidic streams are low because the pH of these streams is low (Fig. 9) and metals released by weathering of the hydrothermally altered areas are dissolved. When mixed with near-neutral water from unaltered areas of the Lake Creek drainage, iron colloids form a substrate for trace metals to sorb as pH increases (Smith et al., 1999). A fraction of these colloids settle out and become part of the stream sediment. Dilution of the abundance of the Fe colloids by uncontaminated sediment from upstream drainage basins (Table 2) results in lower concentrations of metals in the sediment as a function of downstream distance. Sediment from upper Twin Lake contains very diluted metal concentrations and shows that the lakebed sediment is not a sink for iron colloids, rather they are flushed through the lakes and into the Arkansas River.

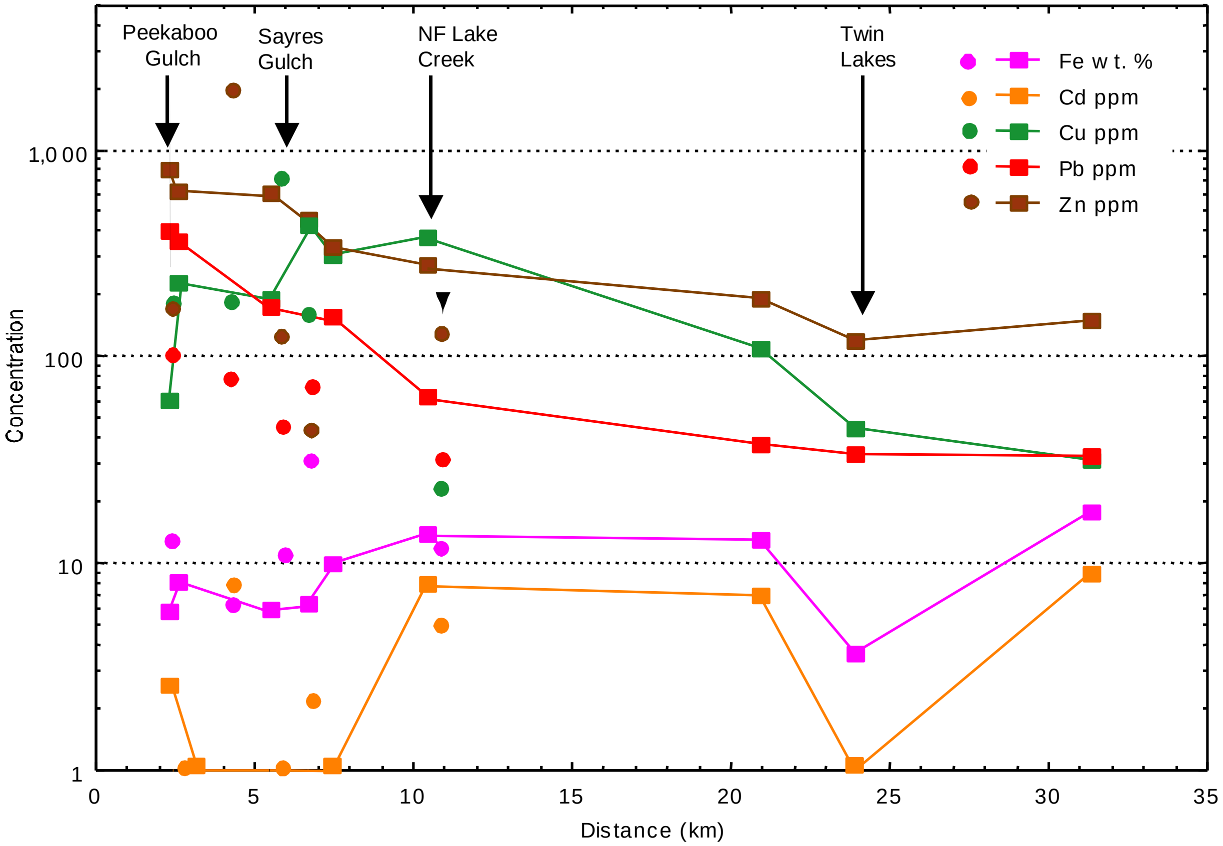

Figure 15. Metal concentrations in sediment from Lake Creek and selected tributaries. Concentrations of metals measured in sediment from Lake Creek are indicated by the filled squares joined by tie lines whereas data from the tributaries are shown as filled circles. Concentrations of metals are shown in different colors plotted versus downstream distance.

Concentrations of metals in streambed sediment of Lake Creek exceed the Probable effects Concentration (PEC) or threshold values recommended by MacDonald et al. (2000) for measurable effects on sensitive aquatic species. The sites where the PEC was exceeded are shown in Table 2 by gray shading. Copper, which has been shown to be most detrimental to trout, (Besser et al., 2006; Farag et al., 2004) exceeds the PEC at every site on Lake Creek, whereas Pb and Zn exceed the PEC in streambed sediment only upstream from Sayres Gulch (Table 2).

Table 2. Geochemical data from streambed sediment, Lake Creek, Colorado (sites where the PEC was exceeded are shown by gray shading).

