



A preliminary summary of multidisciplinary studies in the upper Pecos River area, Santa Fe and San Miguel Counties, New Mexico

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A PRELIMINARY SUMMARY OF MULTIDISCIPLINARY STUDIES IN THE UPPER PECOS RIVER AREA, SANTA FE AND SAN MIGUEL COUNTIES, NEW MEXICO

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Abstract—The Pecos mine and Alamos Canyon mill in the upper Pecos River area have been identified by state and federal agencies as point sources of contamination for Pb, Zn, Cu, Se, Cd and Cr. Atmospheric Hg is suspected as a possible non-point source contaminant. The U.S. Bureau of Reclamation, in cooperation with the NMIMT and NMBMMR, initiated a multidisciplinary study of the headwaters of the Pecos River in 1992 in order to identify and prioritize point and non-point sources of contamination so that measures can be taken to protect water supplies for municipal, irrigation, and recreational use and to protect wildlife habitat. The largest mine in the area is the Pecos mine, a massive-sulfide deposit containing Pb, Zn, Cu, Ag and Au. Waste rock generated during mining activities (1902–1904, 1927–1939, 1943–1944) was piled at the Pecos mine site and is now a source of acidic drainage that carries elevated concentrations of metals and other elements. The crushed ore from the mine was transported by aerial tramway to the Alamos Canyon mill (El Molino site) 18 km south of the mine. This mill site is also a source of acidic drainage that carries elevated concentrations of metals. FAAS, XRF and INAA analyses confirm that elevated concentrations of Cu, Pb, Zn and Cd occur in stream sediments below both the Pecos mine and Alamos Canyon mill sites. In addition, Zn is elevated in sediments collected at a dam above the fish hatchery. Elevated concentrations of Cs, As, Ag, Au, W, Br, Se, Sb and Fe are also found in stream sediments collected near the Pecos mine. Chemical analyses of six sediment size fractions from six sites suggests that the metals are predominantly traveling both as larger mineral or other grains and as suspended material weathered from the mine waste pile and the tailings pile. Partial dissolution techniques designed to estimate exchangeable, organic and oxide-bound forms indicate that the largest amount of Cu and Pb were in forms solubilized by *aqua regia* but not by the three extraction techniques. The largest amount of Zn was associated with Fe and Mn oxides. Water quality is a major concern in the upper Pecos River and many agencies collect water samples from the river, monitoring wells, and the seeps. These data indicate that drainage from the Pecos mine is not significantly affecting the composition of the surface and groundwater in the area, except in the immediate vicinity of the Pecos mine and the mill site. Collectively, these studies suggest that Cu, Pb, Zn and other metals are eroded and leached from the Pecos mine dump and the tailings piles in Alamos Canyon. However, the total metal addition from these sources is insignificant compared to sediment input from drainages south of Pecos village. Atmospheric deposition and weathering in the upper Pecos River basin, not the Pecos mine or mill tailings, appears to account for most of the Hg found in the waters.

INTRODUCTION

The Pecos River is vital to the economy of eastern New Mexico, west Texas, and Coahuila, Mexico (Fig. 1). The headwaters are in the Pecos Wilderness in the southern Sangre de Cristo Mountains. According to federal and state regulatory agencies, the Pecos River basin is experiencing water quality problems. Samples of fish and waterfowl taken from reservoirs along the Pecos River exhibit elevated levels of Se, Hg, Pb, Cd and Cr (U.S. Bureau of Reclamation, Cooperative agreement no. 3-FC-40-13830, December 10, 1992). The Lisboa Springs Fish Hatchery above the village of Pecos (Fig. 2) experienced fish kills in March 1991 and every fall since 1991; reclamation of the Pecos mine and campgrounds began in 1990–1991 (R. Gallegos, New Mexico Fish and Game Department, personal commun., Feb. 21, 1995). The Pecos mine and Alamos Canyon mill (El Molino site) in the upper Pecos River area (Fig. 2) have been identified by state and federal agencies as point sources of contamination for Pb, Zn, Cu, Se, Cd and Cr (McLemore et al., 1993; Johnson and Deeds, this volume). Atmospheric Hg contamination is suspected as a possible non-point source. The U.S. Bureau of Reclamation, in cooperation with the New Mexico Institute of Mining and Technology (NMIMT) and New Mexico Bureau of Mines and Mineral Resources (NMBMMR), initiated a multidisciplinary study of the headwaters of the Pecos River in 1992 in order to identify and prioritize point and non-point sources of contamination so that measures can be taken to protect water supplies for municipal, irrigation, and recreational use and to protect wildlife habitat.

The purpose of this paper is to briefly summarize the various studies in the Pecos area (Table 1). Not all of the geochemical analyses are completed and data interpretation is on-going. In addition, four M.S. theses (Lisa Bockish, Tim Looper, Forrest Hawman, Joann Askins), three senior theses (Tim Pease, Catherine O'Connor, Victoria Romero), one directed study (Doug Jones), and one mid-school science fair project (Chris-

tine McLemore) are in progress or have been completed as part of this project. This report summarizes preliminary results of selected studies as of February 1995.

STUDY AREA

The study area extends from the southern Pecos Wilderness to south of Villanueva and includes many tributaries and the main stem of the Pecos River. The study area also includes Santa Fe Lake, which drains into the Rio Grande, not the Pecos River (Fig. 2). Santa Fe Lake was included because a relatively pristine mountain lake in high elevations within the Pecos Wilderness was needed as a control to compare with the

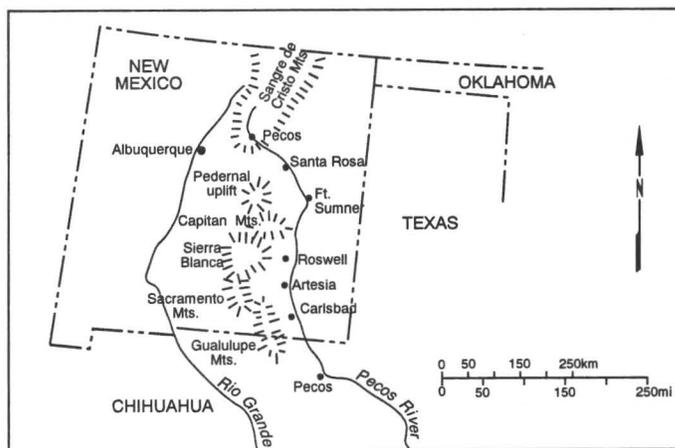


FIGURE 1. Pecos River drainage basin.

