

Overview of Mine Drainage Geochemistry at Historical Mines, Humboldt River Basin and Adjacent Mining Areas, Nevada

By J. Thomas Nash



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Chapter E *of*

Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada

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Preface

Northern Nevada is one of the world's foremost regions of gold production. The Humboldt River Basin (HRB) covers 43,500 km² in northern Nevada (Crompton, 1995), and it is home to approximately 18 active gold and silver mines (Driesner and Coyner, 2001) among at least 55 significant metallic mineral deposits (Long and others, 1998). Many of the gold mines are along the Carlin trend in the east-central portion of the HRB, and together they have produced 50 million ounces of gold from 1962 (when the Carlin mine first opened) through April 2002 (Nevada Mining Association, 2002). Mining is not new to the region, however. Beginning in 1849, mining has taken place in numerous districts that cover 39 percent of the land area in the HRB (Tingley, 1998). In addition to gold and silver, As, Ba, Cu, Fe, Hg, Li, Mn, Mo, Pb, S, Sb, V, W, Zn, and industrial commodities such as barite, limestone, fluorite, sand and gravel, gypsum, gemstones, pumice, zeolites, and building stone, have been extracted from the HRB (McFaul and others, 2000).

Due to the large amount of historical and recent mining in the HRB, the Bureau of Land Management (BLM) in Nevada asked the U.S. Geological Survey (USGS) Mineral Resources Program to conduct a series of mineral-deposit-related environmental studies in the HRB. BLM required data and geoenvironmental interpretations regarding (1) the chemical composition of water, soil, sediment, and mine waste in the HRB, (2) the natural background chemistry of these materials, and (3) how mining activities may have altered their chemistry. The paper that follows describes one of the studies conducted by the USGS Minerals Program to answer these and similar questions.

All papers within this series of investigations can be found as lettered chapters of USGS Bulletin 2210, *Geoenvironmental Investigations of the Humboldt River Basin, Northern Nevada*. Each chapter is available separately online.

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Overview of Mine Drainage Geochemistry at Historical Mines, Humboldt River Basin and Adjacent Mining Areas, Nevada

By J. Thomas Nash

Abstract

Reconnaissance hydrogeochemical studies of the Humboldt River basin and adjacent areas of northern Nevada have identified local sources of acidic waters generated by historical mine workings and mine waste. The mine-related acidic waters are rare and generally flow less than a kilometer before being neutralized by natural processes. Where waters have a pH of less than about 3, particularly in the presence of sulfide minerals, the waters take on high to extremely high concentrations of many potentially toxic metals. The processes that create these acidic, metal-rich waters in Nevada are the same as for other parts of the world, but the scale of transport and the fate of metals are much more localized because of the ubiquitous presence of caliche soils.

Acid mine drainage is rare in historical mining districts of northern Nevada, and the volume of drainage rarely exceeds about 20 gpm. My findings are in close agreement with those of Price and others (1995) who estimated that less than 0.05 percent of inactive and abandoned mines in Nevada are likely to be a concern for acid mine drainage. Most historical mining districts have no draining mines. Only in two districts (Hilltop and National) does water affected by mining flow into streams of significant size and length (more than 8 km). Water quality in even the worst cases is naturally attenuated to meet water-quality standards within about 1 km of the source.

Only a few historical mines release acidic water with elevated metal concentrations to small streams that reach the Humboldt River, and these contaminants are not detectable in the Humboldt. These reconnaissance studies offer encouraging evidence that abandoned mines in Nevada create only minimal and local water-quality problems. Natural attenuation processes are sufficient to compensate for these relatively small sources of contamination. These results may provide useful analogs for future mining in the Humboldt River basin, but attention must be given to matters of scale: larger volumes of waste and larger volumes of water could easily overwhelm the delicate balance of natural attenuation described here.

Introduction

The composition of water discharged from a mine, commonly called “mine drainage,” is largely determined by the ore type, host-rock lithology, and geography of the mine (Plumlee, 1999). Historically mined ores in northern Nevada are generally similar to those mined elsewhere in the Western United States, but local geographic factors cause mine drainage in northern Nevada to differ in important ways. Unlike most mining areas of the Rocky Mountains, historical mines in Nevada are much less likely to discharge acid waters into nearby streams. Acidic mine drainage in Nevada is a rare and local phenomenon and in northern Nevada does not reach the major streams. Historical mines in northern Nevada have the potential to create acidic, metal-rich waters, but this rarely happens because of the low precipitation and caliche soils characteristic of arid climate.

This overview is based on hydrogeochemical studies of more than 40 historical mining areas in northern Nevada (fig. 1) that have been carried out as part of the U.S. Geological Survey’s investigations of the mineral resources and environmental geochemistry of the Humboldt River basin. The Humboldt River basin study was prompted by public concerns and land management issues regarding current and future mining in the watershed (NDWP, 2001). This investigation builds upon studies of Price and others (1995), who described and evaluated mine drainage in Nevada. Studies by the author from 1995 to 2000 have focused on historical mining districts (Nash, 2001) and collection of new hydrogeochemical data for the region (Nash, 2000). Many of the more complex sites were visited more than once to obtain more information on seasonal variability. No active mines were studied, and most of the mining areas studied have been inactive (“abandoned”) for 40 or more years.

In this chapter, several terms will be used collectively to combine similar themes. I will use the term “metal” to describe cations or base metals, and I also include metalloid elements such as Se and As that form oxyanions in water (selenate, arsenate). I use the term “mine waters” and “mine

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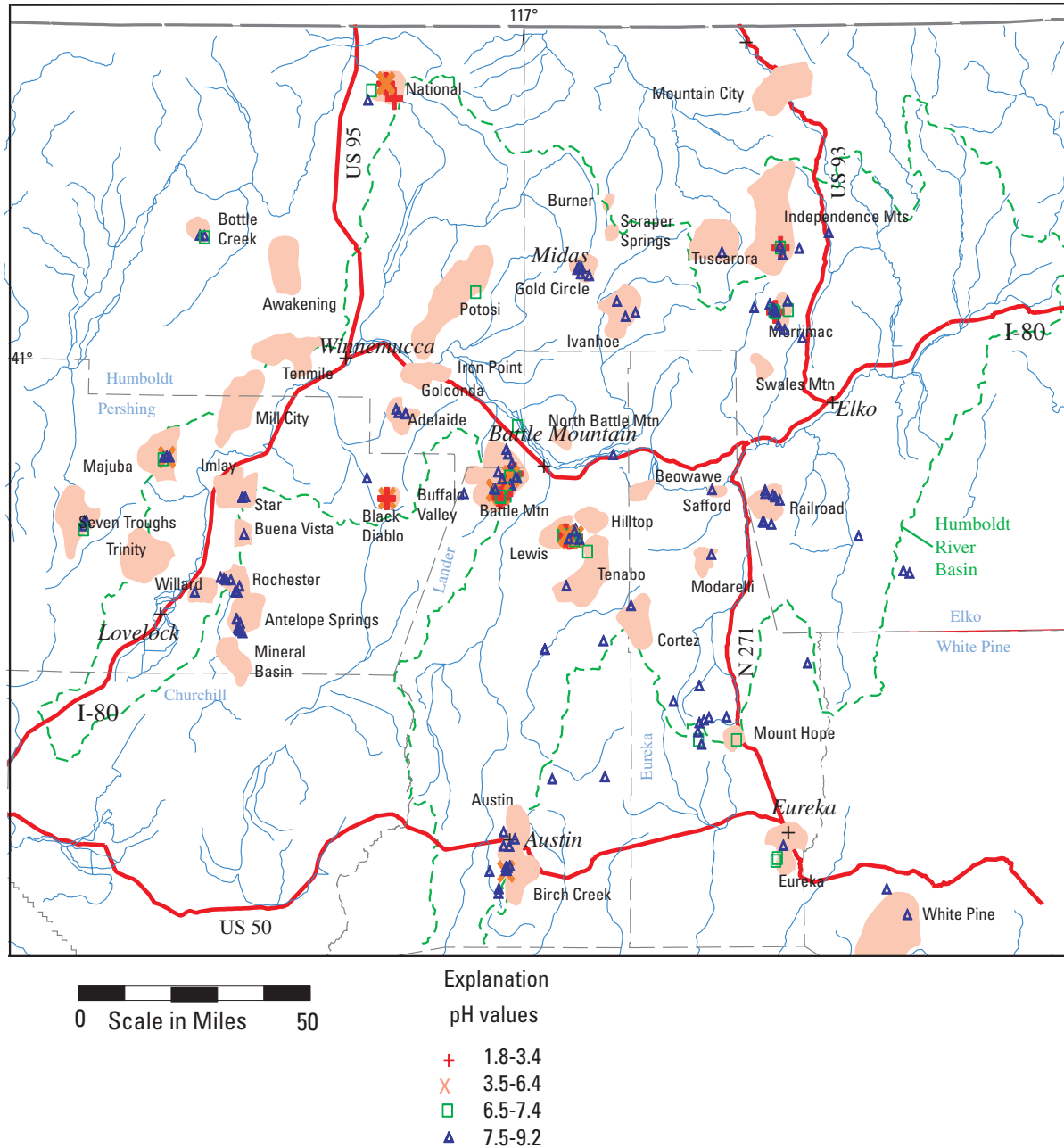


Figure 1. Location and character of surface water samples collected in northern Nevada. The limits of the Humboldt River basin are shown by the green dashed line. Mining districts (tan) are from Tingley (1998).

drainage” interchangeably for waters flowing from mine adits or in contact with mine wastes. Broadly, without qualifiers, the term mine drainage includes waters that have reacted with mine workings, mine waste dumps, or mill tailings. Drainage and other aspects of mill tailings are discussed in more detail elsewhere (Nash, 2003). The term “waters affected by mining” will be used for waters that are partly from mines, dumps, or tailings, but also partly from sources that have no mines or prospects; these stream waters are mixtures of surface, spring, and mine waters. Mining clearly can affect subsurface waters, but ground water is outside of the scope of this study because few wells are available for sampling.

Methods for sampling and analysis are described elsewhere (Nash, 2000; Nash, 2001). Water samples were collected after testing for pH and conductivity with portable instruments. The methods are simplified from those described by Ficklin and Mosier (1999). The pH meter was calibrated several times a day using buffered solutions of pH 4.0, 7.0, and 10.0; calibration was checked after sample readings using reference solutions. Water samples for chemical analysis were collected by a consistent technique adopted for reconnaissance investigations. The water was collected with a disposable 60-mL syringe, then pushed through a disposable 0.45- μm cellulose filter. The syringe and the 60- or 120-mL polyeth-

ylene bottle were rinsed twice in the sampled water prior to collection. Samples for cation analysis was acidified to a pH of about 2 at the site with 5 drops of ultrapure 1:1 HNO₃ per 60 mL. Samples for anion analysis were filtered but not acidified. Analyses of cations were by ICP-MS at a commercial lab for samples collected in 1996 and 1997, and by the USGS for samples collected in 1998 and 1999. Analytical methods and quality assurance are described elsewhere (Nash, 2000).

Climate and Geography in Mine Drainage

Climate and topography are important factors in the development of mine drainage. Three aspects need to be briefly highlighted. First, mine drainage can only happen where there is enough vertical relief to cause water to flow from mine workings. Precipitation that interacts with mined materials on flat terrain may enter ground water, but it would not be called mine drainage as defined here. In Nevada, mine drainage is found only in the hilly or mountainous parts of the region where precipitation can enter disturbed lands either directly or through fractures (ground-water flow) and then flow out on the surface. Mine shafts do not create surface drainage, but mine tunnels driven into mountains may collect ground water and carry it to the surface. Indeed, many mine tunnels were constructed originally to provide an energy-efficient

means of removing water from an underground mine, and after the mining ceases these tunnels continue to carry water (photograph 1). Water pumped from mines is geochemically similar to mine drainage, but will not be considered here.