Site	Date Collected	Distance (km)	Fe wt. %	Al wt. %	Mn ppm	Cd ppm	Cu ppm	Pb ppm	Zn ppm	Mo ppm
North Fork Lake Creek	21-Jul-04	1.0	7.0	7.2	1,350	<2	12	36	89	<2
North Fork Lake Creek	21-Jul-04	1.0	4.8	6.4	980	<2	11	36	86	5.1
Graham Gulch	21-Jul-04	1.0	9.1	6.8	773	<2	22	42	98	<2
South Fork Lake Creek USF PBG	22-Jul-04	2.3	5.9	6.8	1,690	2.6	62	407	812	<2
Peekaboo Gulch	22-Jul-04	2.4	12.7	6.0	422	<2	178	103	169	10
Peekaboo Gulch	2-Sep-04	2.4	14.0	6.2	450	<2	179	115	163	13
South Fork Lake Creek DSF PBG	2-Sep-04	2.6	8.2	7.3	1,330	<2	227	363	638	7
South Fork Lake Creek DSF PBG	22-Jul-04	2.6	8.0	6.6	1,300	2	170	362	660	3.8
McNasser Gulch	22-Jul-04	4.3	6.3	6.5	2,520	8.1	182	79	1,960	<2
South Fork Lake Ck, USF Sayres Gulch	2-Sep-04	5.5	6.0	7.7	1,250	<2	193	176	615	2.8
Sayres Gulch	2-Sep-04	5.9	11.1	7.6	427	<2	722	46	127	44
South Fork Lake Ck, DSF Sayres Gulch	2-Sep-04	6.7	6.4	8.0	1,220	<2	470	163	432	6.7
unnamed ck DSF Sayrs Gulch	2-Sep-04	6.8	31.5	2.4	120	2.2	149	71	45	4.6
South Fork Lake Ck @ USFS Boundary	3-Sep-04	7.4	10.1	7.5	895	<2	312	158	342	13
South Fork Lake Creek	25-Sep-94	10.4	14.0	6.4	910	8	380	64	280	<2
North Fork Lake Creek	25-Sep-94	10.9	12.0	6.3	1,200	5	23	32	130	<2
Lake Creek at USGS gauge	25-Sep-94	20.9	13.0	6.4	1,100	7	110	38	190	<2
Sediment from upper Twin Lake	25-Sep-94	23.9	3.7	6.8	510	<2	45	34	120	<2
Lake Creek DSF Twin Lakes Reservoir	25-Sep-94	31.3	18.0	5.6	2,200	9	32	33	150	<2
Confluence with Arkansas River		35.0								
Consensus sediment quality values (PEC, MacDonald et al., 2000)						**4.98**	**149**	**128**	**459**	

Biota

Data for aquatic vertebrate and invertebrate biomass distribution in the Lake Creek watershed were obtained at low flow in 2004 to allow an assessment of the effects of water and sediment quality on biota in the watershed. The data come from a combination of existing surveys conducted in the past eleven years and new surveys conducted in the summer of 2005. For the vertebrate biota (trout), comparisons are presented between biomass (kilograms per hectare) and the ratio of the concentration of the chemical constituent to its aquatic life water quality standard, and between biomass and pH. For the invertebrates, comparisons are presented between the abundance and the concentration of various constituents and between the abundance and pH.

Trout Biomass

In mid-September 2005, the Colorado Division of Wildlife (DOW), with CGS, the U.S. Forest Service (USFS), and Trout Unlimited participating, conducted electrofishing surveys (Fig. 16) at locations corresponding to five of the CGS water quality sampling sites in the Lake Creek watershed (see Bird et al., 2005). Additionally, the USFS had also conducted electrofishing surveys in early and mid September 2005 at selected locations in the watershed that were also in close proximity to CGS water quality sample sites. Electrofishing data collected in the mid and late 1990's by DOW near other key CGS sample locations were also incorporated.

Figure 16. Electro-fishing survey on Lake Creek in September 2005.

All of the electro-fishing surveys were conducted during low flow conditions utilizing Smith-Root manufactured electro-fishing equipment. A pulsed, direct current was used to momentarily stun fish for capture. Fish were weighed and length determined by species and returned to the water unharmed. A two-pass removal methodology was used to estimate population biometrics.

Brook, cutthroat, and rainbow trout were collected during the surveys. The sample locations and the associated data are reported in Table 3. The number of trout collected at each site ranged from zero to 144. The size ranged from fry up to a maximum length of 36 cm with a maximum weight of 474 g, which was a stocker Rainbow Trout that we suspected had migrated up from Twin Lakes. The largest Brook Trout taken was 31 cm long and weighed 401 grams. The two largest trout taken during the survey were from areas of Lake Creek above Twin Lakes that were visibly impaired with mineral precipitates.

Table 3. Trout Biometrics Data

Location of Survey (nearest water sample site)	**Date of Survey**	**Length of Surveyed Reach (m)**	**Number of Trout**	**Trout Biomass (Kg/Ha)**
Above SF-11	22 Aug 94	205	33	44.4
SF-11	09 Sep 05	84	27	54.0
MG-1	24 Aug 94	53	2	11.2
SG-15	30 Sep 98	183	29	18.8
SG-7	23 Aug 94	85	0	0
SF-5	24 Aug 94	96	0	0
SF-9	14 Sep 05	107	0	0
Above NF-1	16 Sep 05	66	64	199.8
NF-1	14 Sep 05	128	30	14.4
LC-1	15 Sep 05	139	0	0
LC-3	14 Sep 05	121	4	1.9
LC-6	15 Sep 05	141	5	11.2
LC-11	15 Sep 94	151	144	40.1

Figs. 17-21 show trout biomass as a function of the aquatic life water quality standard for dissolved Al, Cu, Ni, and Zn, and total-recoverable Fe; Fig. 22 shows biomass as a function of pH. Figs. 17-21 show the measured trout biomass (kilograms of trout per surface hectare of stream) versus the ratio of the metal’s concentration to its aquatic life standard. The Al chronic toxicity standard is 87 µg/L. For the other four metals shown, the chronic toxicity standard referenced is a function of hardness, and follows the general formula:

$$\text{Standard} = (A-(\ln(\text{hardness})*B)) * e^{(C*\ln(H) + D)}$$

where:

A, B, C, and D are empirically derived constants depending on the metal,

H = hardness, calculated from the concentrations of calcium and magnesium, and

ln = natural log

The standards and their associated formulae can be found online on the Colorado Department of Public Health and Environment website at:

http://www.cdphe.state.co.us/op/regs/waterregs/100231basicstandards1205and1207.pdf