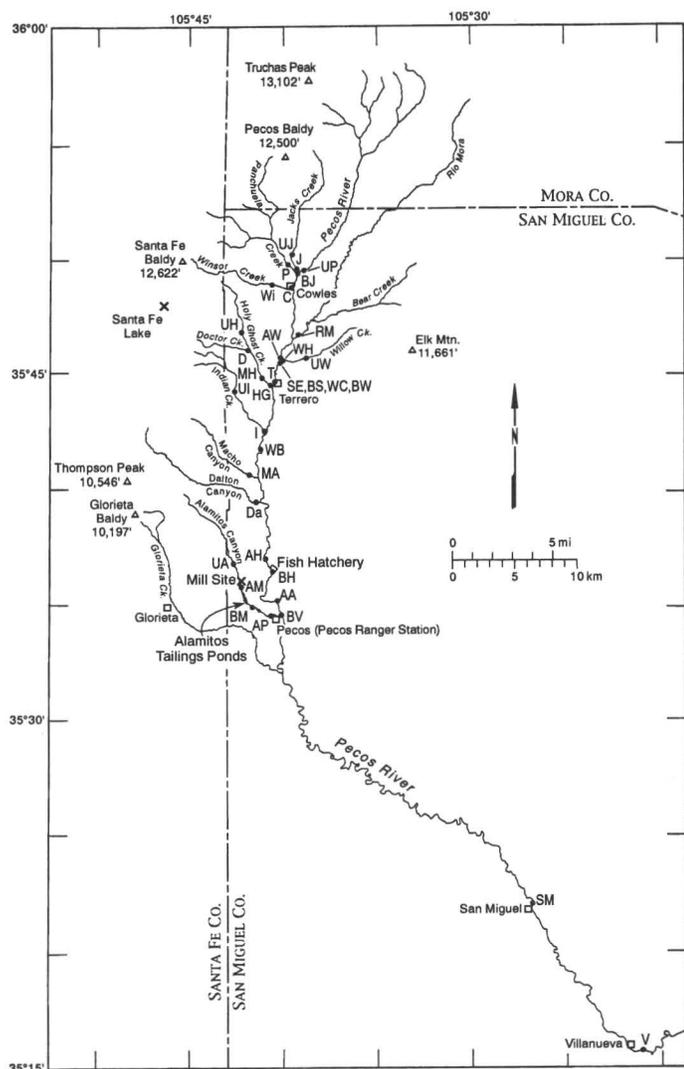


FIGURE 2. Location of sample sites in the upper Pecos River area listed and described in Table 1. Mining districts are shown in McLemore (this volume, fig. 1).

upper Pecos River, which has been disturbed by human activities. Santa Fe Lake was chosen because of relatively easy access; the mountain lakes in the upper Pecos watershed are in more remote areas and difficult to sample. Elevations in the area range from 1800 to nearly 4000 m. Climate varies from semiarid in the valleys to more humid in the mountains. Vegetation and precipitation also vary with elevation, with greater amounts in the mountains. The Pecos River is typically shallow, except during spring runoff. The maximum depth of water in the Pecos River in the study area is 3 m.

METHODS OF STUDY

Sample sites along the Pecos River and its tributaries (Table 2) were determined on the basis of well-maintained and easy access by vehicle and proximity to known mines (Fig. 2). Additional sites were added for various reasons. Samples were collected from the Pecos River during eight separate trips from September 1992 through September 1994. Stream-sediment and water samples were taken at each site during each trip. Insects were collected at selected sites during four trips. Fish were also collected wherever possible in both the Pecos Wilderness Area and in downstream reservoirs. Outcrops, mine dumps and tailings piles were sampled for chemical analyses at various times from 1992 to 1995. In addition, flow measurements and water samples were collected at three sites on a weekly basis from 1992 through 1995. Water, zooplankton and rock samples were also collected from Santa Fe Lake for analysis.

TABLE 1. Summary of multidisciplinary studies in the upper Pecos River area by the NMIMT, NMBMMR, and U.S. Bureau of Reclamation.

1. Geology of study area (V. T. McLemore).
2. History of Pecos mine and Alamos mill (V. T. McLemore).
3. Stream-sediment particle size analysis (V. T. McLemore).
4. Mineralogy and geochemistry of stream sediments (V. T. McLemore, L. Brandvold, P. R. Kyle).
5. Mineralogy and geochemistry of mineralized and unmineralized rocks (V. T. McLemore, L. Brandvold).
6. Heavy metal concentrations in six sediment size fractions (V. T. McLemore, L. Brandvold).
7. Comparison of atomic absorption metal values with those obtained by X-ray fluorescence (V. T. McLemore, L. Brandvold).
8. Partitioning and distribution of Cu, Pb, and Zn in two size fractions between exchangeable, oxide-bound, organic and residual forms (L. Brandvold, V. T. McLemore).
9. Statistical analyses and modeling of geochemical data (A. Hossain, V. T. McLemore).
10. Sediment load and metal concentrations in suspended sediment (D. Brandvold, V. T. McLemore, L. Brandvold).
11. Measurement of river flow rates, volumes, and trace metal loading (R. Radtke, S. Hansen, C. Popp, D. Brandvold).
12. Analysis of river water for major, minor, and trace metal constituents (D. Brandvold, C. Popp, L. Brandvold, R. Radtke).
13. Heavy metals, including Hg in wet and dry precipitation (atmospheric metal loading) (C. Popp, D. Brandvold, R. Radtke).
14. Metal concentrations in aquatic insects, zooplankton and fish (K. Kirk, D. Brandvold, C. Popp).

TABLE 2. Description of sample sites along the Pecos River. Sites are shown in Figure 2.