Second, precipitation is highly variable across distances as short as 1–2 km in Nevada, and these differences can be seen in the amount of water at a mined site. Generalized maps of precipitation in Nevada show the effects of elevation on increased amounts of precipitation, much of that as snow (Houghton and others, 1975). There should be no surprise that there is little or no mine drainage at lower elevations on the flanks of ranges. Orientation also is important because it influences the amount of exposure and evaporation. Large differences in precipitation and evaporation can be seen during and shortly after a spring storm. Just as aspen and fir trees tend to develop selectively in north-facing basins, more water is present in mine sites with a northerly aspect. This is evident in the higher amount of water in small creeks and in mine drainage of north-facing areas of the Battle Mountain, Hilltop, and National mining districts.

A third feature related to climate is the development of alkaline waters and carbonate-rich aridsols and caliche in arid areas, including Nevada (Southard, 2000). The relationship of these soils to climate was first emphasized by Jenny (1941). Carbonate as caliche is a major constituent in alluvium and soils at lower elevations of the study area. The fine-grained and porous aspects of caliche makes the carbonate more reactive and available to ephemeral near-surface waters than calcium carbonate in limestone. Two aspects of the caliche may



Photograph 1. The Buckskin National mine tunnel releases a moderate flow of water during spring snow melt. Reclamation in about 1997 created the cement trough and underground drain to minimize reactions with the mine waste dump. The pH is 3.0.

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be important in mining areas. One, the surface waters have high alkalinity and pH values greater than 8; these waters have high acid-neutralizing capacity. Second, acid mine water that is released during wet periods of the year are effectively neutralized by reactions with caliche as the waters infiltrate this alluvium.

Mine Drainage Compositions

Abundance

Only a small number of historical mines release mine drainage in amounts sufficient to be sampled. Using information from U.S. Geological Survey 1:24,000-scale topographic maps, such as locations of mine adits, topography, and locations of springs and streams, it was possible to anticipate likely sites of mine discharge. While in the field, I searched for signs of mine drainage, which generally can be detected from a distance of 100–200 m as tell-tale streaks of red iron coatings. I was able to identify only 16 mine adits with active discharge of water (sufficient to measure pH and collect a sample for analysis) (photograph 2). This is a very small number when compared to the thousands of mines and prospects in the districts that I traversed. Mill tailings interact with surface water (seasonal streams and ponds) at 12 sites (photograph 3; photograph 4). Small ponds and large puddles (> 5 m wide) form occasionally at nine sites (photograph 5). Mine waste

dumps are wet from streams or mine waters at 10 sites (photograph 6). Although my reconnaissance study probably missed some mines that release drainage waters, I believe I found a representative selection of draining adits and possibly found most of the draining adits in the districts under study. Considering the large area studied, about 25 million acres, and the very large number of historical mines and prospects shown on the topographic maps (possibly 75,000; cf. 225,000 to 310,000 in all of Nevada; Price and others, 1995), the number of wet, draining adits and mine dumps is small. From my observations, I estimate that less than about 0.05–0.1 percent of historical mines and prospects release contaminated drainage during the wettest months of the year. This is similar to the estimate of Price and others (1995). The largest discharge was about 50 to 100 gpm during spring runoff, and most of the mine discharges are 5 to 10 gpm in wet seasons. The largest number of draining adits and associated wet dumps was in the Dean mine complex, western Hilltop district, and these were effectively reclaimed in 1998.

Acidity

The pH of mine discharge waters ranges from 2.1 to 8.3 with a median value of 3.4. Some atypical mine-water samples, such as puddles and small ponds, have pH values as low as 1.7. The range of pH values and the associated metal concentrations are shown in figure 2. The number of highly acidic water samples exceeds the number of sites because most of those extreme waters were sampled more than once



Photograph 2. The Majuba mine adit releases a small amount of water with a pH of 7.4 and low metal concentrations. It is not a problem.



Photograph 3. Rochester Creek has eroded a deep cut into the large mill tailings impoundment. The creek with a pH of 8.3 picks up a relatively small amount of contamination from the tailings.



Photograph 4. Tailings from the 1930s milling of copper ore at the site of the future Big Mike mine collects water during rainy periods. The water attains a pH of 3.6 and accumulates very high metal concentrations, in part from evaporative concentration.

during 4 years of study. The acidic mine waters carry high to extremely high concentrations of metals. All but a few of these acid sources appear to be seasonal, according to my observations of zero or low flow in September visits and comments from BLM staff.

Metal Concentrations

Metal solubility and transport by mine waters is largely a function of pH and pE (oxidation potential). Numerous reports describe sources of acid and the solubility relations of metals



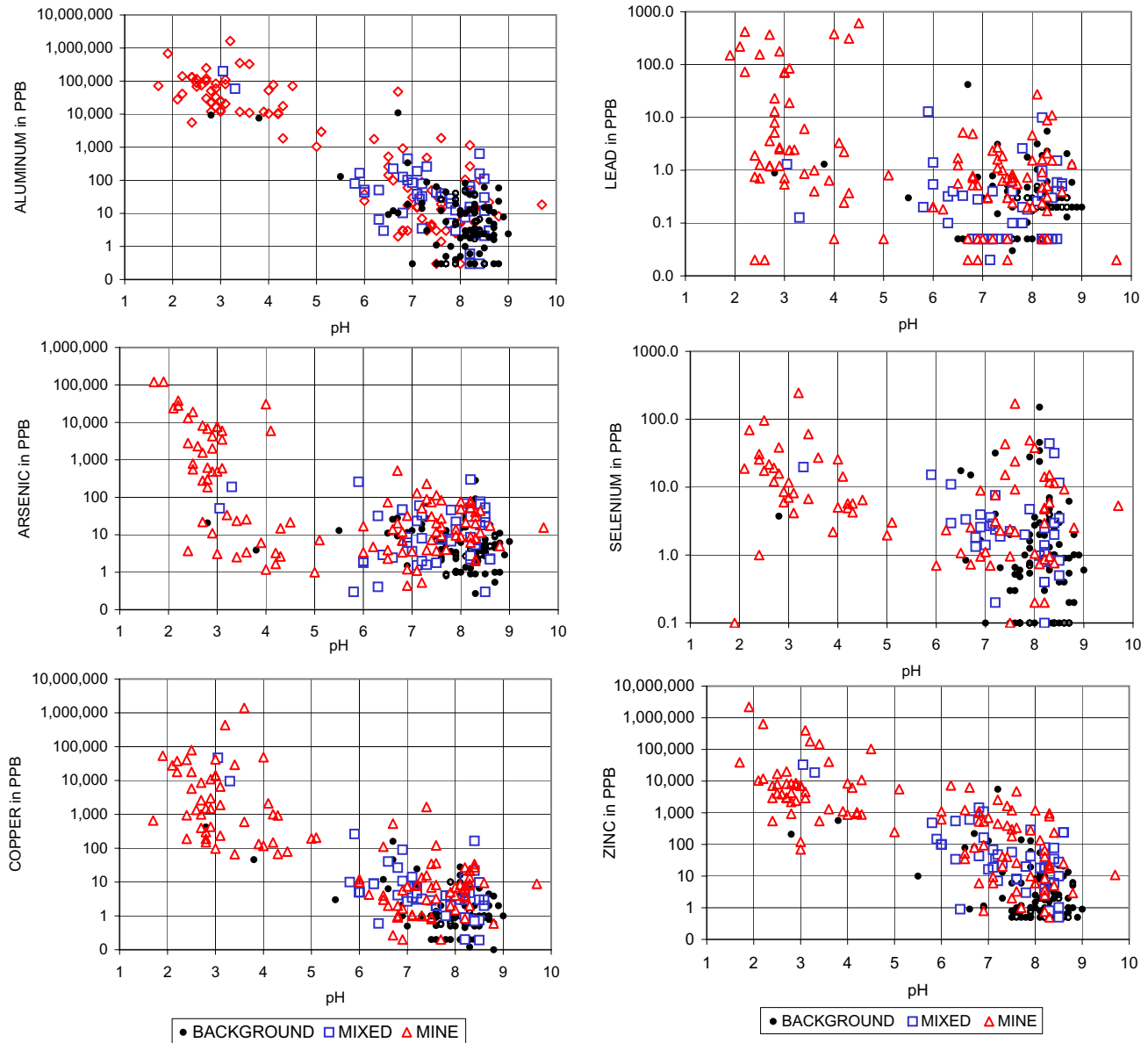
Photograph 5. A bulldozer cut at a mercury mine in the Antelope Springs district collects water with a very high Hg concentration.



Photograph 6. Drainage from this mine tunnel reacts with sulfidic waste to create even more acidic (pH 2.6) water and extremely high metal concentrations. The adit was plugged and the dump was reclaimed in 1998.

as a function of pH (Drever, 1997; Nordstrom and Alpers, 1999). The compositions observed in the Humboldt River basin are similar to those of most hard-rock metal-mining areas, including well-studied mining areas of Colorado (Plumlee and others, 1999; Nash, 2002; Mast and others, 2000). At pH values below about 4, many potentially toxic metals are

often highly to extremely concentrated (relative to water-quality standards for drinking water or aquatic life; NDEP, 2002). As in most metal-mining areas, waters released from adits, dumps, or mill tailings tend to carry high metal concentrations at the source, roughly in proportion to acidity (fig. 2). These compositions evolve to more neutral pH values and lower



Explanation: mine waters, sampled at adit or mine dump; mixed waters, sampled in stream below mines; background water from areas having no mines

Figure 2. Relations of metal concentrations to pH in surface waters.

metal concentrations as mine waters are diluted and neutralized by natural processes in streams.

The composition of mine waters and waters affected by mining is summarized in table 1, which also summarizes waters from areas with no mining or altered unmined rocks (background). The mine drainage sampling describes 42 sites (mine adits, tailings seeps, pit lakes, or ponds); another 20 samples characterize unusual temporary features such as puddles on mine dumps and are in a separate part of table 1. The median value is perhaps the best guide to typical concerns, whereas the maximum value shows how concentrated and

potentially toxic these waters can be at the source. The graphs in figure 2 show that metal concentrations are highest below a pH of about 4. Some mine waters (adits and pits have pH values of 4 to 9—alkaline waters contain lower metal concentrations than acidic waters. At higher pH values, metals tend to hydrolyze, with a resulting decrease in concentration. Reactions with atmospheric oxygen tend to cause Fe to precipitate as fine-grained iron-oxyhydroxides (FeOx) that are capable of adsorbing many metals, including As, Cu, and Pb. Near-neutral-pH waters tend to carry relatively low amounts of most metals, but some potentially toxic metals (Zn and Cd) can be

Table 1. Summary of surface-water compositions, northern Nevada.