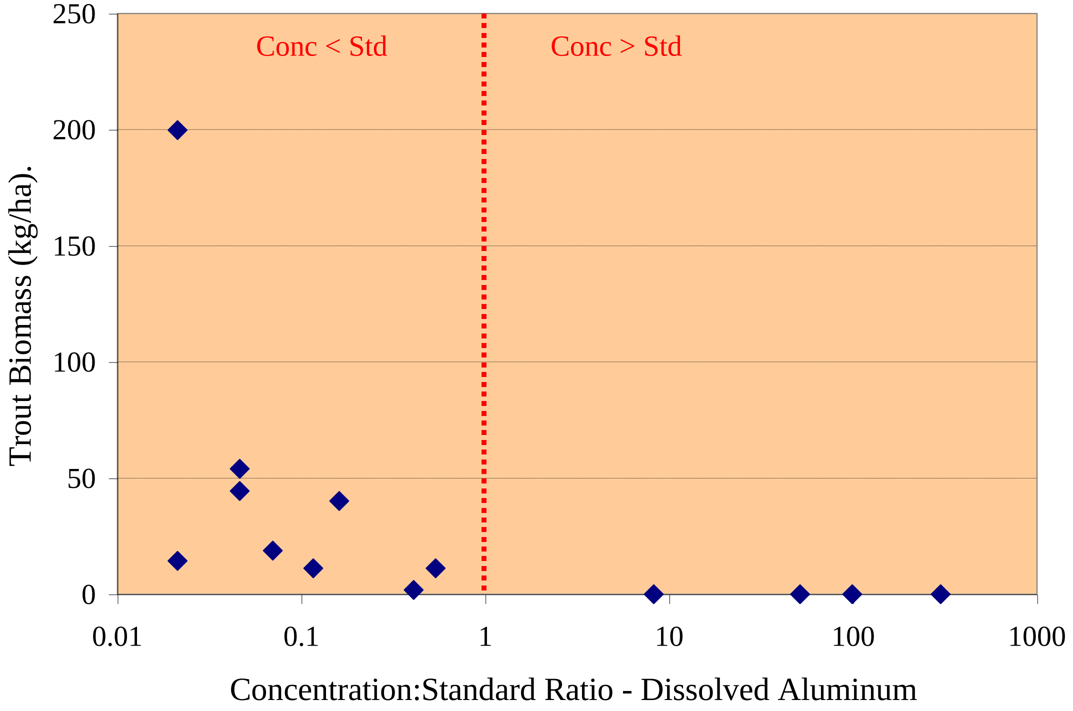

Figure 17. Trout biomass versus ratio of dissolved Al concentration to aquatic life standard.

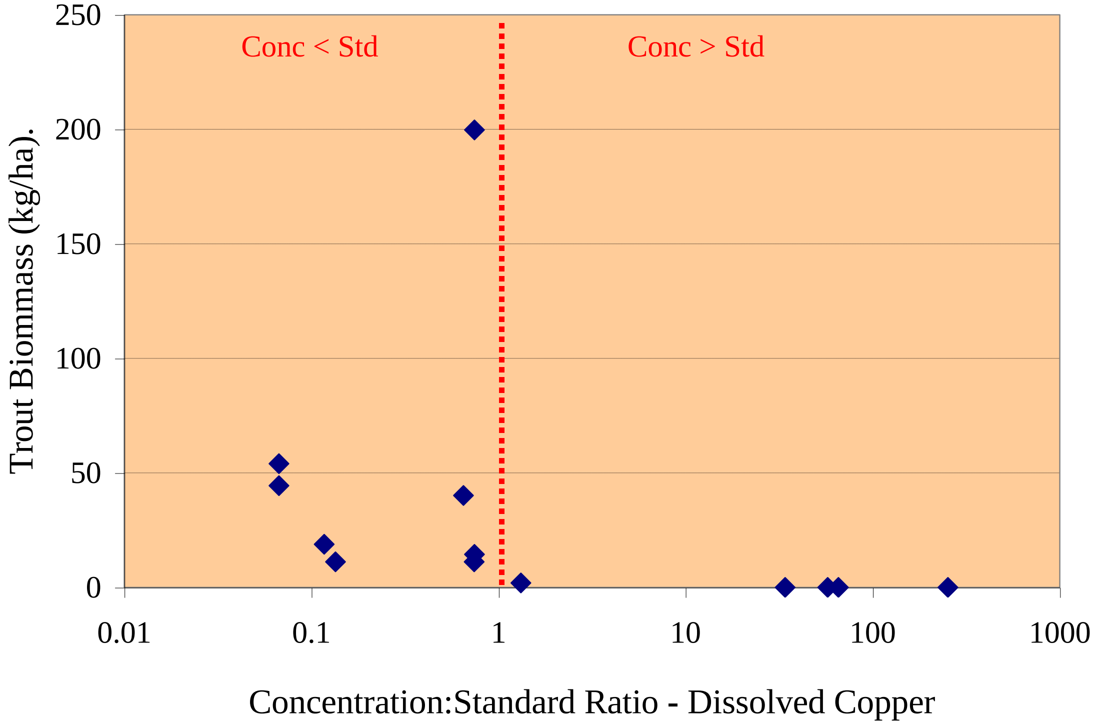

Figure 18. Trout biomass versus ratio of dissolved Cu concentration to aquatic life standard.

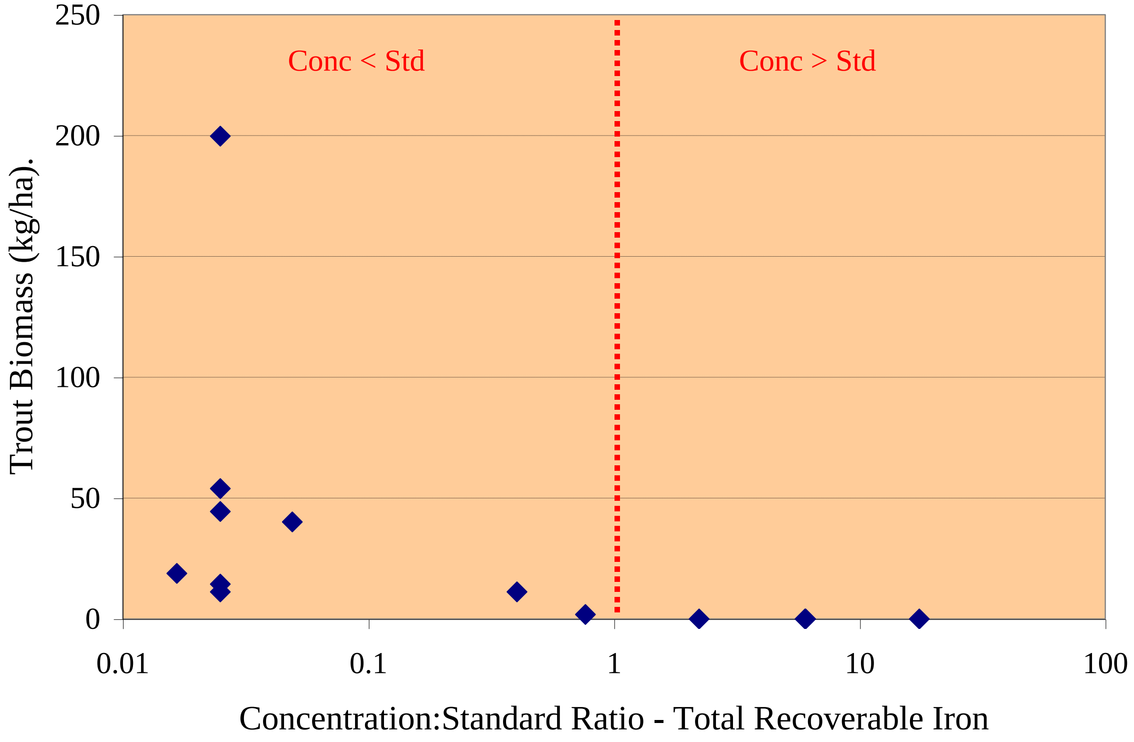

Figure 19. Trout biomass versus ratio of total recoverable Fe concentration to aquatic life standard.