Symbol	Name	Latitude	Longitude
UP	Upper Pecos	35°49'30"	105°39'5"
UJ	Upper Jacks Creek	35°50'00"	105°39'7"
J	Jacks Creek	35°49'30"	105°39'7"
P	Panchuela Creek	35°49'55"	105°39'5"
BJ	Pecos below Jacks Creek	35°49'28"	105°39'1"
Wi	Winsor Creek	35°48'56"	105°40'3"
C	Pecos at Cowles	35°48'42"	103°39'3"
RM	Rio Mora	35°46'44"	105°39'1"
AW	Pecos above Willow Creek	35°45'43"	105°40'1"
UW	Upper Willow Creek	35°45'42"	105°38'5"
WH	Willow Creek at State Highway	35°45'34"	105°40'6"
SE	Seep, below mine	35°45'33"	105°40'7"
BS	Below seep	35°45'33"	105°40'8"
WC	Willow Creek at Pecos	35°45'35"	105°40'8"
BW	Pecos below Willow Creek	35°45'27"	105°40'1"
T	Pecos at Terrerro campground	35°44'35"	105°40'3"
UH	Upper Holy Ghost Creek	35°46'35"	105°41'59"
MH	Middle Holy Ghost Creek	35°46'35"	105°40'55"
HG	Holy Ghost Creek	35°44'30"	105°40'40"
D	Doctor Creek	35°46'3"	105°41'59"
UI	Upper Indian Creek	35°44'3"	105°42'5"
I	Indian Creek	35°42'30"	105°41'5"
WB	Pecos at Windy Bridge	35°41'50"	105°41'5"
Ma	Macho Canyon	35°40'35"	105°41'10"
Da	Dalton Canyon	35°39'35"	105°41'7"
AH	Pecos above hatchery	35°37'00"	105°41'00"
BH	Pecos below Hatchery	35°36'30"	105°41'00"
AA	Pecos above Alamos	35°35'15"	105°40'30"
UA	Upper Alamos Canyon	35°37'00"	105°42'35"
AM	Alamos at mill site	35°35'45"	105°42'25"
BM	Alamos Below mill site	35°35'05"	105°41'25"
AP	Alamos in Pecos Village	35°34'45"	105°40'45"
BV	Pecos below village	35°34'32"	105°40'10"
SM	Pecos at San Miguel	35°22'00"	105°26'45"
V	Pecos at Villanueva	35°15'30"	105°20'15"

Stream-sediment and rock samples were analyzed for metal concentrations using flame atomic absorption spectroscopy (FAAS); water samples were analyzed using graphite-furnace atomic absorption spectroscopy (GFAAS). Rock, ore and stream-sediment samples were also analyzed for major and trace elements by X-ray fluorescence (XRF) and instrumental neutron activation (INAA). FAAS analytical procedures and quality control data were described by McLemore et al. (1993, this volume), Pease (1994) and Brandvold et al. (1995). XRF analyses were performed only on samples with sufficient material remaining after FAAS analyses (approximately 15 g were required), using procedures described by Norrish and Chappell (1977), Hallet and Kyle (1993) and Pease (1994). INAA were performed on 23 samples collected in May 1994 to determine if INAA is applicable to environmental studies and to determine the concentrations of environmentally sensitive elements such as Sb, As, Zn, etc. Analytical procedures and quality control were described by Hallet and Kyle (1993) and Pease (1994). Aquatic insects were acid digested and subsequently analyzed for metal concentrations by GFAAS, using procedures described by Lynch et al. (1988). Fish were acid digested using the microwave heating techniques and analyzed by FAAS using the procedures of Nakashima et al. (1988).

GEOLOGY

The geology of the upper Pecos River area is complex, with rocks ranging in age from Proterozoic to Recent. Proterozoic rocks crop out along the Pecos River and several tributaries north of Pecos. The oldest rocks are Proterozoic mafic metamorphic and volcanoclastic rocks that comprise the Pecos greenstone belt. The most abundant Proterozoic rocks are plutonic, consisting of granite, tonalite-trondhjemite, gabbro, diabase and ultramafic rocks (Robertson and Condie, 1989). Chemical composition of these rocks was determined by Wyman (1980), Fulp (1982), Coddling (1983), Klich (1983), and Robertson and Condie (1989).

Overlying sedimentary rocks consist of limestone, sandstone and shale. Mississippian sedimentary rocks of the Arroyo Peñasco Group unconformably overlie Proterozoic rocks and consist of as much as 71 m of sandstones and limestones. Pennsylvanian sandstones, shales, thin coals and limestones overlie Mississippian and, locally, Proterozoic rocks in the Pecos River area. Pennsylvanian-Permian strata include the Magdalena Group (686 m thick) and the Sangre de Cristo Formation (>610 m thick), and are overlain by Permian siltstones, limestones and sandstones of the Yeso (91–152 m thick), San Andres (12–67 m) and Bernal (23–46 m thick) Formations. Triassic sandstones (Santa Rosa Sandstone, 58–76 m thick) crop out in the extreme southern portion of the study area. Samples of each formation were collected and analyzed for major and trace elements. Pleistocene to Recent alluvial, terrace and floodplain deposits occur throughout the area.

MINING ACTIVITIES

Mining began in the late 1880s in the southern Sangre de Cristo Mountains. Seven types of deposits are found in nine mining districts in the area (Harley, 1940; McLemore, this volume). The largest is the volcanic-massive sulfide deposit at the Pecos mine in the Willow Creek district. Production from the Pecos mine occurred in 1902–1904, 1927–1939 and 1943–1944. It was the largest Pb and Zn producer in New Mexico from 1927 to 1939 and is one of the top ten Pb and Zn producers in New Mexico. Production from other deposits in the area is insignificant.

DESCRIPTION OF PECOS MINE DUMP AND ALAMITOS CANYON TAILINGS PILE

Waste rock generated during mining activities was piled at the Pecos mine site and is now a source of acidic drainage that carries elevated concentrations of metals and other elements (S.M. Stoller Corp., 1993). The waste pile consists of several dumps within an area of approximately 7.7 ha. Estimates of waste rock volume vary from 66,151 to 72,630 m³ of material. The waste pile is underlain by a layer of colluvial materials, less than 5 m thick and consisting of clay and sedimentary rock fragments (Johnson and Deeds, this volume).