[Table shows more significant figures than are reliable in some entries. Analytical values by ICP-MS. N, number of samples. WQS (wqs), approximate water quality standard; the second column for each metal (with *) is recalculated as a multiple of the water quality standard]

	pH	Cond ($\mu\text{S}/\text{cm}$)	Al (ppb)	Al* (\times wqs)	As (ppb)	As* (\times wqs)	Cd (ppb)	Cd* (\times wqs)	Cu (ppb)	Cu* (\times wqs)
All surface-water samples (N = 280)										
Minimum	1.7	80	0.3	0.00	0.3	0.01	0.0	0.00	0.1	0.01
Median	7.6	480	22.2	0.22	9.6	0.19	0.5	0.09	4.7	0.47
Maximum	10	4,590	1,800,000	18,000	3,800,000	76,000	26,000	5,200	3,900,000	390,000
Background samples (N = 52)										
Minimum	7.0	105	0.3	0.00	0.9	0.02	0.0	0.00	0.2	0.02
Median	8.2	320	1.9	0.02	3.8	0.08	0.1	0.02	0.8	0.08
Maximum	9.0	>2,000	44.0	0.4	18.0	0.4	2.0	0.4	10.1	1.0
Altered rocks/baseline (N = 55)										
Minimum	2.8	80	0.3	0.00	0.3	0.01	0.0	0.00	0.1	0.01
Median	8.1	480	10.5	0.10	5.5	0.11	0.1	0.02	1.2	0.12
Maximum	8.8	>2,000	11000	110	284	6	18	4	423	42
Mixed mine effects (N = 48)										
Minimum	3.1	160	0.3	0.00	0.3	0.01	0.0	0.00	0.2	0.02
Median	7.6	550	31.2	0.31	8.1	0.16	0.7	0.15	4.0	0.40
Maximum	8.6	>2,000	59,000	590	299	6	728	146	47,000	4,700
Mine dump effects (N = 43)										
Minimum	1.7	228	0.3	0.00	0.4	0.01	0.0	0.00	0.2	0.02
Median	7.2	583	36.4	0.36	10.3	0.21	3.4	0.67	8.6	0.86
Maximum	8.8	>2,000	1,630,000	16,270	120,000	2,400	14,900	2,981	437,000	43,700
Mine drainage (N = 42)										
Minimum	2.1	240	1.4	0.01	0.5	0.01	0.1	0.01	0.3	0.03
Median	3.4	1,095	12,000	120.0	187.3	3.75	10.9	2.19	117	11.7
Maximum	8.3	4,590	352,000	3,520	30,800	615	5,110	1,020	79,000	7,900
Mine pits and ponds (N = 21)										
Minimum	1.9	80	4.0	0.04	3.1	0.06	0.0	0.00	0.8	0.08
Median	7.1	530	593.0	5.93	42.0	0.84	3.2	0.63	44.5	4.45
Maximum	9.7	>2,000	680,000	6,800	122,000	2,440	12,000	2,400	1,395,500	139,500
Miscellaneous other waters (N = 20)										
Minimum	1.8	290	10.0	0.10	6.1	0.12	0.0	0.01	3.5	0.35
Median	3.0	1,330	14,500	145.0	420.0	8.40	35.8	7.16	1,000	100.0
Maximum	9.2	2,500	1,800,000	18,000	3,800,000	76,000	26,000	5,200	3,900,000	390,000
WQS (ppb)				100		50		5		10

Table 1. Summary of surface-water compositions, northern Nevada—*Continued*.

	Fe (ppb)	Fe* (× wqs)	Mn (ppb)	Mn* (× wqs)	Pb (ppb)	Pb* (× wqs)	Se (ppb)	Se* (× wqs)	Zn (ppb)	Zn* (× wqs)
All surface-water samples (N = 280)										
Minimum	0.2	0.00	0.1	0.00	0.0	0.00	0.1	0.02	0.5	0.01
Median	502.8	0.50	34.1	0.03	0.4	0.01	2.2	0.44	24.9	0.25
Maximum	32,000,000	32,000	3,600,000	3,600	5,800	116	1,340	268	2,600,000	26,000
Background samples (N = 52)										
Minimum	12.0	0.01	0.1	0.00	0.0	0.00	0.1	0.02	0.5	0.01
Median	43.0	0.04	3.0	0.00	0.2	0.00	0.6	0.12	0.8	0.01
Maximum	2,871	2.9	29.0	0.0	1.9	0.0	27.8	5.6	130.0	1.3
Altered rocks/baseline (N = 55)										
Minimum	0.2	0.00	0.3	0.00	0.1	0.00	0.1	0.02	0.5	0.01
Median	308.3	0.31	9.6	0.01	0.3	0.01	1.1	0.23	2.3	0.02
Maximum	18,410	18	2200	2	42	1	151	30	5544	55
Mixed mine effects (N = 48)										
Minimum	25.0	0.03	0.1	0.00	0.0	0.00	0.1	0.02	0.5	0.01
Median	408.5	0.41	47.0	0.05	0.2	0.00	2.4	0.47	33.9	0.34
Maximum	42,000	42	8,430	8	13	0	44	9	33,000	330
Mine dump effects (N = 43)										
Minimum	56.0	0.06	0.1	0.00	0.0	0.00	0.1	0.02	0.5	0.01
Median	664.6	0.66	87.2	0.09	0.7	0.01	4.0	0.79	335.0	3.35
Maximum	2,000,000	2,000	85,000	85	1,600	32	244	49	180,500	1,805
Mine drainage (N = 42)										
Minimum	330.0	0.33	1.0	0.00	0.0	0.00	0.7	0.14	3.3	0.03
Median	37,305	37.31	3,156	3.16	1.2	0.02	8.2	1.64	2,200	22.0
Maximum	772,000	772	65,100	65	422	8	96	19	148,000	1,480
Mine pits and ponds (N = 21)										
Minimum	35.0	0.04	7.8	0.01	0.0	0.00	0.1	0.02	0.8	0.01
Median	1,303	1.30	223.8	0.22	1.1	0.02	5.3	1.07	67.6	0.68
Maximum	9,600,000	9,600	3,600,000	3,600	369	7	170	34	2,200,000	22,000
Miscellaneous other waters (N = 20)										
Minimum	300.0	0.30	2.8	0.00	0.2	0.00	0.1	0.02	3.0	0.03
Median	100,000	100.0	8,300	8.30	3.7	0.07	30.9	6.19	9,360	93.6
Maximum	32,000,000	32,000	3,100,000	3,105	5,800	116	1,340	268	2,600,000	26,000
WQS (ppb)		1,000		1,000		50		5		100

carried at these pH values. Near-neutral to alkaline waters (pH 7–9) can carry significant concentrations of metal-oxyanions (Mo, As, Se) and uranium, as shown in the Humboldt data and discussed elsewhere.

Because the toxicity of metals varies greatly from metal to metal, receptor to receptor (Smith and Huyck, 1999; Kelly, 1999) metal-concentration values may be easier to understand in the context of water-quality standards that are set relative to the health of humans and wildlife (NDEP, 2002)¹. Human health tends to be more sensitive to some metals than is wildlife, hence drinking-water standards are quite low for As (50 ppb), Pb (50 ppb), and Tl (thallium, 13 ppb). Aquatic wildlife is more sensitive than man to other metals, including Cd (ca. 5 ppb), Cu (ca. 10 ppb), Hg (0.01 ppb), Mo (19 ppb), Se (5 ppb), and Zn (ca. 50 ppb). Iron is not a health risk to aquatic wildlife until concentrations reach 1,000 ppb. Enrichment factors shown in table 1 express magnitudes relative to water-quality standards. In general terms, the metal concentrations in some acidic mine waters in Nevada exceed various water-quality standards by large factors: As 100–600×, Cd 50–1,000×; Cu 50–>5,000×, Pb 25–400×, Se 10–100×, and Zn 25–1,500×.

Some ephemeral ponds located on mine dumps and tailings impoundments are even more metal rich than mine drainage waters, attaining extreme compositions by collection and evaporation of runoff waters (photograph 7). These waters can contain more than 10,000 ppb of several metals, including Cu and Zn, and also are rich in other elements including As, Cd, Hg, Se, and U. Compared to commonly applied water-quality standards, values for these metals are 200 to more than 75,000 times higher than the regulatory standard. These ephemeral ponds are not typical of mine-related waters but are mentioned as a special problem that needs consideration in reclamation because acute toxicity in short-term exposure is likely.

Relation to Ore Type

The mineralogy and chemical composition of metallic ore deposits and their host rocks would logically determine the composition of mine waters from those deposits (Plumlee and others, 1999; duBray, 1995), but in my experience the wide range in water compositions from a deposit type blur the distinctions between deposit types (Nash, 2001; Nash, 2002). Compositions of mine waters from northern Nevada plotted by deposit type on figure 3 are not as distinctive as postulated by others. Some trace metals of concern, such as Se and U, can be elevated in acidic mine waters even from deposits that are not normally considered to be enriched in those elements.

¹ The biology and chemistry of toxic metals are complex topics that are reviewed elsewhere (Langmuir, 1997; Kelly, 1999; Smith and Huyck, 1999). Water-quality standards are explained by Smith and Huyck (1999) and NDEP (2002), including aspects such as acute and chronic exposure, and drinking-water and aquatic-life criteria. In detail, the toxic effects of many base metals (eg., Cd, Cu, Pb, Zn) are inversely related to water hardness; the values cited here are approximate and not corrected for hardness.

Acidic mine waters are capable of mobilizing a wide array of elements, including many such as Al and Ti that are often considered “immobile” by geochemists.

The most effective predictor of metal mobilities in waters affected by mining is pH, which relates to the abundance of acid-generating minerals such as pyrite relative to acid-consuming minerals such as calcite. In many settings in Nevada, host-rock lithologies provide sufficient acid-neutralizing capacity to dominate acid production, producing neutral to alkaline waters that are capable of transporting only low concentrations of most metals (but locally high concentrations of a distinct suite of elements that includes As, Cd, Mo, Se, U, Zn, and occasionally Cu). Sedimentary rocks, especially calcareous shales and limestones, commonly provide the required neutralizing capacity, and in other terranes caliche in alluvium is effective.

Evolution of Surface Waters Within Mining Areas

The composition of mine drainage waters changes downstream from the sources in response to several processes that generally improve water quality. The one exception is the case of mine waters reacting with mine dumps, which generally results in added acidity and increased metal concentration. In Nevada, attenuation of metal concentration can be observed up to the point at which waters infiltrate alluvium and cannot be sampled. Reactions continue in shallow ground water but are not considered here because wells generally are not available for sampling. In most situations, water compositions change over a distance of 100 m or more downstream from a mine source; these waters are here termed “mixed” if there is evidence for addition of other surface or spring waters and reactions, all of which raise pH and lower conductivity. The mixed waters have pH values in the range of 3 to 8. These mixed waters are of interest for both their geochemistry and their implications for beneficial use—they are important because they are much larger in volume than mine-source waters and provide more wildlife habitat.

Improvements in water quality by natural processes involve reactions of several kinds that raise pH and decrease metal concentrations. Several processes can be involved: (1) oxidation and formation of Fe- and Mn-oxyhydroxide phases; (2) ion exchange, as on clays or organic materials; (3) adsorption, especially on fine-grained or amorphous Fe- and Mn-phases; (4) flocculation of colloids and sedimentation of particles; (5) sulfate reduction, generally mediated by bacteria; and (6) uptake by plants. In the study area, processes 1 and 3 seem to be most important, whereas 5 and 6 are rare.

Hydrous iron oxide (FeOx) phases of various compositions and red, orange, and yellow hues are typically involved and are important for the removal of metals such as Cu, Pb, and As, consistent with the theory and observations of Smith



Photograph 7. Very acidic (pH 1.9) water collects in this cut into sulfidic mill tailings at the Caselton mill tailings impoundment. Metal concentrations are extremely high, in part by seasonal evaporation.

(1999). The fact that the Nevada acid mine waters start with high iron concentrations makes these reactions possible. These adsorption reactions in nature, over the pH range of about 3 to 7, are the basis for the concept of “self-mitigating capacity” (Smith, 1999). Mixing and precipitation is evident in several of the larger mine drainages in the study area where several kinds of surface and spring waters mix with mine waters over distances of hundreds of meters. Examples of natural attenuation and improvement of water quality in five mining areas will be discussed next.

