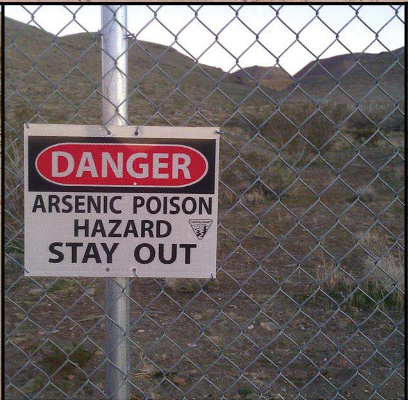
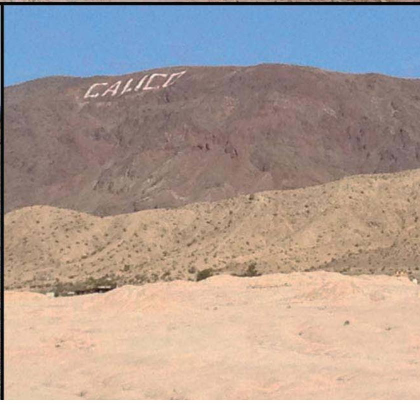
Journal of Environmental Monitoring

Cutting-Edge Research on Environmental Processes & Impacts

www.rsc.org/jem

Volume 14 | Number 7 | July 2012 | Pages 1721–2004





ISSN 1464-0325

RSC Publishing

PAPER

Kim *et al.*

Fluvial transport and surface enrichment of arsenic in semi-arid mining regions: examples from the Mojave Desert, California

Journal of Environmental Monitoring

Dynamic Article Links

Cite this: *J. Environ. Monit.*, 2012, **14**, 1798

www.rsc.org/jem

PAPER

Fluvial transport and surface enrichment of arsenic in semi-arid mining regions: examples from the Mojave Desert, California†

Christopher S. Kim,*[a] David H. Stack[a] and James J. Rytuba[b]

Received 14th February 2012, Accepted 16th May 2012
DOI: 10.1039/c2em30135k

As a result of extensive gold and silver mining in the Mojave Desert, southern California, mine wastes and tailings containing highly elevated arsenic (As) concentrations remain exposed at a number of former mining sites. Decades of weathering and erosion have contributed to the mobilization of As-enriched tailings, which now contaminate surrounding communities. Fluvial transport plays an intermittent yet important and relatively undocumented role in the migration and dispersal of As-contaminated mine wastes in semi-arid climates. Assessing the contribution of fluvial systems to tailings mobilization is critical in order to assess the distribution and long-term exposure potential of tailings in a mining-impacted environment. Extensive sampling, chemical analysis, and geospatial mapping of dry streambed (wash) sediments, tailings piles, alluvial fans, and rainwater runoff at multiple mine sites have aided the development of a conceptual model to explain the fluvial migration of mine wastes in semi-arid climates. Intense and episodic precipitation events mobilize mine wastes downstream and downslope as a series of discrete pulses, causing dispersion both down and lateral to washes with exponential decay behavior as distance from the source increases. Accordingly a quantitative model of arsenic concentrations in wash sediments, represented as a series of overlapping exponential power-law decay curves, results in the acceptable reproducibility of observed arsenic concentration patterns. Such a model can be transferable to other abandoned mine lands as a predictive tool for monitoring the fate and transport of arsenic and related contaminants in similar settings. Effective remediation of contaminated mine wastes in a semi-arid environment requires addressing concurrent changes in the amounts of potential tailings released through fluvial processes and the transport capacity of a wash.

Introduction

Extensive gold and silver mining over the past 150 years throughout the state of California has left an environmental legacy of exposed mine wastes containing elevated levels of potentially toxic trace metal(loid)s and other elements. For example, the natural enrichment of arsenic (As)—a known carcinogen—in mine tailings has been observed at a number of gold mining districts in the state, some of which contain the highest naturally occurring arsenic levels in the contiguous United States.[1–3] A growing awareness of this environmental issue has increased concerns about the health risks facing communities that either live in former mining regions or visit them for recreation or tourism purposes.[4–7] Endangered species such as the desert tortoise are also affected by metal-enriched tailings and other environmental stressors.[8,9] Additionally, the

[a]*School of Earth and Environmental Sciences, Schmid College of Science and Technology, Chapman University, Orange, CA 92866, USA. E-mail: cskim@chapman.edu*
[b]*U.S. Geological Survey, Menlo Park, CA 94025, USA*
† Published as part of a special issue dedicated to Emerging Investigators.