Mineralogically the mine waste pile is very heterogeneous (Table 3). Chemical analyses of the mine waste rock samples are summarized in

TABLE 3. Mineralogy of the ore deposits at the Pecos mine and vicinity (Harley, 1940; this study). *Found in the mine waste pile at Pecos mine (this study).

<i>Major Ore Minerals</i>	
*sphalerite	ZnS
*galena	PbS
*chalcocite	Cu ₂ S
<i>Minor Ore Occurrences</i>	
*bornite	Cu ₅ FeS ₄
tetrahedrite	(Cu,Fe) ₁₂ Sb ₄ S ₁₃
native gold	Au
argentite	Ag ₂ S
proustite	Ag ₃ AsS ₃
<i>Oxidized Minerals</i>	
*malachite	Cu ₂ CO ₃ (OH) ₂
*azurite	Cu ₃ (CO ₃) ₂ (OH) ₂
*angelsite	PbSO ₄
*smithsonite	ZnCO ₃
*chalcocite	Cu ₂ S
cerussite	PbCO ₃
*chalcantite	CuSO ₄ · 5H ₂ O
<i>Selected Gangue Minerals</i>	
*pyrite	FeS ₂
*pyrrhotite	Fe _{1-x} S
*quartz	SiO ₂
*chlorite	(complex silicate)
*actinolite	Ca ₂ (Mg,Fe) ₅ Si ₈ O ₂₂ (OH) ₂
*tourmaline	(complex silicate)
*epidote	Ca ₂ (Al,Fe) ₂ (Al,Si ₃ O ₁₂)(OH)
*Fe and Mn oxides	
*arsenopyrite	FeAsS
*biotite	K(Mg,Fe) ₃ AlSi ₃ O ₁₀ (OH) ₂
*fluorite	CaF ₂
*kaolinite	Al ₂ Si ₂ O ₅ (OH) ₄
*sericite	KAl ₂ (AlSi ₃ O ₁₀)(OH) ₂
*calcite	CaCO ₃

Table 4. Concentrations of these elements are variable, as expected from the mineralogy.

Numerous discrete and diffuse seeps occur along the base of the mine waste pile. The number of seeps and amount of water flow varies with daily storm events and snow melt as well as yearly fluctuations in precipitation. During August 1994 many seeps were dry and the total of flow was lower than on previous visits in 1992 and 1993. White and brown precipitates or froth are present along the course of the seeps that drain into Willow Creek. X-ray diffraction (XRD) and chemical (Table 5) analyses of these precipitates indicate they are a mixture of Fe, Cu and Zn sulfates and Fe and Al oxides and hydroxides, including goslarite (ZnSO₄ · H₂O).

The ore was crushed at the mine and then transported by aerial tramway to the Alamitos Canyon mill (El Molino site), 18 km south of the mine (Fig. 2; Anderson, 1938). Sulfide grains entering the mill were as large as 3 mm. A typical analysis of the mill feed was reported as 4.9% Pb, 15.4% Zn, 0.8% Cu, 113 ppm Ag, and 3.4 ppm Au (Bemis, 1932). Mill recoveries were good by the standard of the day, although variable (Bemis, 1932). The rejected waste material was conveyed to the tailings pond in Alamitos Canyon and held in place by two earthen dams, 0.7 km and 1.5 km downstream of the mill site.

Today the tailings pile occupies approximately 14 ha in the bottom of Alamitos Canyon (Sidle et al., 1991). The depth varies from 0 to 20 m and averages 9–12 m. Wet meadows with pockets of water cover some of the tailings. Reclamation is currently underway, with construction of a stream channel through the tailings pile and stabilization of the tailings by covering with clay, gravel, and soil.

The tailings consist of predominantly sand-size material (Table 6). More silt and higher concentrations of metals are found in the southern, lower end of the pile than the north end. Discharge from the tailings pile enters Alamitos Creek, is acidic, and contains elevated levels of metals (Sidle et al., 1991; Brandvold et al., 1995).

TABLE 4. Chemical analyses of mine waste rock at the Pecos mine (in ppm) using various methods of analyses (S.M. Stoller Corp., 1993). Ave. - average, Std. Dev. - standard deviation, Max. - maximum concentration, Min. - minimum concentration, No. - number of samples analyzed, na - not analyzed.

Element	Ave.	Std. Dev.	Max.	Min.	No.	Pecos mine dump (this report)
Cu	1,840	1,960	7,140	40	25	11,81
						0
Pb	9,380	10,400	33,100	41.8	25	238
Zn	17,330	30,600	150,00	204	25	31,35
			0			0
As	25	23	101	1	20	na
Cd	68	136	607	0.65	20	7.5
Hg	0.65	0.81	2.49	0.033	10	<0.1
						0
Ag	10	11	32.6	0	20	na
Al	13,740	9,880	27,000	23	5	na
Fe	52,650	35,120	129,15	10,960	12	5.3
			0			
Co	18	14	59.5	3.2	13	na
Cr	18	13	52.4	2.4	20	na
Ni	12	6	23.3	1.7	13	29

TABLE 5. Chemical analyses of sediment and precipitate from seeps along the base of the mine waste pile at the Pecos mine. Samples were digested using *aqua regia* and analyzed by FAAS at NMBMMR.

Sample Name	Date collected	Cu ppm	Pb ppm	Zn ppm	Cd ppm	Fe %
Seep 1 white	9/92	470 0	150 0	12700	na	4.09
Seep 1 brown	9/92	100 0	600	12000	na	4.9
Seep 1 (at pipe-360)	5/94	127 9	461	3455	16	na
Seep 2 (at confluence with Willow Creek-361)	5/94	193 3	134 0	5900	15	na
Seep (253)	6/93 0	163	490	38000	31	na

TABLE 6. Selected average physical and chemical properties of the tailings pile at Alamitos Canyon (from Sidle et al., 1991).