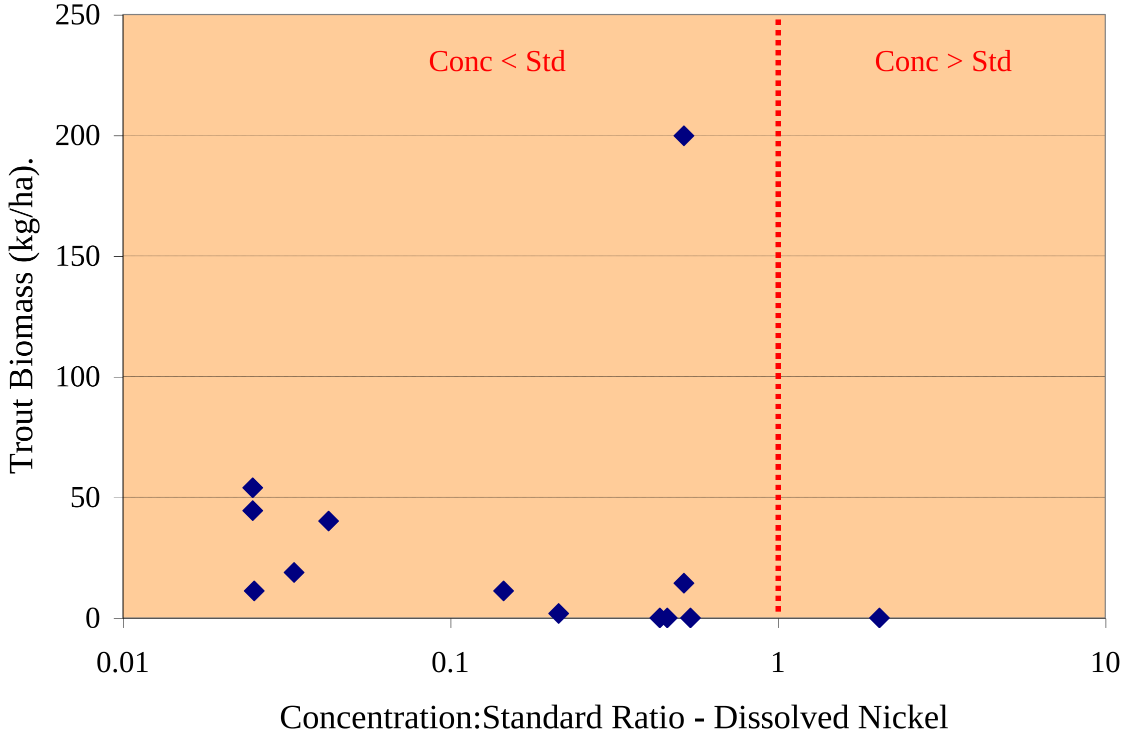

Figure 20. Trout biomass versus ratio of dissolved Ni concentration to aquatic life standard.

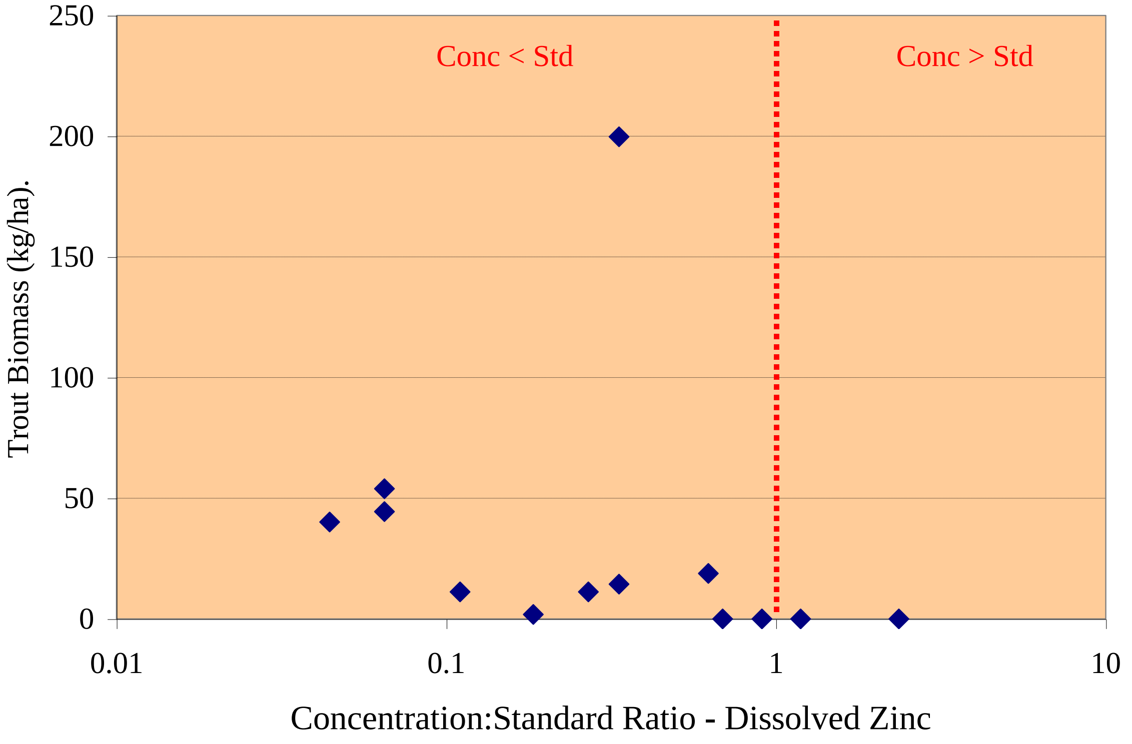

Figure 21. Trout biomass versus ratio of dissolved Zn concentration to aquatic life standard.