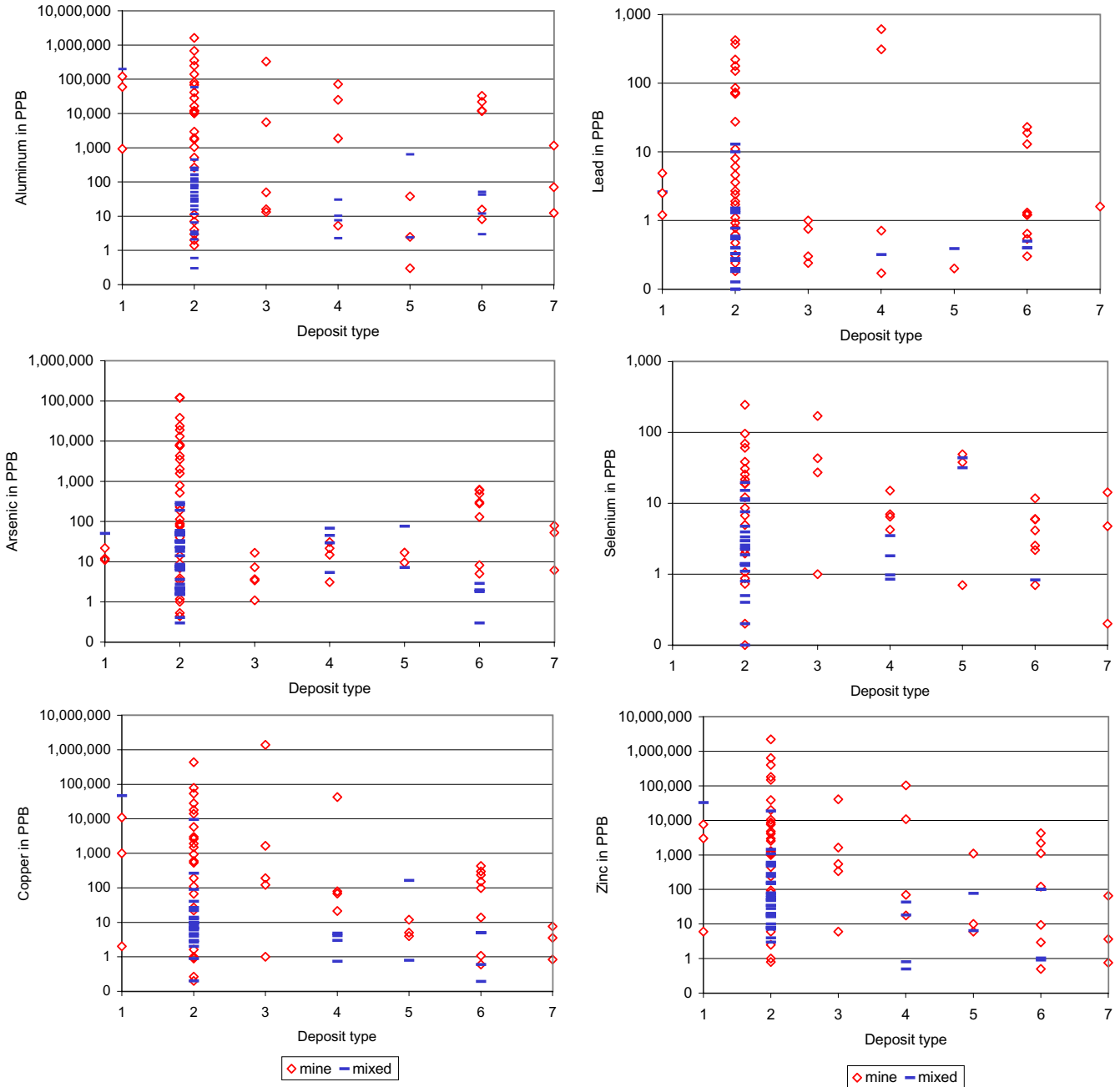
National Mine Area

A simple example of natural attenuation is the case of the National mine complex (photograph 8) and evolving water compositions in Charleston Gulch, shown graphically in fig. 4. The collapsed mine adit releases a moderate flow (10–20 gpm) of pH 2.8–3.1 water (photograph 9) that interacts with mine waste for about 125 m (photograph 10), at which point the main flow of mine water joins a stream from the southwest (a basin with small prospects). The mixed waters flow over the remains of a tailings pond and through several breached catch ponds. Small streams from the east and west join the stream about 550 to 650 m north of the adit. Probing of water in the area of the dump, stream inflow, and tailings (125–250 m north) showed large local changes in conductivity and somewhat smaller variation in pH readings, both of which are considered to indicate mixing of several kinds of surface and shallow ground waters. The chemical analyses (fig. 4) show

that metal concentrations increase during reaction of the acid mine drainage and mine waste. North of the mill tailings, pH values rise from less than 3 to 4.3, and conductivity values decrease, possibly from diffuse inflows (springs). Relatively small amounts of FeOx precipitate in this reach. The stream does not change much in appearance or pH values until two side inflows—each larger than the stem from the mine; this quadruples the volume of the stream—at which point pH rises to 6.0 and conductivity decreases by more than 60 percent. Metal concentrations are greatly reduced after these mixing reactions: Zn concentration is down to 100 ppb, and Cu is down to 5 ppb. The quality of the evolved water about a 0.6 km north of the adit has improved to approximately the aquatic-life standard.

Hilltop Mine Area

Another example, from the central Hilltop district, involves acidic mine drainage from a mine adit that flows over mill tailings in an unnamed small creek (photograph 11; fig. 5). The adit (in siliceous rocks with low neutralizing capacity) yields about 10 gpm of pH 2.7–2.9 water. The mine drainage flows into the creek, which then flows over eroded mill tailings for about 150 m. About 550 m north of the adit, the small stream joins the East Fork, a larger stream from a basin with only a few small mine prospects. The East Fork joins another large stream about 1,800 m north-northwest of the adit to become Rock Creek. Spring-fed headwaters in altered sedimentary rocks start with low metal concentrations (fig. 5). Metal



Explanation: water types: mine waters sampled at adit or dump; mixed waters are streams sampled below mines or mill tailings.
 Deposit types: 1, acid-sulfate; 2, polymetallic vein; 3, massive sulfide; 4, skarn; 5, sediment-hosted gold; 6, epithermal vein; 7, mercury.

Figure 3. Relations of metal concentrations in mine drainage to deposit type.

concentrations increase in the creek from the adit inflow, but it is not clear if metals are released from the tailings. Relatively small amounts of FeOx coat the stream channel, which could be explained by several kinds of mixing reactions, including seeps from the tailings. There is relatively little precipitation of iron oxides from these mixed waters compared to the examples described next. The unnamed creek joins the larger East Fork and for about a hundred meters there are thin white films on the stream bed, probably an Al-oxyhydroxide mineral. The pH

rises from 4.2 to 7.1–7.8, and samples collected about a hundred meters north of the junction have much lower metal concentrations and meet quality standards for aquatic life.

Dean Mine Area

Tunnels created during mining of sulfide-rich veins in the western part of the Hilltop district nearly 100 years ago were



Photograph 8. The National mine and associated mine dumps at an elevation of 1,800–2,100 m receive substantial snow and rain, causing more mine drainage than in most areas in northern Nevada.



Photograph 9. The collapsed mine tunnel at the National mine releases acidic mine drainage (pH 2.9), but the flow is only about 10–20 gallons/minute.

reopened for exploration in 1988–1994. These mine workings, about 3 km west of the Hilltop mine, created very acidic, metal-rich drainage (fig. 6) for about six years until the tunnels and mine dumps were reclaimed in 1998. The abandoned Dean adits created flows and pools of pH 2–3 waters (photograph 6, photograph 12) where the workings were in siliceous rocks, but a similar tunnel exploring the same vein system in

limestone released pH 7 to 7.5 waters (in detail, the pH varied over a 3-year time period). The mine drainage from several upper adits flowed less than 50 m to a small stream, and for about 600 m those waters precipitated large amounts of ocher FeOx on the stream bed. The mixing zone, from about 600 to 1,100 m north (fig. 6) involved a combination of limestone strata and numerous spring inflows with conductivity values



Photograph 10. Acidic mine drainage from the National mine flows over mine waste and tailings (left side of photograph), thereby accumulating even more acid and metals.

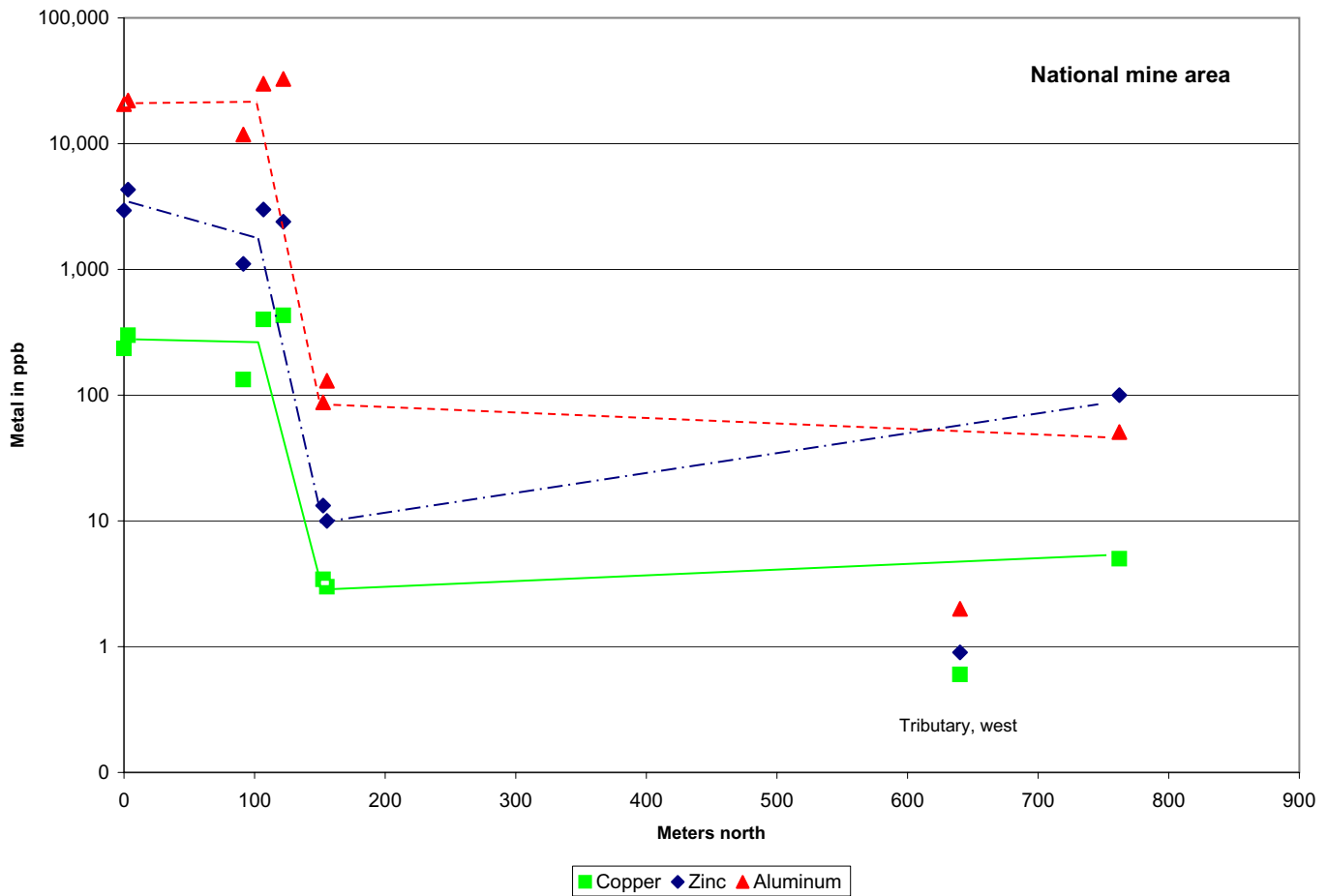


Figure 4. Evolution of mine drainage in the National mine area.