Property	Upper, north end of pile	Lower, south end of pile
% Sand	65.7	37.7
% Silt	22.9	46.5
% Clay	11.3	15.8
% Organic matter	0.91	1.61
pH	3.41	3.71
Cu mg/kg (total)	586.9	1873.0
Pb mg/kg (total)	4154.4	7225.4
Zn mg/kg (total)	245.6	1572.2
Cd mg/kg (total)	0.6	5.9

PARTICLE SIZE ANALYSES

The stream-sediment samples are poorly sorted and range in size from clay (<63 μ) to boulders as much as 1 m or more in diameter. The texture also varies from very angular to well-rounded grains. After air drying, the samples were fractionated into three size fractions by sieving: >2 mm, 63 μ -2 mm, and <63 μ . Each fraction was weighed and weight percentages were calculated. Collection and analytical procedures were described by McLemore et al. (this volume).

Statistical analyses confirm that particle size distribution varies from site to site. The <63 μ size fraction is the smallest weight percentage of most samples collected, averaging approximately 8%. The weight percentage of the >2 mm and 63 μ -2 mm size fractions varied from site to site as well as from trip to trip. Typically, more of the >2 mm size fraction was collected at most sites in the fall trips as compared to spring and summer. With a few exceptions, more of the <63 μ size fraction was collected at most sites in the spring trips.

Samples collected in May and September 1994 were also completely size fractionated into quarter phi size fractions, in order to characterize the particle size distribution. Six samples from the May trip were fractionated and chemical analyses were performed on each size fraction. In three samples exhibiting low total metal concentrations, the concentrations (Cu, Pb, Zn, Cd) increase with decrease in particle size. The <63 μ size fraction contained the highest metal concentrations. In three samples with elevated total metal values, the highest metal concentrations correspond to the largest (0.5-1 mm, 1-2 mm) and smallest (63 μ -0.125 mm, <63 μ) size fractions. This suggests that metals are traveling both as larger mineral or other grains and as suspended material weathered from the mine waste pile and the tailings pile.

MINERALOGY OF THE SEDIMENTS

Only qualitative techniques were employed (e.g., visual identification and XRD analyses) in mineral identification. The sediments consist primarily of lithic fragments and quartz (>50%), with biotite, pyroxene, and hornblende decreasing downstream away from the Proterozoic rocks. Lithic fragments consist predominantly of Proterozoic rocks. Most sediments contain minor mineral constituents (10%), including micas, clay minerals, Fe and Mn oxides, and resistant minerals (magnetite, garnet, zircon, titanite, apatite, monazite, rutile, titanium oxides). Clay minerals accumulate in the <63 μ size fractions and constitute less than <10% of most sediment samples. Pyrite occurs below the Pecos mine. Galena, chalcopyrite, and sphalerite are found only in samples from where Willow Creek crosses the Pecos mine waste dump.

CHEMICAL COMPOSITION OF THE SEDIMENTS

FAAS and XRF analyses confirm that elevated concentrations of Cu, Pb, Zn and Cd occur in stream sediments below the Pecos mine (WH to T) and Alamitos Canyon mill site (AM to BV) (Table 7). The metal concentrations varied with sampling trip at Jacks Creek (J), Pecos Below Jacks Creek (BJ), and Cowles (C), probably because of contamination resulting from cleanup of nearby campgrounds at the time these samples were collected. In addition, Zn is elevated at the Pecos Above Hatchery (AH) site. The smallest size fraction (<63 μ) typically has the large concentrations of metals. Preliminary statistical analyses indicate that Cu, Pb and Zn are slightly correlated with Fe and Mg, suggesting that these metals are associated with iron-bearing and ferro-magnesium minerals such as magnetite, pyrite, biotite, pyroxene and hornblende.

INAA is applicable to environmental studies, unless the metal concentrations are extremely high. Elevated concentrations of Cs (4-11 ppm), As (4.4-7.8 ppm), Ag (0.67-4 ppm), Au (0.011-0.156 ppm), W (0.9-10 ppm), Br (1-15 ppm), Se (below detection-2.8 ppm), Sb (0.8-2.7 ppm), Co (11-16 ppm), and Fe (3.9-4.7%) are found in samples collected near the Pecos mine. Arsenic concentrations are typically higher in samples upstream from the Pecos mine (3.2-7.8 ppm), compared to samples downstream of Terroer (1.6-4.4 ppm), suggesting that As may be anomalously high in the Proterozoic rocks in the upper Pecos River area. Samples with elevated Zn concentrations are also elevated in Fe, As and Sb, but not all samples with high As and Fe contain high Zn. A strong correlation exists between Zn and Cs.

TABLE 7. XRF analyses (in ppm) of stream sediments (<2 mm size fraction) from the Pecos River and tributaries. Sample descriptions are in Table 2 and located in Figure 2. Procedures and quality control data are in Pease (1994).

Sample site	No.	Cu avg.	Range	Pb avg.	Range	Zn avg.	Range
UJ	4	10	<10-19	23	14-43	126	98-175
J	2	69	20-117	347	67-627	729	356-1102
UP	6	14	<10-31	19	11-36	93	65-136
BJ	3	102	11-269	377	16-1093	1243	97-3534
P	5	<10	<10-11	17	13-18	45	33-61
C	2	21	18-23	63	55-70	157	117-197
Wi	4	27	11-69	51	19-136	138	52-333
RM	5	15	<10-25	17	12-20	106	85-132
AW	5	16	14-16	32	20-53	145	108-195
UW	5	13	<10-20	17	15-19	105	88-142
WH	4	136	74-786	308	164-2056	1266	617-9175
SE	4	1132	360-2070	1285	630-1960	22,15	800-57,000
WC	2	555	229-880	674	458-890	7824	4748-10,900
BW	8	241	21-470	265	28-520	3257	399-8300
T	5	18	16-21	32	27-42	383	293-560
UH	2	15	11-18	19	18-19	50	47-53
MH	1	7	na	19	na	48	na
HG	2	17	17-17	66	40-91	148	145-150
D	3	11	9-13	24	23-25	50	47-50
UI	2	12	10-13	18	17-19	38	34-41
I	3	15	11-22	17	13-25	64	46-99
WB	4	14	13-15	22	18-30	77	55-119
MA	3	12	9-13	16	15-17	56	45-67
Da	2	16	13-18	15	14-16	68	61-75
AH	5	19	11-23	33	19-44	421	285-509
BH	7	22	14-36	43	23-99	381	164-460
AA	4	13	<10-19	25	19-30	276	231-337
UA	3	14	12-16	17	17	67	58-73
AM	3	165	16-310	552	27-1000	1732	57-4040
BM	3	243	79-350	413	229-540	870	370-1210
AP	2	106	101-110	218	210-226	588	580-595
BV	7	35	11-160	80	15-430	260	104-680
SM	4	17	8-23	26	12-43	76	15-121
V	5	<10	<10-20	16	11-24	48	19-120