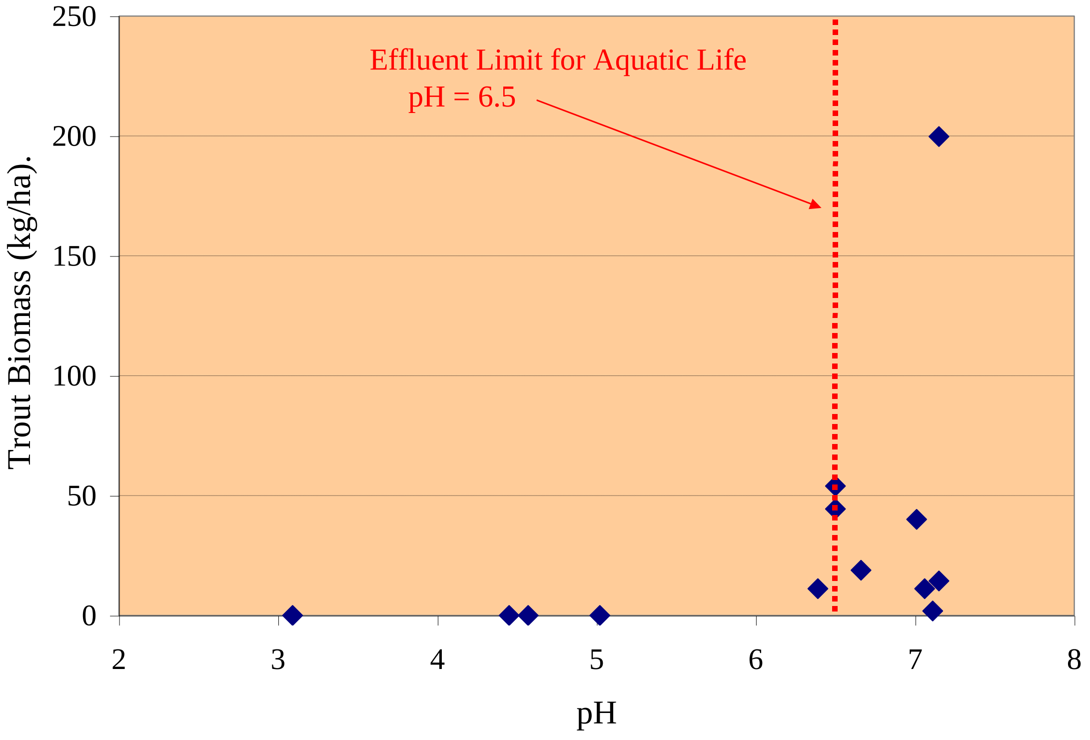

Figure 22. Trout biomass versus pH.

The data show a strong relationship between metals toxicity and trout abundance. As expected, trout are absent or severely impacted where metal concentrations exceed standard or where pH is low (SF-9, LC-1, LC-3, LC-6, SF-5, SG-7). Furthermore, there is little downstream recovery, as evidenced by relatively low trout populations at the two lowest sites above Twin Lakes (LC-3 and LC-6). Trout are abundant at most survey sites that lie upstream from sources of metals to the watershed (NF-1, above NF-1, MG-1, SF-11, above SF-11, SG-15), and below Twin Lakes where metal contamination is ameliorated (LC-11).

Hydrological impacts on the fish population are also evident. Trout biomass below Graham Gulch (3.4 km upstream from site NF-1) is significantly less than biomass above Graham Gulch (site "above NF-1). North Fork Lake Creek above Graham Gulch supported a biomass 199.8 kg/ha trout, stream below Graham Gulch the biomass was only 14.4 kg/ha. Trans-mountain diversion water enters the system in Graham Gulch. Extreme spring/summer flows are common and channel modification has occurred within the watershed from Graham Gulch down to Twin Lakes (e.g., channel braiding and instability, gravel bar deposition, scouring). High flows likely impact fishery viability below Graham Gulch through habitat alteration, but are secondary to the effects of metal contamination.

Invertebrate Biomass

A sampling program for aquatic invertebrates was done independently of the NASA-funded portion, by CSU personnel working cooperatively with the USGS to ascertain the influence of catchment geology on invertebrate populations such as caddisflies, mayflies, and stoneflies. All invertebrate sampling data were collected by T.S. Schmidt in August of 2004, at sites on North and South Fork Lake Creek shown on Fig. 23. Replicate benthic macroinvertebrate samples (*n*=5) were collected using a 0.1-m^2 Hess sampler (350-µm mesh net) from shallow riffle areas (<0.5 m). The substrate was disturbed to a depth of approximately 10 cm, removed, and the remaining material was sieved using a 350 µm-mesh sieve. All organisms retained were preserved in 80 percent ethanol in the field. In the laboratory, samples were sorted and organisms were identified to the lowest practical taxonomic level (genus or species for most taxa; subfamily for chironomids).

Selected results of this study are shown on Figs. 24-28. Figs. 24-26 plot invertebrate abundance (the number of individuals collected during a sampling event) against the filtered (0.45-micron) concentrations of Cd, Cu, and Zn, Fig. 27 plots abundance versus pH, and Fig. 28 plots abundance versus conductivity, which is analogous to TDS. In general, the results depict a very depaupreate community that is impaired when compared with stream sites that are not influenced by ARD. Although invertebrate abundance is a highly variable metric, average abundances of invertebrates from Colorado mountain streams not affected by ARD would be two to three orders of magnitude greater than those observed in the Lake Creek watershed (T.S. Schmidt, unpub. data, 2004). Acidic pH is known to impair aquatic invertebrate communities. However, a number of sites were observed to have impaired communities even though pH was circum-neutral. Nearly all the sites had concentrations of Cu and Zn that exceeded the criteria for the preservation of aquatic life, which includes both vertebrate and invertebrate aquatic life (note: the USEPA ambient water quality criteria are designed to be protective of 95 percent of aquatic genera; U.S. Environmental Protection Agency, 1993; Stephan et al., 1985). Because aquatic invertebrates are generally sessile organisms moving very little throughout their life span, they are good time-integrators of water quality conditions that may predominate at a particular location. The results presented here suggest that the impairment of the aquatic invertebrate communities of Lake Creek is not solely the result of acidic pH, but also that concentrations of both dissolved and sediment-borne trace-metals at these locations have impacted aquatic invertebrate life throughout the year.