Photograph 11. Mill tailings from the Hilltop mill, placed in the channel of an ephemeral stream, react with seasonal surface waters, adding acid and metals.

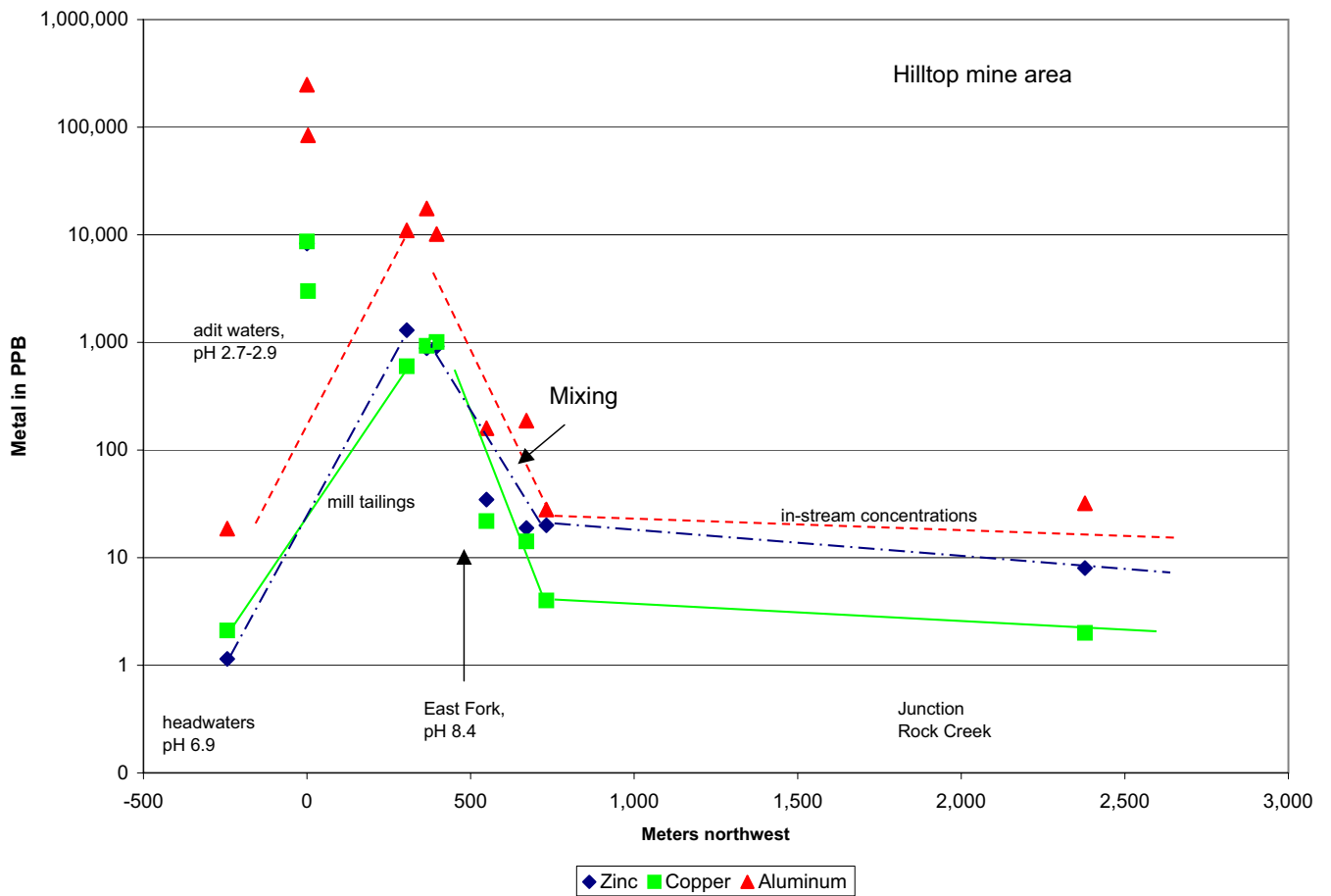


Figure 5. Evolution of mine drainage in the Hilltop mining area.

that varied by more than 100 percent at sites a meter apart. Mixing of pH 3–4 stream waters with pH 8.2 spring waters caused immediate flocculation of FeOx and reduction of metal concentrations by more than an order of magnitude. Mixing in the vicinity of the lower adit flow and limestone-rich waste dump was complex: the mine drainage clearly added metals, but it also added alkalinity and raised the pH. Reactions continued down the stream, and at the 2,100 m mark the metal concentrations were at or below aquatic-life standards. Mixing with the main stem of Rock Creek further attenuated metal concentrations. Two relatively large mill tailings piles (5,800- to 7,200-ft marks of fig. 6) produced no measurable input to the creek, but sampling of ground water (which would require wells) might yield definitive results. This small basin demonstrates the self-mitigating effects of high-iron waters described by others (Drever, 1997; Langmuir, 1997; Smith; 1999). Brief study and sampling in June of 1999, after the mine adits were plugged and mine dumps were reclaimed by NDEP-BLM in 1998, suggested greatly improved water quality (photograph 13).

Galena Canyon Area

A fourth example comes from a complex watershed on the northeast side of the Battle Mountain district in the area

of Butte, Galena, and Iron Canyons. High precipitation in the spring seasons of 1998 and 1999 created substantial flow from some historical mine adits and springs in this area of polymetallic veins in sedimentary rocks (siltite and chert). The springs in this area are notable for their high conductivities (2,000–4,500 microsiemens per centimeter— $\mu\text{S}/\text{cm}$) and high sulfate content (150–4,000 ppm), and pH values from 3 to 4. Mixing of several kinds of surface and spring waters produced copious amounts of ocher FeOx (photograph 14) that resembled schwertmanite (Fe-hydroxy-sulfate; Desborough and others, 2000), which forms below pH 3.5. A traverse, shown schematically on figure 7, starts with extremely acid, metal-rich mine drainage that flows over a large sulfidic dump (photograph 15) and mixes with surface waters and spring waters over a distance of about 1,200 m. Mixing in this zone caused FeOx deposition, but the pH stayed between 3.2 and 3.4, probably reflecting acid released during hydrolysis of iron. Another factor in this reach was a layer of ferricrete that coated alluvium in the bed. At the 1,500-m mark (fig. 7) this small flow (20–40 gpm) joined the much larger Galena Canyon creek (400–700 gpm during flood stage), resulting in a pH rise to 6.8. This mixing zone of milky and rusty waters extended for 100–200 m. The evolved waters had much lower metal concentrations, less than 1 percent compared to the source, but still high in Al, Cd, Cu, Fe and Zn. The outflow of metals and acid in June of 1999 appears to have overwhelmed the capacity of the area



Photograph 12. A series of mine tunnels in the Dean Mine complex released acidic drainage that reacted with sulfidic waste rocks. The siliceous wallrocks at the upper tunnels provided no acid neutralization, but the lower tunnel (gray rocks, upper part of photograph) was in limestone and the mine drainage was near neutral. These tunnels were plugged and the dumps reclaimed in 1998, with major improvements in water quality.



Photograph 13. The creek flowing north from the Dean mine workings and dumps was acidic and choked with iron flocculate in 1997, but the reclamation in 1998 produced a marked improvement in water quality. In June of 1999 the water was clear and created a small amount of white precipitate of aluminum at pH 7.2.

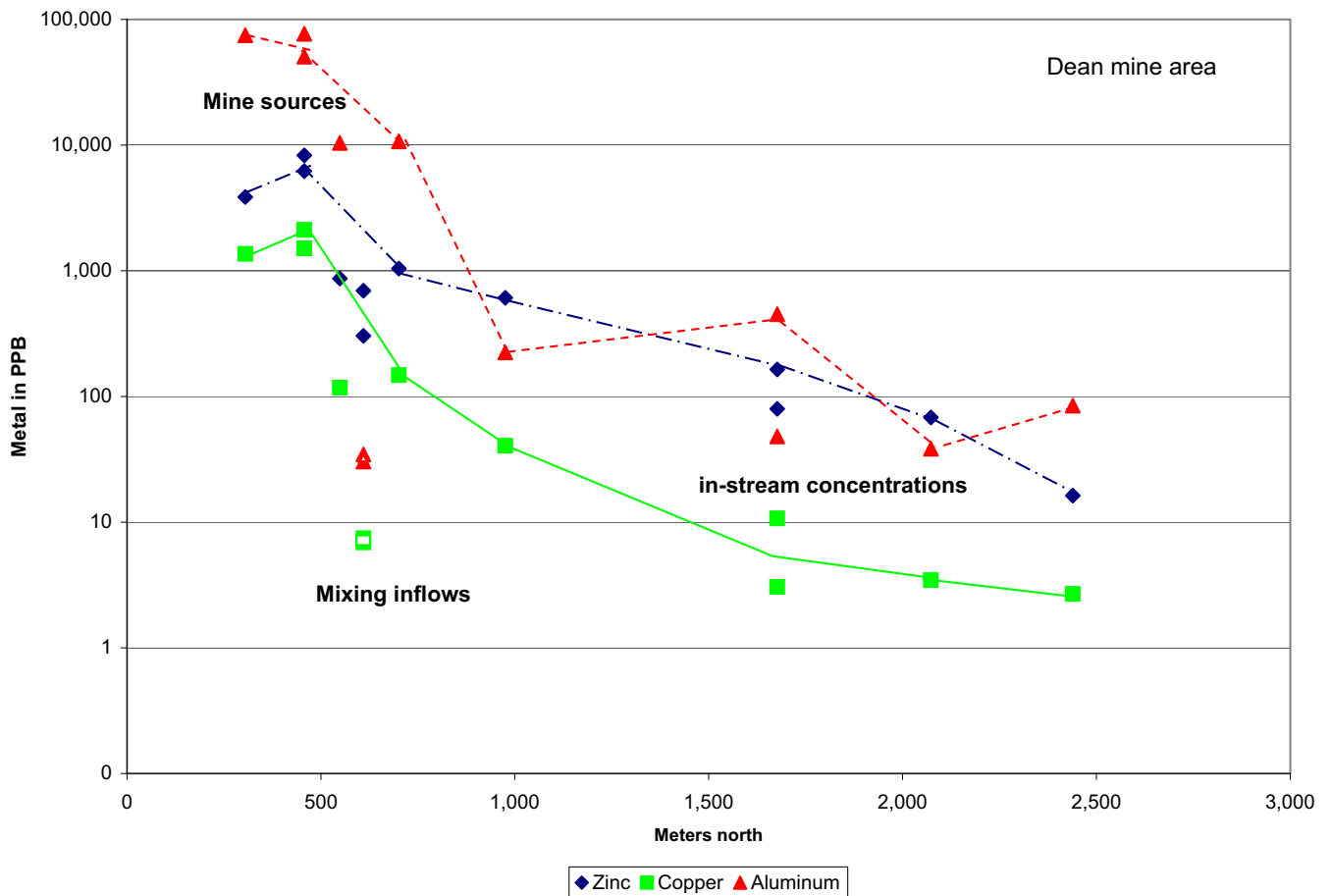


Figure 6. Evolution of mine drainage in the Dean mining area.



Photograph 14. The ocher materials shown here formed when acidic mine drainage in Iron Canyon evolved to higher pH, causing iron minerals (possibly schwertmanite) to precipitate. Concentrations of copper and other base metals decreased as they were adsorbed on the iron flocculate.



Photograph 15. The sulfidic mine dump in Butte Canyon is fairly typical of mine waste from a polymetallic vein deposit. Mine drainage reacts with the dump waste and adds acid and metals to water that has a pH of 2.2 at the collapsed portal.

to accomplish natural attenuation. During this unusual spring “flood” of 1999, similar acidic waters from historical mine adits and springs were treated by Battle Mountain Gold using a temporary water-treatment plant in adjacent Iron Canyon. During normal spring runoff, the springs and adit discharges in these canyons flow on the surface for only 100–200 m.