CHEMICAL COMPOSITION OF SUSPENDED SEDIMENTS

Suspended sediment is sediment that is suspended in the water and is related to flow rates and local erosion. Typically, suspended sediment represents clay-size material and is more readily transported downstream than bottom sediments. Total suspended sediment is typically higher in water samples collected from the Pecos River downstream of Pecos village than in samples collected upstream of Pecos, because less consolidated Pennsylvanian-Permian shales and sandstones at Pecos and downstream weather more readily than Proterozoic metamorphic rocks and Paleozoic limestones found upstream. Total suspended sediment is also higher in water samples collected from Willow Creek downstream of the Pecos mine and from Alamitos Creek downstream of the tailings piles. Total suspended sediment and flow rates of the Pecos River is typically highest during spring snow melt and after heavy rainfalls in the summer and fall.

Suspended sediment was collected by one of two methods. River water was collected in large plastic buckets and allowed to settle for several hours. The water was siphoned off, leaving a few liters of water and suspended sediment in the bottom. The residue was poured into acid-washed polyethylene bottles; the buckets were rinsed with distilled water which was also poured into the bottles. At times of high turbulent flow, river water was collected in polyethylene bottles without settling in the field. All samples were transported in coolers to the laboratory where the samples were filtered and the filtrate was dried. The filtrate (suspended sediment) was then analyzed by FAAS as previously described.

The metal concentrations in the suspended-sediment samples are variable. Metal concentrations from suspended sediment collected from Willow Creek below the Pecos mine and Alamitos Creek below the tailings pile are higher than from sites upstream; maximum concentrations for selected metals are: 306 ppm Cu, 223 ppm Pb, and 1139 ppm Zn from Willow Creek and 900 ppm Cu, 7100 ppm Pb, and 17,000 ppm Zn from Alamitos Creek. Maximum concentrations for selected metals from samples elsewhere along the Pecos River are 70 ppm Cu, 152 ppm Pb and 760 ppm Zn.

PARTITIONING AND DISTRIBUTION OF METALS IN SEDIMENTS

Metals released through weathering will be partitioned and distributed into various chemical species by processes such as adsorption, solubilization, precipitation and ion exchange. Knowledge of these species is essential in estimating the transport and bioavailability of these metals. Partial dissolution techniques have been used by many researchers to identify these various metal species (Tessier et al., 1979; Popp and Laquer, 1980; Hickey and Kittrick, 1984; Levy et al., 1992; Prusty et al., 1994; Brandvold et al., 1995). Extraction procedures were performed on the 2 mm-63 μ and <63 μ size fractions from selected Pecos River sediments using the terminology and methods of Levy et al. (1992) with some changes. The analytical procedures are discussed by Brandvold et al. (1995).

Typically, less than 5% of the metal values were found in the exchangeable fraction, with exceptions for Cu and Zn in seeps from below the mine waste dump (SE). Copper was significantly (26%) associated with the organic fraction, but the greatest percentage of Cu (56%) was associated with forms solubilized by *aqua regia* but not solubilized by the three extraction methods (ie., mineral or amorphous forms). Lead was significantly (38%) associated with the oxide fraction but the greatest percentage (56%) was also associated with forms solubilized by *aqua regia* but not solubilized by the three extraction methods. Zinc differed from both Cu and Pb in that the greatest percentage (52%) was associated with oxide forms. A similar partitioning study of suspended sediments from the Rio Grande also showed that Cu, Pb and Zn are mostly associated with crystalline forms (Popp and Laquer, 1980).

In most Pecos samples, the amount of metals in the exchangeable fraction was below the detection limit, indicating very low bioavailability (Harrison et al., 1981). This was not true for Cu and Zn in sediments below the seeps (SE), where large amounts of the metals were available.

CHEMICAL COMPOSITION OF THE WATER SAMPLES

Water quality is a major concern in the upper Pecos River and many agencies collect water samples from the river, monitoring wells and the seeps. Only some preliminary observations from this massive database are presented here. The waters downstream of the Pecos mine are similar in composition to waters upstream of the mine (Fig. 3), and are typical of surface water throughout New Mexico. The pH is average for surface waters in New Mexico (pH ranges 7.4-8.5), except for waters seeping from the Pecos mine dump and the Alamitos Canyon mill site (pH ranges 2-6). The groundwaters are also similar in chemical composition to the river waters (Fig. 3; S.M. Stoller Corp, 1993). However, the waters from seeps draining from the mine dump and from monitoring wells in the mine dump are dramatically different in chemical composition as a result of leaching and acidification of the dump (Fig. 3). The metal concentrations from river waters and groundwaters are low. However, the waters from the seeps draining the mine dump have elevated concentra-