Environmental impact

Arsenic enrichment in mine tailings, and the dispersion of contaminated tailings through natural weathering mechanisms, is a persistent environmental concern in abandoned mine lands throughout the western United States. This study characterizes the fluvial transport of arsenic through field sampling, chemical analysis, and geospatial mapping of dry streambed sediments, tailings piles, and alluvial fans at multiple mine sites. The result is a conceptual model in which episodic precipitation events mobilize mine wastes downstream and downslope as a series of discrete overlapping sediment pulses, with arsenic concentrations declining exponentially as distance from the source increases. Such a model is transferable to other abandoned mine lands in similar settings as a predictive tool for the fate and transport of arsenic and similar contaminants.

uncontrolled movement of mine tailings by erosion and natural transport processes poses challenges to the long-term containment and remediation of these contaminated materials.

The typically fine-grained size distribution of mine tailings (which are commonly produced by crushing Au–Ag ores in stamp mills to increase available surface areas prior to processing), combined with decades of exposure and weathering of large tailings piles, has resulted in the mobilization of arsenic-bearing mine wastes both by fluvial means (rainwater runoff and streams)[10–16] and by wind transport of windblown mine waste particles.[16–18] In semi-arid mining areas with relatively low rainfall rates, fluvial transport is sporadic, with dry streambeds (washes) serving as the primary conduit for tailings mobilization during intermittent storm events. While airborne mobilization of mine tailings is diffuse and covers large areas, fluvial transport is much more localized and directed down narrow and semi-linear washes, which facilitates the movement of tailings across significant distances and into ephemeral lakes or playas.

Research examining the vertical distribution and chemical characteristics of sediments within alluvial fans has been conducted in other regions of the world.[19–21] Some studies have focused on the spatial distribution of tailings around mine sites and atmospheric transportation of tailings material[22,23] while others have focused on the sources of the heavy metals.[7,24] Razo *et al.* described the transport of arsenic and other heavy metals within tailings down washes in Mexico, but an empirical model that can be used to reconstruct the observed patterns in mine-impacted regions has not yet been developed.[16] The role that fluvial transport plays in the migration and dispersion of contaminated mine wastes has been documented in tropical and temperate environments,[25] but in semi-arid environments these processes are poorly understood, despite their importance in assessing the potential distribution and exposure of tailings in mining environments.

It is critical to understand the erosion and transport processes during the rare storm events that mobilize tailings from semi-arid mining areas in order to develop effective long-term contaminant containment strategies and scientifically sound monitoring efforts. Broader conclusions from such studies may also be applied to understanding the mass transport of sediments in semi-arid environments, with implications for the formation of alluvial fans and bank sediments. The historic release of contaminated mine wastes in semi-arid environments such as the Mojave Desert serves as a tracer experiment that provides insights on sediment migration patterns as sediment loads are increased during mining and subsequently reduced at the conclusion of mining, or when environmental measures are implemented to control sediment release from the mined areas.

The purpose of this study is to characterize and model the transport of arsenic-bearing mine tailings by fluvial processes in the Randsburg Historic Mining District and other mine areas in the western part of the Mojave Desert in Southern California. This involves the geochemical and mineralogical characterization of tailings, the measurement of surface arsenic enrichment in soils surrounding tailings piles, the identification of arsenic concentration trends with distance in sediments located within different washes, and the real-time collection of surface water runoff from a tailings pile during a rare storm event. By documenting erosion and fluvial transport of arsenic-enriched tailings at various mines sites, a conceptual and quantitative model for the transport of mine wastes within alluvial systems can be developed that provides a sound basis for formulating strategies for the effective remediation and monitoring of historical mine areas in semi-arid environments.