Coon Creek—An Unusual Example

Coon Creek, flowing west from the Rip Van Winkle mine (photograph 16), is an example of how physical conditions control the chemistry of mine waters. The lower tunnel is dry, and no seeps come from the waste dumps. The concern here is

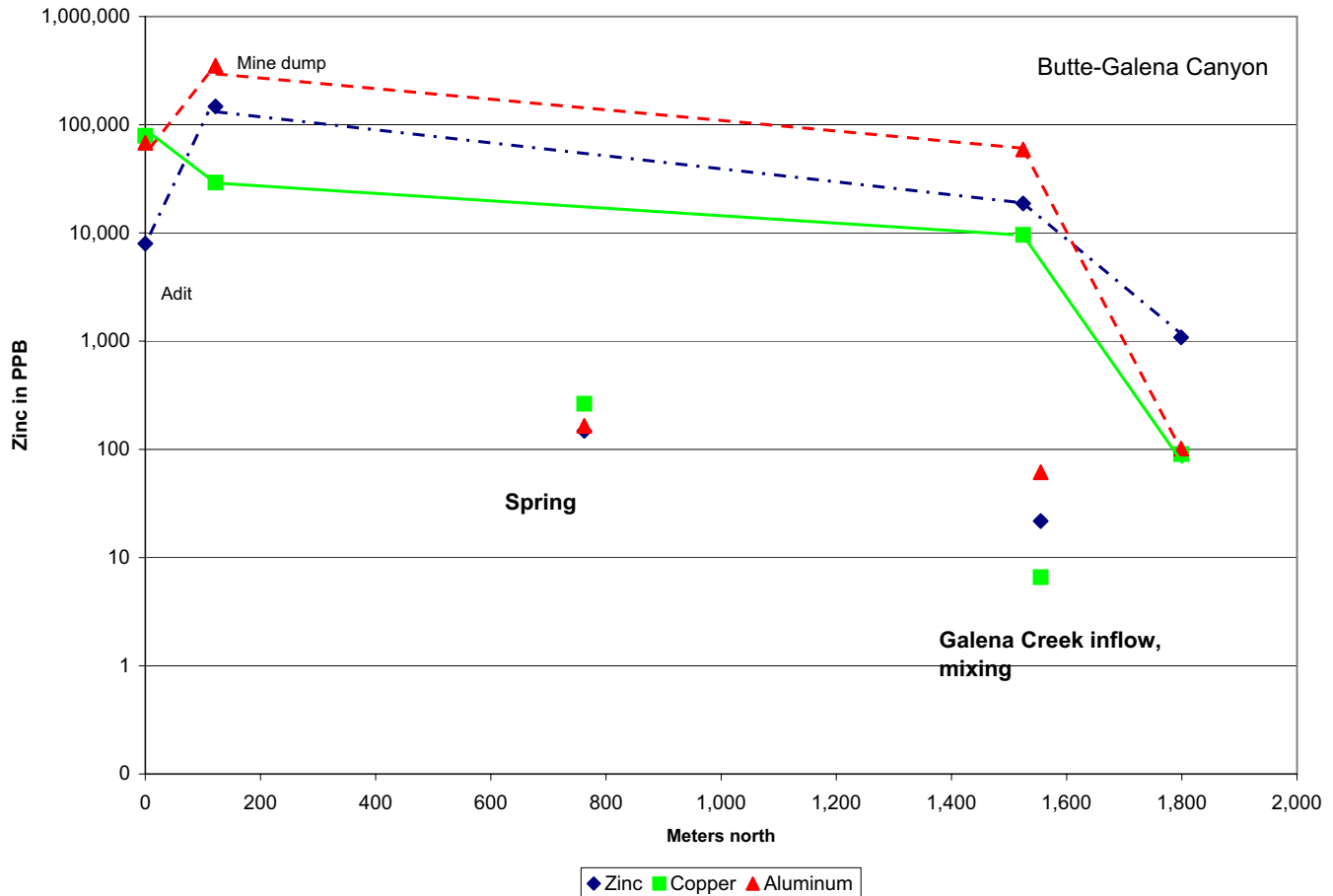


Figure 7. Evolution of mine drainage in the Galena mining area.

for stream waters flowing over, and through, mill tailings (photograph 17). Geochemical results are summarized on figure 8. Four visits to this area from 1996 to 1999 provided results that seem paradoxical on first examination. Measurements of pH of stream waters in contact with tailings showed values to be consistently in the range of 6.8 to 7.4, rising to about 8.4 west of the tailings. Laboratory leach tests (Nash, 2001) confirmed the expectation that the sulfidic tailings should create acidic, metal-rich waters, but no such surface waters were detected. Closer inspection on the third visit disclosed thin films of red FeOx precipitate along the edge of the creek next to the tailings, and depressions made by cattle hooves contained small pools of reddish water. The red seeps proved to have pH values of 1.7 to 2.1 and very high conductivity (2,000–4,000 microsiemens per centimeter). Not surprisingly, chemical analyses of the acidic seeps showed extremely high metal concentrations, especially for Cu and Zn, which were more than 40,000 and 1 million ppb, respectively. Cadmium mimics Zn, reaching more than 8,000 ppb in tailings seeps. Repeated sampling of Coon Creek shows that relatively small concentrations of metals actually enter the stream (about 200–400 ppb Zn) despite the evidence in leach tests and in the seep waters for thousands of ppb of Zn and other metals. The

discrepancy appears to be explained by high clay content in the tailings that gives them very low permeability: only small amounts of water can infiltrate, react, and exit these tailings. The conclusions for this mining area are (1) despite moderate precipitation (about 25 cm/year), little or no water from waste dumps and mine workings enters the nearby creek, and (2) although mill tailings are in contact with stream waters, the high potential for acid generation and metal release are limited by low permeability. Poor mining practices and potentially reactive waste materials at this mine ultimately produce only slightly degraded water. Natural attenuation further minimizes metal concentrations within about a 0.5 km of the last tailings impoundment.

Attenuation Mechanisms

Three stages in a related process appear to be involved in the attenuation of metals in the areas described above (1) mixing of waters, (2) rise in pH, and (3) precipitation of Fe-Mn oxides and adsorption of trace metals. The attenuation reactions start with mixing of waters, seen clearly at the junction of tributary streams, and inferred from measure-



Photograph 16. View of Rip Van Winkle mine area with tailings six ponds in Coon Creek. The mine tunnel and waste dump (dark gray) are in the right side of the view.



Photograph 17. Acidic seepage from the Rip Van Winkle tailings create thin films of red iron minerals on mixing with Coon Creek. Shown here is a high flow stage for this small creek in June of 1997.

ments of locally variable and low conductivities that suggest ground-water inflow (springs) into the stream. Reactions of acidic mine waters with rocks and alluvium also are likely but not evident in the spatial distribution of conductivity and pH values, which do not change immediately at lithologic

contacts. More specifically, the inflowing surface and ground waters attain high alkalinity values by reaction with rocks and alluvium, and the high-alkalinity waters neutralize the acidity of the mine waters. The high alkalinity of surface and ground waters (median 170 ppm CaCO_3 , many values > 200 ppm

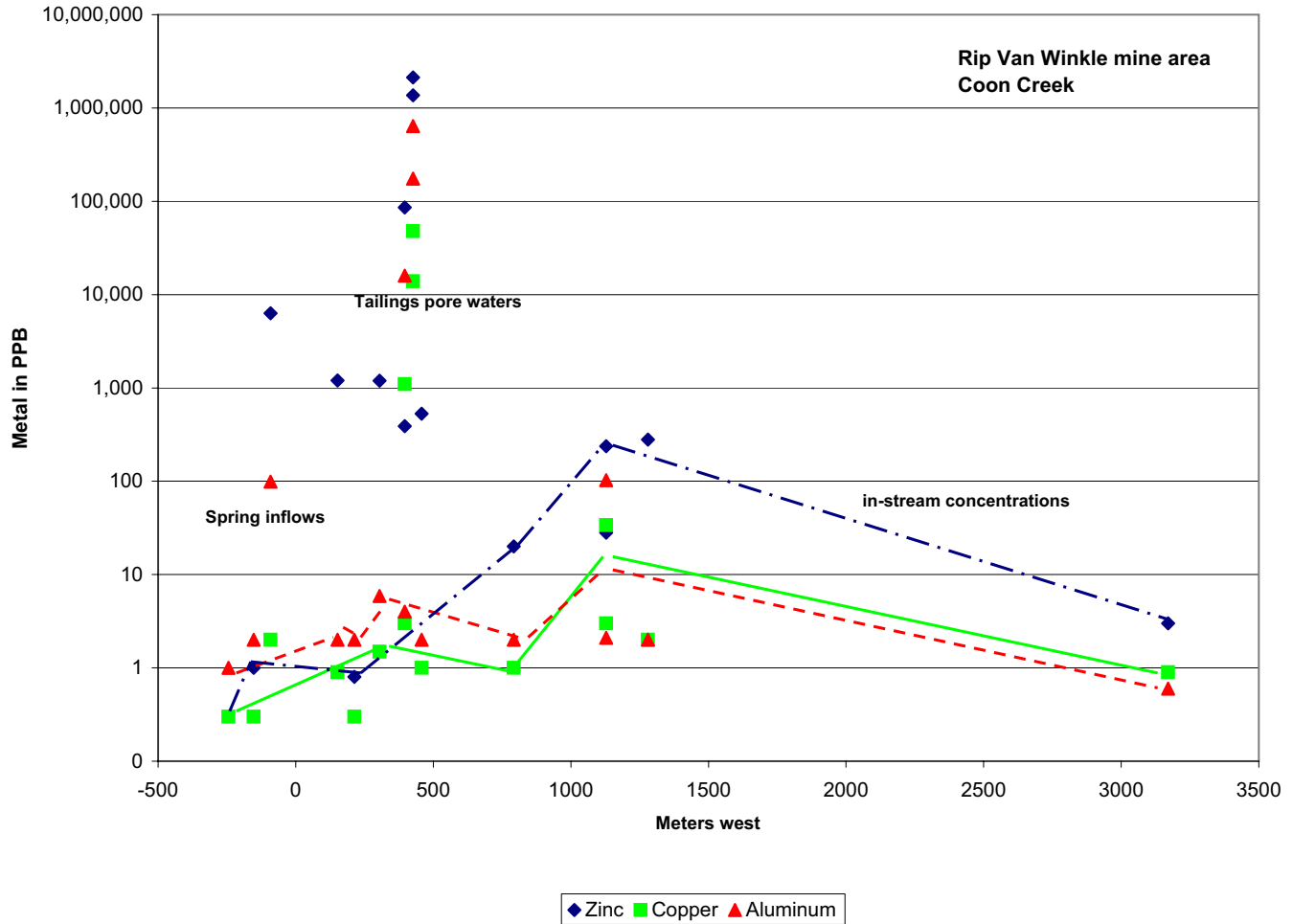


Figure 8. Evolution of mine drainage in Coon Creek west of Rip Van Winkle mine.

CaCO₃) is an important factor in the efficacy of this process.