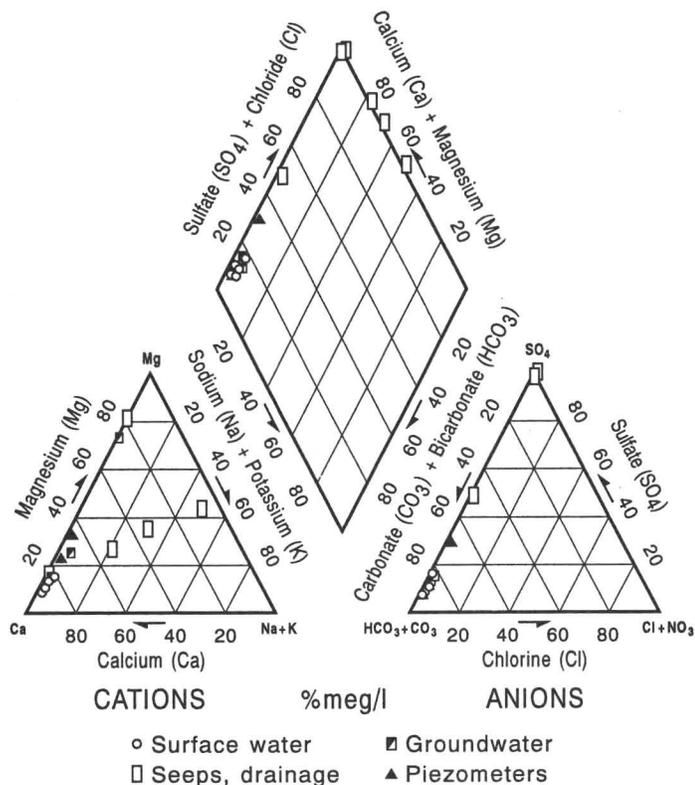


FIGURE 3. Piper diagram showing the major element composition of water samples from the Pecos mine area (data from S.M. Stoller Corp., 1993 and this study).

tions of metals (McLemore et al., 1993; S.M. Stoller Corp., 1993). These data indicate that acidic drainage from the Pecos mine is not significantly affecting the composition of the surface and groundwater in most of the study area.

TRACE METAL LOADING VIA THE MINE TAILINGS POINT SOURCE

Because the mine waste dump is a point source for Cu, Pb and Zn, water samples were collected weekly immediately above (AW) and below (BW) Willow Creek, which drains through the mine waste dump into the Pecos River (Fig. 2). These samples were collected in high density polyethylene, acid-washed bottles, acidified, filtered through 0.45 micron membrane filters and analyzed for trace metals by GFAAS. Stream flows were also determined at collection times to aid in calculating loading rates (Table 8). Without exception, trace metal loading BW increased, but the percentages varied widely, from 13% for Cd to 370% for Zn. The metals Cd, Cr and Ni showed the smallest increase (13–24%) while Cu and Zn were the highest (Table 8). Since the flows BW were higher than AW, one would expect a small increase in loading.

TRACE METAL LOADING IN THE UPPER PECOS RIVER VIA ATMOSPHERIC DEPOSITION AND WEATHERING

A goal of this study has been to estimate the relative contributions of various non-point and point sources to the concentrations of selected trace metals in the upper Pecos area. The trace metals selected include Hg, which is known to accumulate in fish in downstream reservoirs, as well as several metals (Cu, Pb, Zn) associated with the mine tailings. Cd, Cr and Ni were chosen as control species to complete the trace metal suite. These metals are not known to be associated in enhanced concentrations with the mine operations, nor are they known to be accumulating in the biota downstream of the mine.

The Pecos Wilderness encompasses the major portion of the Pecos River drainage above Willow Creek and therefore anthropogenic influences are minimized. The two major non-point sources for trace metals in surface waters are atmospheric deposition (both wet and dry) and geo-

TABLE 8. Preliminary estimate of the trace metal loading above (AW) and below (BW) Willow Creek, which drains through the Pecos mine waste pile. Values are in kg/y except where indicated. * >100% suggests that Cu and Pb are not readily transported to surface water. Sample sites located in Figure 2.

Site	Cd	Cr	Cu	Hg	Pb	Ni	Zn
Above Willow Creek (AW)	807	901	211 4	61	971	925	4270
Below Willow Creek (BW)	908	111 3	422 7	87	138 3	109 7	20210
% Increase AW to BW	13	24	100	43	42	19	370
% Contribution by Atmospheric Deposition AW	45	45	260 *	11	191 *	60	71

logic weathering of the soils and rocks. The simple model used in this study assumes that trace metal concentrations in the Pecos River above Willow Creek, which drains the entire upper Pecos River, must come from one of these two sources. In order to estimate the contribution from atmospheric deposition, two wet-dry samplers were deployed from April through October at the Pecos Ranger Station in the village of Pecos, about 20 km downstream from the Pecos mine, and at the Panchuela Cabins Campground (P) a few hundred meters from the Pecos Wilderness boundary (Fig. 2). These samples were collected weekly in acidified, acid washed, high density polyethylene bottles, and transported in coolers. Samples were filtered through 0.45 micron membrane filters, split, and analyzed for trace metals and major anions and cations. Samples for trace metals were acidified with redistilled or ultrapure nitric acid. Dry deposition was collected by rinsing the dry bucket with 500 ml of distilled water and splitting the sample for trace metals and major element chemistry. In addition to the wet-dry collectors, snow samples were collected at Santa Fe Lake during the late winter. The accumulated snow pack was sampled at 30 cm intervals and the snow was returned to the laboratory for melting, treatment, and analysis as described above. The contribution from wet deposition was then calculated by averaging the snow and rain sample concentrations and multiplying by an estimate of the average yearly precipitation (70 cm) over the entire upper Pecos River drainage. The highest estimates for trace metal contribution from wet deposition are for Cu, Pb and Zn (Table 9). The contribution from dry deposition was calculated by determining the mass of trace metal in each sample, assuming that the mass was collected over the time interval between samples on the surface area of the bucket opening. This resulted in a value in mg/km²/y for each metal, which then was multiplied by the surface area in the drainage basin, resulting in an estimate of kg/y (Table 9). By far the largest contribution from dry deposition is Cu. With the

TABLE 9. Preliminary estimate of trace metal deposition to the upper Pecos River basin via dry and wet deposition. Values in kg/y.

Site	Cd	Cr	Cu	Hg	Pb	Ni	Zn
Pecos (upper basin)-wet deposition	300	350	1470	5.5	1440	360	2830
Pecos (upper basin)-dry deposition	65	54	4100	1.1	416	197	202
Total deposition	365	404	5570	6.6	1856	557	3030
% Wet	82	87	36	83	78	65	93

exception of Cu, wet deposition contributes from 65 to 93% of the total atmospheric deposition of trace metals.