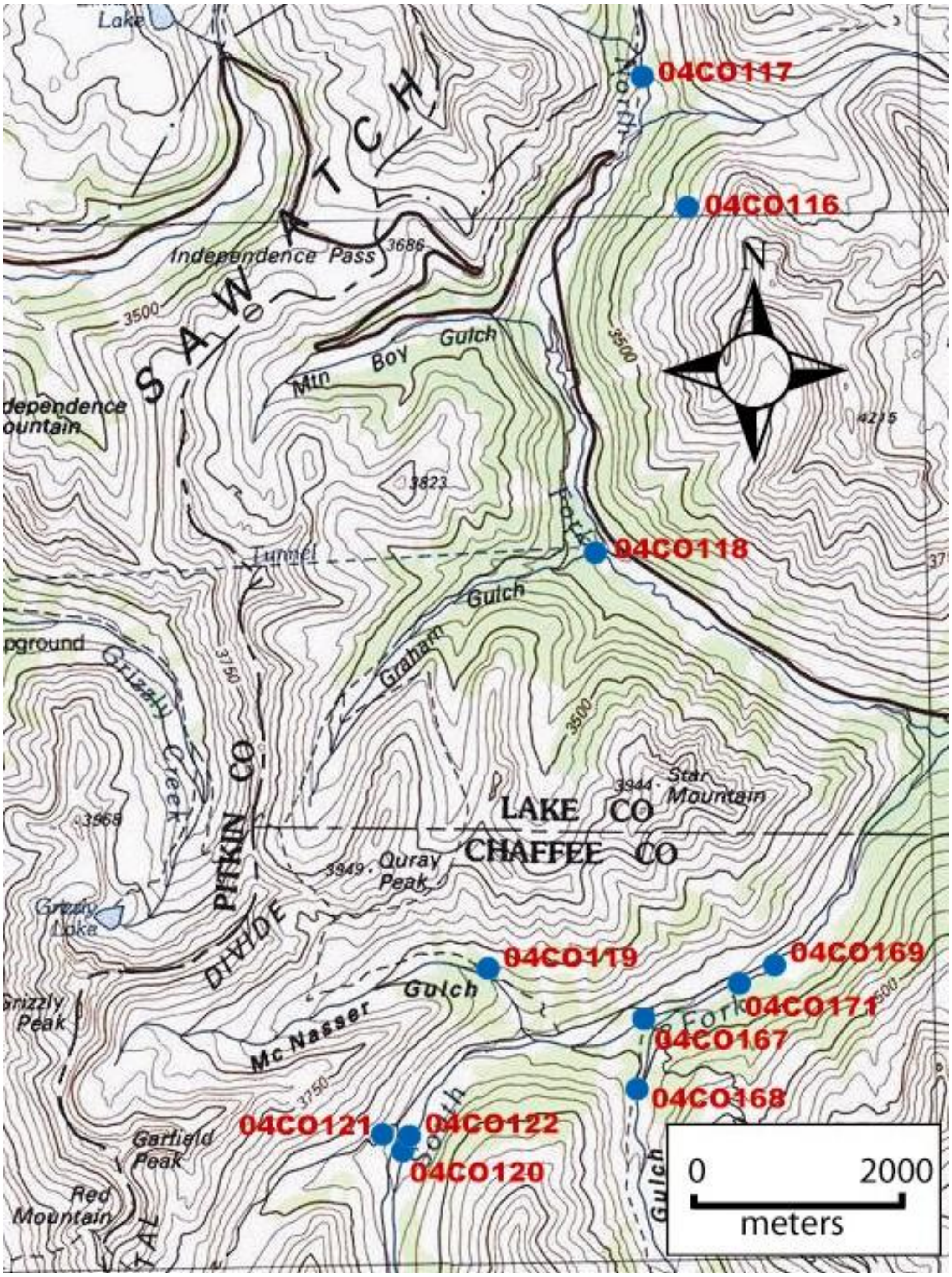

Figure 23. Locations of invertebrate sampling sites.

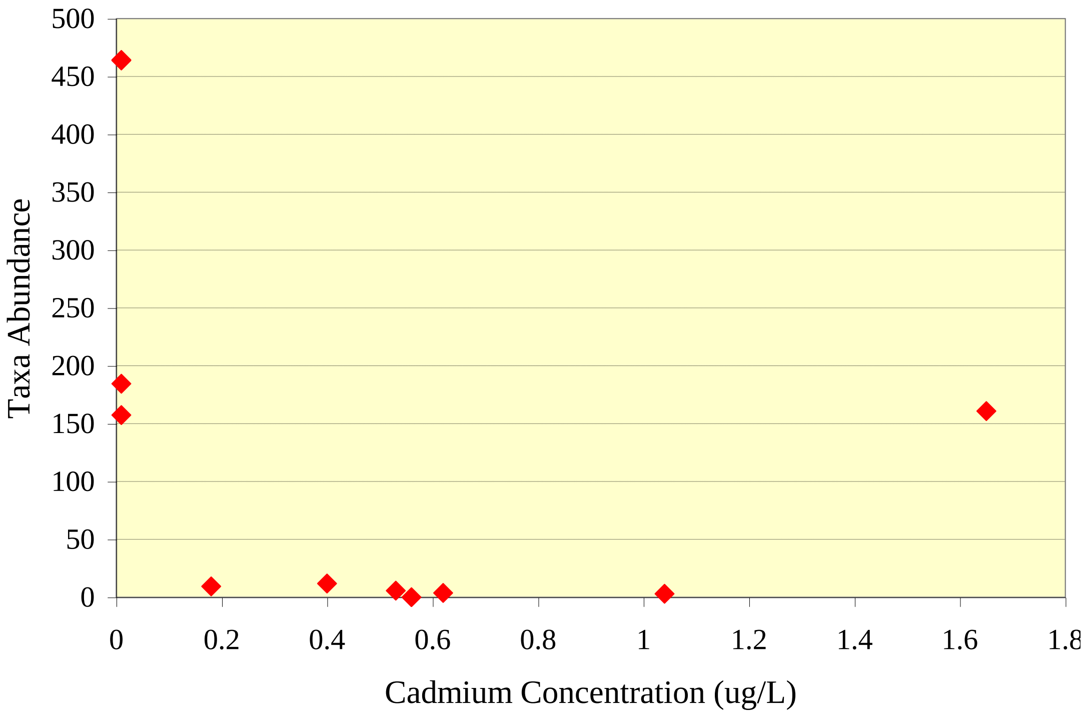

Figure 24. Invertebrate abundance versus Cd concentration.