As the pH of the mixed water rises from below 3 to more than 4, red to ochre FeOx coatings precipitate in the channel. Some of this has the appearance of schwertmanite (Fe-oxy-sulfate; Desborough and others, 2000) and is especially abundant in the Iron Canyon–Butte Canyon area (photograph 14). Concentrations of trace metals in water, especially As, Cu and Pb, decrease sharply along with the decrease in Fe at about pH 4 (fig. 2; fig. 9). Concentrations of Zn and Cd also decrease, but less dramatically, and a higher fraction of these metals stay in solution at pH values of 4 to 7. Plots of metal concentrations vs. Fe concentration show the strong correlation (fig. 9); concentrations of Cd, Co, Cu, Ni, Pb, and Zn decrease with Fe over the pH range of about 4 to 7. The behavior of As, which is not a base metal, differs from those metals. The decrease in As concentration from pH 3 to 5 could be evidence for adsorption onto FeOx as they flocculate. The general increase in As at pH values above 7 (fig. 9) suggests the adsorption mechanism does not hold under alkaline conditions and low Fe concentrations where As is soluble or desorbs from FeOx. If one plots the trace-metal concentrations against an unreactive element, such as Na or Sr (which are called “conservative”) there

is no correlation (fig. 9)—suggesting that dilution is not a significant factor in the attenuation of metals. The compositional trends and metal associations strongly resemble the adsorption experiments of Smith (1999). More detailed, more closely spaced sampling would clarify the attenuation mechanism(s).

As observed elsewhere (Nash, 2002; Plumlee and others, 1999), Zn and Cd concentrations, and in places Cu concentrations, remain high after neutralization in these mixing reactions. This is predicted by adsorption reaction models (Smith, 1999). Once the waters evolve through the pH 4–7 range and FeOx phases flocculate, there are few other natural reactions that can remove significant amounts of Zn and Cd. Carbonate and hydroxide phases of Zn–Cd can precipitate, but only at higher concentrations or higher pH conditions than observed here. Alkaline waters can carry significant amounts of the oxyanions As, Mo, and Se above pH 7, regardless of whether there is acidic input to those waters. Because alkaline waters predominate in Nevada, more attention is needed on the effect of metals (including oxyanions) in these waters and the possibility of long-distance transport to playas or sinks where evaporation will increase metal concentrations.

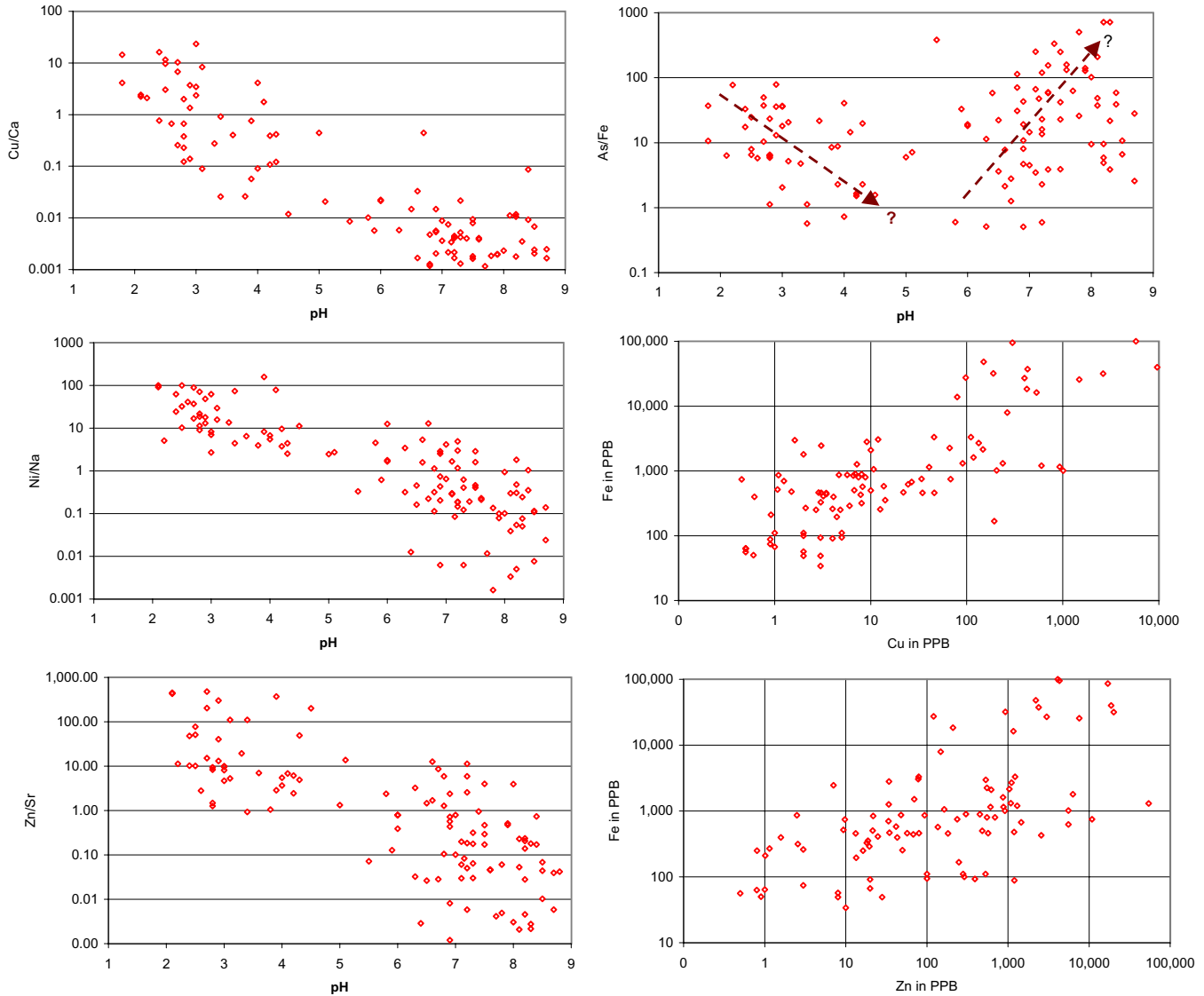


Figure 9. Evolution of mixed mine-related waters as a function of pH, iron, and unreactive elements.

Quality of Streams Leaving Mining Areas

The quality of surface waters flowing a kilometer or more from mining areas may be of greater significance than that found locally at mine adits or near mine waste because those waters more distant from mining are used by wildlife, ranches or farms, and by humans. However, few streams actually flow out of the historical mining districts in the Humboldt River basin. Study of the 40 mining areas shows that 17 mining areas have no streams flowing near the mines, or the streams flow only on rare occasions (i.e., they were not flowing during the wet years of 1998 and 1999). Eight (20 percent) of the mining areas have ephemeral streams that flow after storm events, and 5 (12 percent) have intermittent streams that flow

for several weeks of the wet season. Ten mining areas (25 percent) are drained by substantial streams that may flow most of the year, but the largest of these is less than 3 m wide. Only one of the streams, the North Fork of the Little Humboldt River (east of the Buckskin-National mine), flows into a tributary of the Humboldt River. Several of the larger streams flow into internal drainages (such as Star Creek, outside of the Humboldt River watershed) and most flow out of canyons and infiltrate thick caliche-bearing alluvial deposits at the range front (such as Galena and Iron Creeks).

Water was sampled from 13 streams downstream from where these streams interacted with mines, mine waste, or mill tailings to determine the amount of metal contamination leaving the mining area. Several streams flowing from areas of mining were not sampled because they did not interact with significant mines or mined materials. Analytical results

are summarized for four of the most significant, potentially toxic metals (As, Cd, Cu, and Zn) in table 2. The sampling sites were as far from the mining areas as possible (close to the point of disappearance into alluvium) or about 2–4 km downstream from mining. The metal concentrations are quite low at these sites, and all appear to be close to or lower than the concentration values stipulated for likely beneficial uses, chiefly aquatic life. Concentrations of As are high at six sites, but the measured values of 19 to 37 ppb are below the most demanding criterion, domestic drinking water. Zinc is elevated at several sites, but the highest values in the range of 43 to 100 ppb, are close to the aquatic life water-quality standard. Copper is elevated (3 to 13 ppb) at six or more sites, and these values may be high enough to have adverse effects on aquatic life. Some of these more complicated situations are discussed next for streams that have class designations.

Six headwater streams in northern Nevada that are contaminated by mine-related effluent are shown on figure 10. The metal concentrations in these streams are thought to be elevated and a possible threat to aquatic life, but more detailed sampling needs to be done. Only short distances, comprising a small fraction of the larger streams in northern Nevada, appear to be contaminated by effluent from historical mines.

Nevada Class-A Waters in Mining Areas

The waters of Nevada are classified in a system of classes, A to D, based on the amount of human or industrial activity and beneficial uses (NDEP, 2002). Some streams in or near mining areas have been designated as class-A waters, the most pristine in the State and therefore having the most stringent quality standards. The NDEP quality standards for class-A waters use phrases such as “None attributable to man’s activities” and “None” for toxic materials (NDEP, 2002). The chemical criteria for water quality are related to beneficial uses such as municipal or domestic water supply and aquatic life, and the tabulated criteria (NDEP, 2002, code 445A.119 and elsewhere) are generally based on the same scientific and technical information used by EPA and other State agencies.

Where there are multiple beneficial uses, the most stringent criterion is used; for instance, the Cu criterion for aquatic life and the As criterion for drinking water. Many pages of class-A waters are listed and are a bit confusing because of the “tributary rule” whereby headwater tributaries apply if the stream is listed.

Parts of eight historical mining districts studied here are in headwaters designated class-A waters: (1) Star Creek, Pershing County; (2) Bottle Creek, Humboldt County; (3) Quinn River, Humboldt County; (4) North Fork Little Humboldt River, Humboldt County; (5) Lewis Creek, Lander County; (6) Birch Creek, Lander County; (7) Maggie Creek, Elko County; and (8) North Fork Humboldt River, Elko County. The Cu concentration in Star Creek and the Zn concentration in Coon Creek (tributary to Maggie Creek) appear to exceed the stringent standards in those class-A waters. Birch Creek near the Quito mine may be slightly contaminated by seeps from mine waste, but the main stem of Birch Creek seems to have good water quality. Bottle Creek in the Jackson Mountains does not appear to be influenced by the Bottle Creek mercury district, which is in a basin to the northeast. The contamination from the National mine, described earlier, influences Charleston Gulch, a tributary of the Quinn River that is designated a class-A water. Gance Creek, a tributary of the North Fork of the Humboldt River in the Independence Range, flows through the Black Beauty mine (LaPointe and others, 1988); seeps from the mine waste dumps contaminate Gance Creek (photograph 18), but the seeps are small in comparison with the stream and the high neutralization capacity from the carbonate rocks of the area probably mitigates the acidic seeps within 200 m (but no analyses were made). The headwaters of Lewis Creek (Dean Creek) flow close to mine waste and mill tailings from the Morning Star mine, which discharge a few low-flow seeps of relatively low metal concentration; no downstream sample was collected, but I presume that natural processes reduce the concentrations to acceptable levels within a few hundred meters. I did not sample the headwaters of the North Fork of Little Humboldt River east of the Buckskin mine, but it probably is somewhat contaminated (fig. 10).

Table 2. Composition of streams leaving six mining areas in northern Nevada.