The relative contribution from atmospheric deposition can be calculated by comparing the loading AW per year to the summation of the estimates from atmospheric deposition. These values range from 11% for Hg to 260% and 191%, respectively, for Cu and Pb (Table 10). The control metals Cd, Cr and Ni were fairly consistent at 45%, 45%, and 60%, respectively. The high values for Cu and Pb suggest that while atmospheric loading is high, these metals are not readily transported to the surface waters and may be accumulating in the watershed. This phenomenon warrants further examination.

METAL CONCENTRATIONS IN AQUATIC INSECTS, ZOOPLANKTON AND FISH

Aquatic insects were collected from sites along the upper Pecos River and tributaries and analyzed for metal concentrations using modified EPA methods (Lynch et al., 1988). Plecoptera (stoneflies) were the dominant group in numbers and approximate biomass in all samples except that from Villanueva, which contained predominantly Trichoptera (caddisflies). Mercury concentrations of insects are low and exhibit no clear pattern of variation between sites and do not increase downstream from the Pecos mine (Table 11). Mercury levels in aquatic insects from areas uncontaminated by industrial sources typically range from 0.02 to 0.20 ppm, whereas those from some contaminated areas (e.g. adjacent to pulp mills using Hg fungicide) range from 1 to 23 ppm (Johnels et al., 1967; Huckabee et al., 1979; Wren and Stephenson, 1991). The other metal concentrations do show a significant pattern. Aquatic insects at sites downstream of the Pecos mine accumulated more Cu, Pb, Zn and Cd compared to insects collected upstream from the mine (Table 11); similar results were found near the Questa Mo mill in Taos County (Lynch et al., 1988). The aquatic insects are reflecting the increase in metal concentrations observed in the small size fraction (<63 μ) of the sediment.

Several other studies have examined metal concentrations in fish from throughout the Pecos River. Metal concentrations in fish taken upstream of Villanueva are low and the fish are safe to eat (Neary, 1991). Mercury is elevated in large fish from the reservoirs south of Villanueva; safety guidelines are available from the New Mexico Environment Department.

SUMMARY

Collectively, these studies suggest that Cu, Pb, Zn, and other metals are eroded and leached from the Pecos mine dump and the tailings piles in Alamitos Canyon. However, the total metal addition from these sources is insignificant compared to sediment input from the Wilderness Area and drainages south of the Pecos village, especially Glorieta Creek. Zinc concentrations are elevated in samples collected from the dam above the Lisboa Springs Fish Hatchery, especially in the <63 μ size fraction, and may be contributing to fish kills at the hatchery. Atmospheric deposition and weathering in the upper Pecos River basin, not the Pecos mine or mill tailings, accounts for most of the Hg found in the waters. Multidisciplinary studies of the entire area, not just contaminated sites, are useful and necessary in environmental evaluations.

TABLE 10. Comparison of trace metal concentrations for the Pecos River basin and Socorro samples (Popp et al., 1982; this study). Wet values are averages of 29 precipitation samples (rain and snow) from Santa Fe Lake, Pecos Ranger Station (in Pecos), and Panchuela Cabins Campground (P, Fig. 2). na - not analyzed.

Site	Cd	Cr	Cu	Hg	Pb	Ni	Zn
Socorro (1993; 1994)	1.5	1.5	6.1	0.031	6	1.4	12
Pecos (1993; 1994)	1.3	0.9	4.1	0.068	3	2.5	39
Socorro (1982)	2.3	8.5	16	0.6	4	2	na

TABLE 11. Metal concentrations (in ppm) of aquatic insects collected from the upper Pecos River and tributaries (Fig. 2) in November 1992, June, September, and November 1993. na - not analyzed.

SITE/ COLLECTION DATE	Cu	Pb	Zn	Ni	Cd	Cr	Hg
Panchuela Creek							
Nov-92	19	6	360	5	0.4	1.4	0.006
Jun-93	<20	<1	339	3	1	2	0.36
Nov-93	na	na	na	na	na	na	0.4
Jacks Creek							
Nov-92	35	2	710	6	0.3	1	0.11
Jun-93	<20	1	626	1	<1	2	0.11
Nov-93	na	na	na	na	na	na	0.34
Willow Creek							
Nov-92	23	<1	410	6	0.4	0.9	0.08
Jun-93	<20	<1	319	3	4	2	0.14
Sep-93	<20	<1	57	<1	6	1	0.06
Nov-93	na	na	na	na	na	na	0.35
Winsor Creek							
Jun-93	<20	<1	318	4	<1	1	0.11
Sep-93	<20	<1	201	1	8	2	0.06
Rio Mora							
Nov-92	27	<1	320	9	0.4	0.4	0.07
Jun-93	<20	2	368	1	<1	1	0.11
Sep-93	<20	<1	208	4		2	0.17
Nov-93	na	na	na	na	na	na	0.37
Above Willow Creek							
Nov-92	31	4	530	5	0.9	2.6	0.17
Jun-93	<20	<1	491	2	na	1	0.07
Sep-93	<20	2	358	1	6	3	0.07
Nov-93	na	na	na	na	na	na	0.32
Below Willow Creek							
Nov-92	42	8	660	17	1.1	2.9	0.16
Jun-93	21	<1	857	3	3	4	0.07
Sep-93	33	14	1996	2	7	2	0.06
Nov-93	na	na	na	na	na	na	0.23
Villanueva							
Nov-93	21	3	220	4	0.5	2.2	0.17
Jun-93	<20	<1	258	1	3	2	0.42
Sep-93	<20	2	240	4	<1	2	0.07
Nov-93	na	na	na	na	na	na	0.38
Oyster tissue standard (1556a)							
values this study	51	0.4	845	4.5	1.2	5.5	na
accepted values	66.3	0.341	830	2.25	1.43	4.15	na
±	4.3	0.014	57	0.44	0.46	0.38	na

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