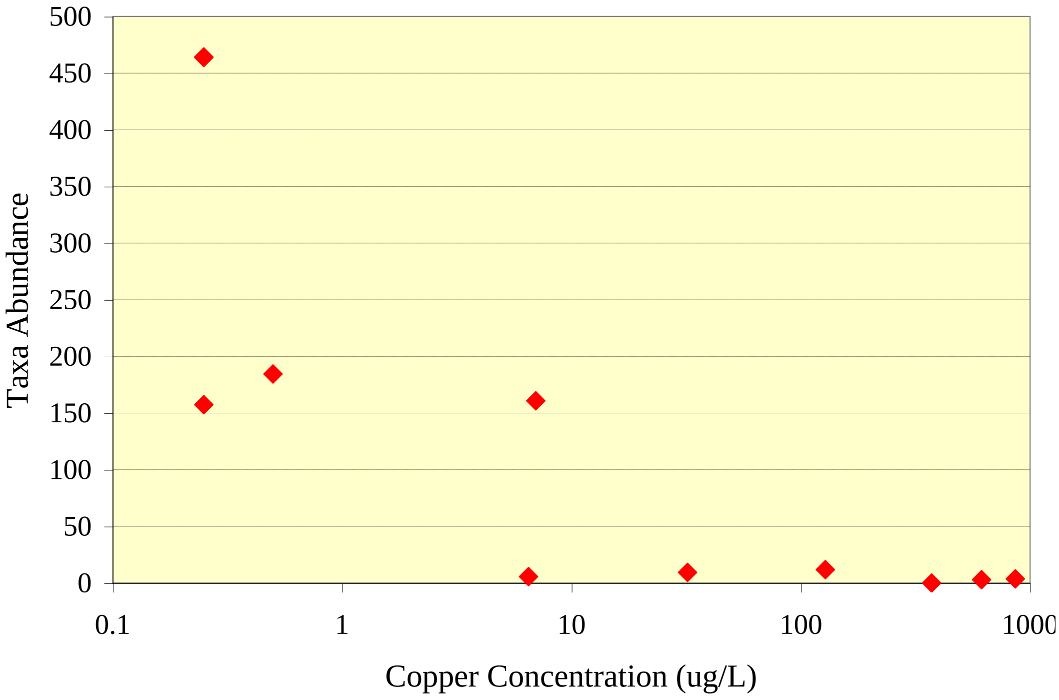

Figure 25. Invertebrate abundance versus Cu concentration.

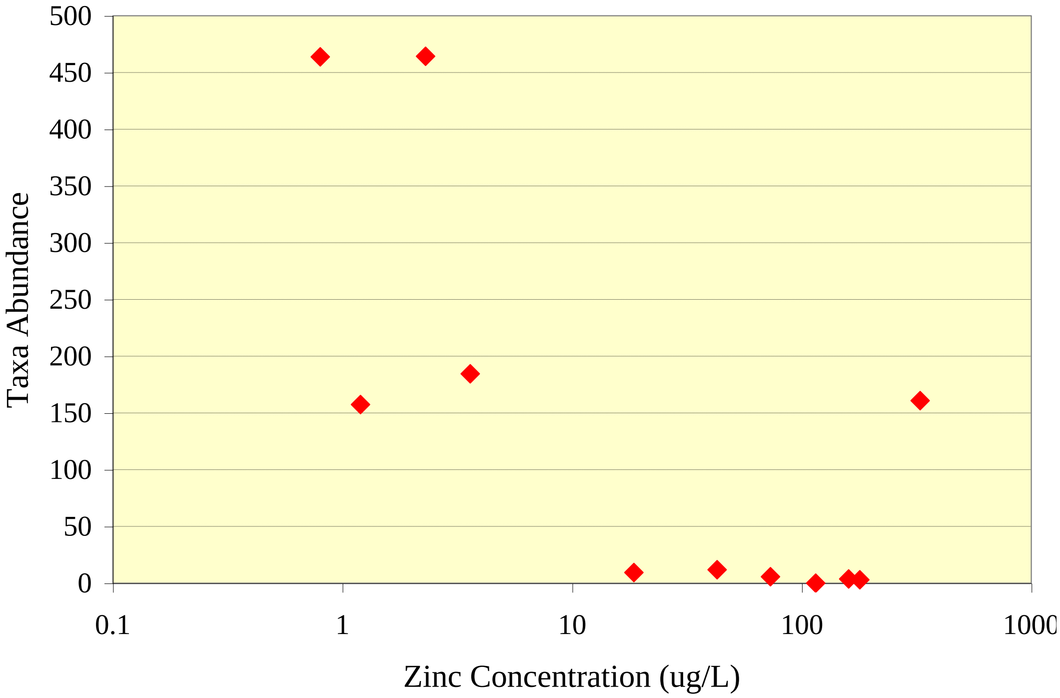

Figure 26. Invertebrate abundance versus zinc concentration.