[Cond, conductivity]

Site	Number of samples	Distance (m)	pH	Cond (μS/cm)	Al (ppb)	As (ppb)	Cd (ppb)	Cu (ppb)	Fe (ppb)	Zn (ppb)
Dean mine	avg 2	2,050	7.6	440	66	3.0	2.9	2.9	355	48
Hilltop mine	avg 2	700	7.5	500	108	35	1.6	9.1	222	19
Hilltop district	1	2,400	7.6	290	32	7.8	0.2	2.0	49	8.0
Butte mine	1	1,800	6.9	810	102	6.2	63	91	1,310	1,085
National mine	1	760	6.0	200	51	2.0	0.3	5.0	110	100
Rip Van Winkle mine	avg 3	1,200	8.1	420	36	24	3.7	13	320	265

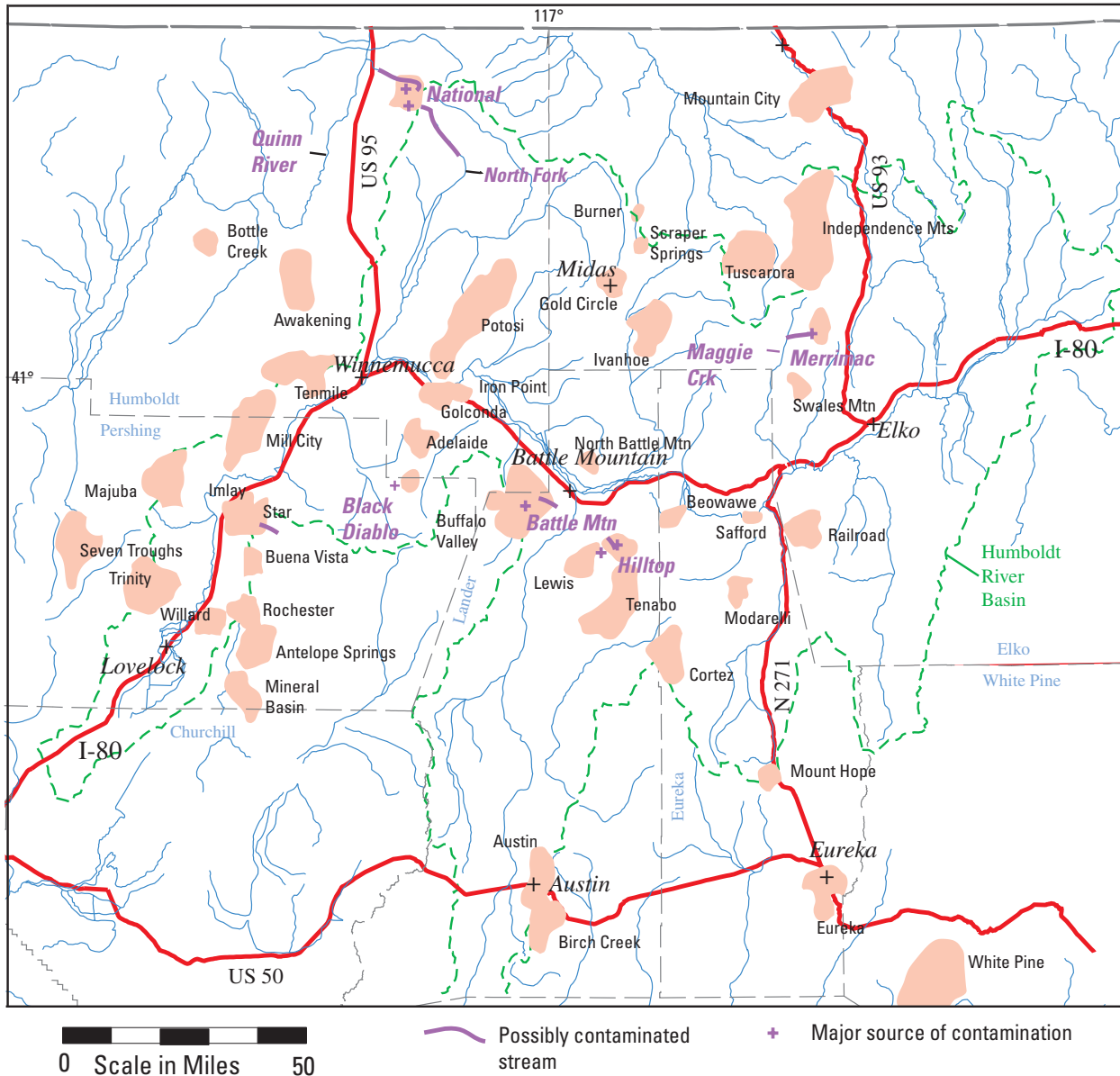


Figure 10. Major sources of contamination and possibly contaminated streams in northern Nevada. Six stream segments, shown in purple, have elevated metal concentrations that may be threats to aquatic health within a few kilometers of mines.

Class-B waters, with less stringent quality standards than class A, are downstream from the headwater reaches, often in the foothills regions bordering the National Forest lands, where there is minor to moderate influence by man’s activities (such as ranching). None of the areas studied were in class-B waters, but many of the current mining operations, such as the Carlin trend, are near these waters.

Nevada also classifies some of its larger streams and rivers by a system of beneficial uses that differs from the class system. Six segments of the Humboldt River are described in detail (NDEP, 2002, 445A.202-445A-207), including quality standards based on beneficial uses. Tributaries are covered by the tributary rule but not specifically listed. Some of the head-

water streams in historical mining districts described above under class-A waters may be considered tributaries to the Humboldt River.

Metal Loads and Total Maximum Daily Loads

Toxicity and health effects of water are generally related to concentrations of contaminants (Manahan, 1994; Smith and Hyuck, 1999), but in recent years there has been increasing use of metal loads for watershed management (Black, 1996; NDEP, 2002). Metal loads and associated concepts were part of the original Clean Water Act in 1972 when the concept of



Photograph 18. Sulfidic mine waste at the Black Beauty mine, Independence District, releases acid (pH 2.4) and metals to seeps that flow into Gance Creek.

total maximum daily load (TMDL) was introduced. The State of Nevada is developing methods and priorities for water-quality management by TMDLs (www.ndep.state.nv.us/ndep/bwqp/tmdl/htm/).

Metal loadings, defined as the metal concentration times flow volume and expressed in terms such as pounds or grams per day, provide an alternative way to evaluate or rank mining-related water contamination. One complication is the need for a measurement of stream flow, a complicated task. I have made estimates for small flows from mine workings, seeps, and streams in the 1- to 300-gallons-per-minute range. Examples of metal loads are in table 3 in which loads, in grams/day (g/d), are computed for four sources and four downstream flows after mixing and attenuation. To help understand magnitudes, the loads are compared with those computed for the Humboldt River. All of these values are approximate estimates, with an uncertainty of about ± 100 percent (for uncertainties in both analytical values and in Q, flow volume). The Humboldt River samples (three) are from the main stem between Battle Mountain and Dunphy. The loading values are easiest to grasp when considered relative to other values in the same units (grams per day):

1. Metal loads decrease significantly downstream from sources, reflecting the benefits of attenuation reactions. The in-stream values are low compared to those at source adits or seeps.
2. Metal loads for all metals at historical mine sources are low in comparison to those of the Humboldt River, chiefly because of the low flow volume at the mine sources.

A good example of the load “paradox” is in the values for As: the concentration of As is relatively low (8 to 9 ppb in my analyses) in the Humboldt River, well below the drinking-water standard (50 ppb), but the load of 10 grams/day is much higher than for the mine drainages. Likewise, for Cu and Zn the concentrations in the Humboldt River are low (3 and 1 ppb, respectively), but the loadings are 100-fold higher than the highly concentrated but low-flow mine drainages. None of the sampled mine waters flow into the Humboldt River. This comparison to the Humboldt River is highly simplistic but makes the point that the metal loadings from historical mining areas studied are low relative to the largest flow of water in the region.

Discussion and Conclusions

Reconnaissance hydrogeochemical studies of the Humboldt River basin and adjacent areas of northern Nevada have identified local sources of acidic waters generated by historical mine workings and mine waste. Where waters attain pH values of less than about 3, the waters mobilize extremely high concentrations of many potentially toxic metals; these conditions generally occur where large amounts of pyrite are oxidizing but also can be created when sulfate mineral crusts on the surface of mine waste and mill tailings dissolve during brief storm events. Metals that are enriched and potentially toxic in these acidic mine waters include Al, As, Cd, Cu, Fe, Mn, Pb, Se, and Zn. Only in a few rare instances are some

Table 3. Examples of metal loads from mining areas compared to Humboldt River.

[Cond, conductivity in microsiemens per centimeter. Q, flow in gallons per minute (gpm); LRH, load relative to Humboldt River; loads in grams per day (g/d). Water types—MDW, mine drainage; SW, stream; SWL, stream leaving mining area; TPW, tailings pore water. na, not analyzed]

Sample ID	pH	Cond (μ S/cm)	Water type	Q (gpm)	Al (g/d)	Al (LRH)	As (g/d)	As (LRH)	Cu (g/d)	Cu (LRH)	Fe (g/d)	Fe (LRH)	Zn (g/d)	Zn (LRH)
Battle Mountain district														
NNW131	3	>2,000	MDW	2.5	0.18	0.00	0.11	0.01	0.19	0.03	2.86	0.01	0.10	0.23
NHW834	8.5	510	SWL	25	0.01	0.00	0.00	0.00	0.00	0.00	0.11	0.00	0.00	0.01
Hilltop district														
NHW498	2.7	1,740	MDW	2.5	3.38	0.09	0.11	0.01	0.12	0.02	3.01	0.01	0.11	0.26
NHW505	7.1	470	SWL	25	0.03	0.00	0.00	0.00	0.00	0.00	0.05	0.00	0.00	0.01
NNOW320	7.8	414	SWL	250	0.01	0.00	0.01	0.00	0.00	0.00	0.06	0.00	0.03	0.06
Merrimac district														
NHW650	1.8	2,500	TPW	0.1	0.35	0.01	0.10	0.01	0.03	0.00	2.63	0.01	0.74	1.72
NNW995	7.9	444	SWL	5.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.02
National district														
NHW629	3.1	1,430	MDW	10.0	1.13	0.03	0.03	0.00	0.01	0.00	6.27	0.01	0.16	0.37
NNW120	2.7	1,415	MDW	10.0	1.64	0.05	0.02	0.00	0.02	0.00	1.47	0.00	0.16	0.38
NNW124	6	202	SWL	500.0	0.14	0.00	0.01	0.00	0.01	0.00	0.30	0.00	0.27	0.63
Humboldt River														
Hum. R. (avg 3)	7.8	370.0	SW	225,000	35.9	1.00	10.4	1.00	5.88	1.00	438.6	1.00	0.43	1.00

other elements, such as Mo, Sb, Te, Tl, and U, enriched sufficiently to pose a health threat to humans or wildlife. The processes that create these acidic, metal-rich waters in Nevada are the same as for other parts of the United States or the world, but the scale of transport and the fate of metals differs. In Nevada, acidic solutions do not migrate as far as in mining areas elsewhere because natural processes generally act to neutralize and attenuate metal concentrations within less than a kilometer of the source. The arid climate and associated soil-forming processes explain the reduced scale of metal mobility in Nevada. The same processes and the importance of caliche soils can be expected in similar climatic regimes of the Great Basin or other arid parts of the world.

Acid mine drainage is rare in historical mining districts of northern Nevada, and the volume of drainage rarely exceeds about 20 gpm. My findings are in agreement with those of Price and others (1995) who estimated that less than 0.05 percent of inactive mines are likely to be a concern for acid mine drainage. Most historical mining districts have no draining mines, and only a few have as many as three. Most drainage from mine workings appears to be related to melting snow plus spring rains; runoff from mine-waste dumps or mill tailings is generally limited to a few weeks of a year. Only in two districts (Hilltop and National) does water affected by mining flow into streams of significant size and length (more than 10 km).

The results of these reconnaissance studies offer encouraging evidence that abandoned mines in northern Nevada create only rare and local water-quality problems. In this semi-arid climate, the high neutralization capacity of caliche soils and other natural processes are sufficient to compensate for these generally small sources of contamination. A few of the headwater streams in class-A watersheds may warrant more specific studies by specialists to determine in more detail the scale and magnitude of contamination. These results may provide useful analogs for future mining in the Humboldt River basin, but care must be given to matters of scale. Larger volumes of waste and larger volumes of water could easily overwhelm the delicate balance of natural attenuation described here. One example of this may be the problems that developed in Iron Canyon of the Battle Mountain district in the unusually wet spring of 1998 that caused acidic drainage to flow 2 to 5 times farther than in normal seasons.

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