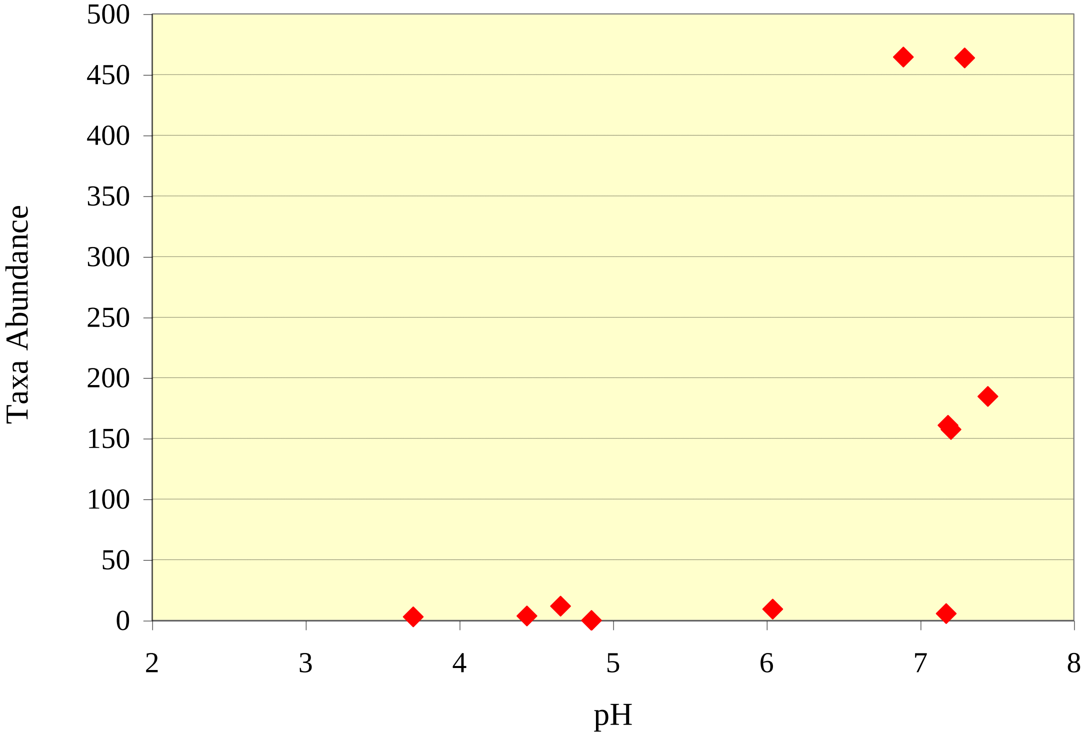

Figure 27. Invertebrate abundance versus pH.

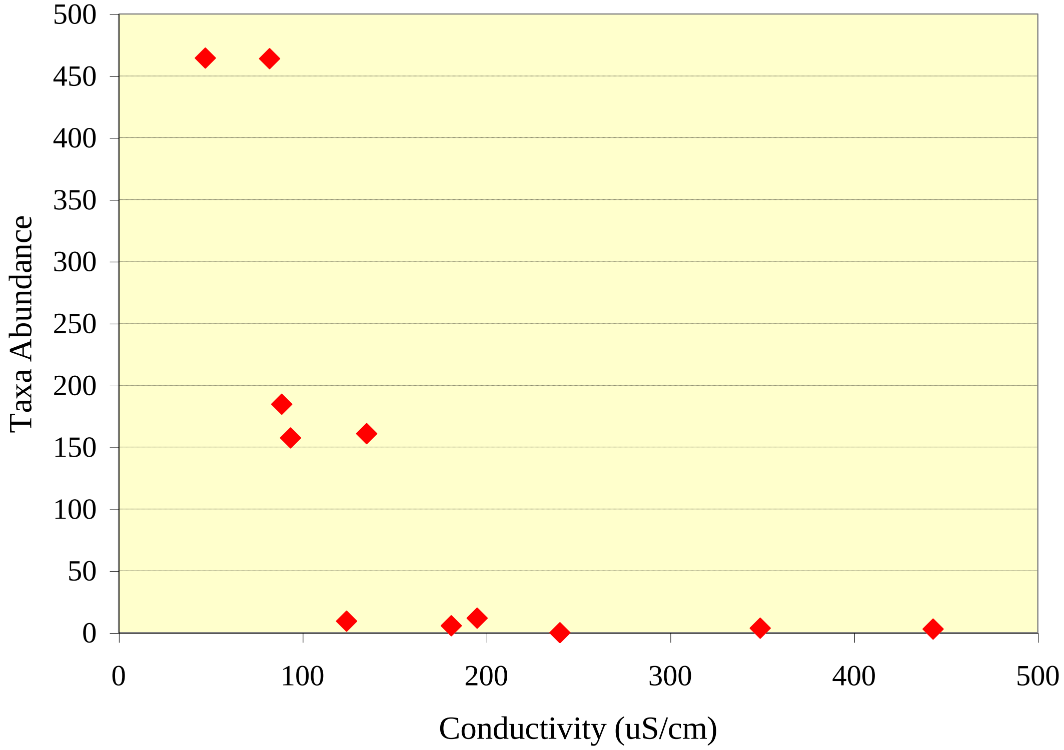

Figure 28. Invertebrate abundance versus conductivity.

Summary and Conclusions

Colorado's Lake Creek watershed is severely affected by natural acid rock drainage over most of its reach, from the headwaters in an area of hydrothermal alteration in the Grizzly Peak Caldera, to its inflow into the Twin Lakes Reservoir 27 km downstream. With pH as low as 2.74 and metals concentrations as great as 498 mg/L Fe, 277 mg/L Al, 10 mg/L Cu, 1.2 mg/L Zn, and 3,400 mg/L SO_4^{-2}, this watershed hosts ARD impacts as severe as many streams that have been affected by historical mining (Nimick et al., 2004; Church et al., 2006a). Weathering of hydrothermally altered rock produces ferricrete/ferrosinter sources of elevated metals which demonstrate that historical mining activity is not required to produce stream drainages that have elevated geochemical baseline values for potentially toxic metals. Similar results have been demonstrated for work conducted in the Animas River watershed (Church et al., 2006b, Verplanck et al., 2006; Wirt et al., 2006; Yager et al., 2003).

A comparison of biologic communities with water quality under low flow conditions reveals a strong relationship between metals toxicity and the abundance of trout and macroinvertebrates. With only one minor exception (dissolved Cu at site LC-3; see Fig. 18), trout populations in this watershed exist only where the water quality does not exceed the chronic aquatic life water quality criteria, and where sediment quality does not exceed the probable effects concentration. Trout are absent or severely impacted where metals exceed standard or where pH is low. There is little downstream recovery evidenced by low trout numbers at the two lowest sites above Twin

Lakes. Trout are abundant at sites upstream of metal sources and below Twin Lakes where metal contamination is ameliorated.

Macroinvertebrate community abundances were depaupreate throughout the sampling area. Because macroinvertebrates are sessile organisms unlike trout, they cannot avoid adverse conditions. In addition, benthic communities recolonize from upstream to downstream. These results suggest that toxic levels of trace metals persist in the upper reaches of the watershed throughout the year.

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