Historical background

Mining history

Since the 1860s, several Au–Ag deposits have been identified and mined throughout the Mojave Desert in California, including both the largest Ag deposit (Kelly) and largest Au deposit (Randsburg) in the southern part of the state. The Au–Ag ore deposits occur primarily in Miocene volcanic and intrusive rocks that consist of silicic domes and associated flows, pyroclastic rocks, and subvolcanic intrusions that were emplaced in Mesozoic and earlier Cenozoic intrusive rocks.[26–28] In a few of the deposits, such as the Ruth and Randsburg, Au–Ag veins occur primarily in the Mesozoic and Cenozoic intrusive rocks. The Au–Ag deposits were mined intermittently until the end of WWII, when all of the mines were closed. During this period, when environmental regulations and monitoring were largely absent, massive mine waste piles and tailings accumulated adjacent to the stamp mills and cyanide leach plants that were used to crush and process the ores. Since the 1980s, three of the mines (Cactus, Randsburg, and Standard Hill) were reopened as large tonnage, open pit mines in which Au and Ag were recovered using the cyanide heap leach process. At the Cactus Mine, mercury (Hg) was also recovered as a byproduct from the mineral corderoite, $Hg_3S_2Cl_2$.[29] Stricter environmental controls during this more recent period of mining have been more effective at stabilizing mine wastes in order to minimize their release from the mine sites.

The Au–Ag deposits in the western Mojave Desert are primarily low-sulfidation epithermal deposits.[30] In most of them, gold and electrum (gold–silver alloy) occur in association with pyrite and arsenopyrite (FeAsS). In the silver-rich deposits, typified by the Kelly Mine, miargyrite ($AgSbS_2$), stylotypite ($(Cu_2Ag_2Fe)_3Sb_2S_3$), proustite (Ag_3AsS_3) and pyrargyrite (Ag_3SbS_3) are the main ore minerals. Low-sulfidation epithermal ore deposits typically contain anomalous concentrations of As, Hg, and Sb.[30] However, the deposits in the western Mojave Desert contain unusually high concentrations of arsenic, commonly up to several tenths of a percent as a result of the presence of arsenopyrite and arseniosiderite.[2,3] Arseniosiderite ($Ca_2Fe^{3+}O_2(AsO_4)_3 \cdot 3H_2O$), which had not previously been identified in the Mojave Desert, is common in veins in the Kelly and Randsburg ore deposits, where it occurs as monoclinic, pseudotetragonal crystals. Arseniosiderite is also common in the processed tailings at both of these mines, where it occurs as radial fibrous aggregates.

The primary sulfide ore minerals have been oxidized and altered to secondary As-bearing phases such that only scorodite, arseniosiderite and As(V) sorbed to FeOOH are present in the tailings.[2,3] These phases are relatively insoluble in the arid environment and persist in tailings as they are transported downstream from the mine sites.

Transport of tailings

Mine wastes and tailings from precious metal deposits in the western Mojave Desert were typically processed at stamp mills that were often located in the upper parts of alluvial fans. Stamp mills crushed the ore to a fine grain size, primarily between 125 and 1000 μm[17]. The concentration of arsenic in tailings has been shown to increase with decreasing grain size, with as much as forty times the arsenic concentration occurring in the finest size fraction compared to the largest size fraction.[17] Mine tailings were disposed of in piles adjacent to the stamp mills, where they were susceptible to weathering and erosion because the piles were not vegetated and had artificially steepened slopes. Significant erosion and transport of tailings took place at all of the mine sites, mostly facilitated by large storm events. High precipitation events with $\geq$10 cm of precipitation in a 24 hour period have been relatively rare in the Mojave Desert (which receives an average of 17 cm precipitation per year). Anecdotal information indicates that some of the largest storm events occurred in the winter of 1861–1862, when floods destroyed all the mining camps in the Mojave Desert. This event, however, occurred before large-scale mining, so likely had minimal impact on tailings redistribution. Subsequent major storm events in the late 1800s and early 1900s had significant if sporadic impact on the redistribution of mine wastes and tailings from mine sites.

Starting in 1903, stamp mill tailings from the Randsburg mine were deposited on the upper part of the alluvial fan from which the Fiddler Gulch emanates. During this early phase of mining, large amounts of tailings were eroded and transported into the upper part of Fiddler Gulch during the storm events of 1913 and 1914. Tailings were initially deposited in the upper part of Fiddler Gulch as the input of tailings exceeded the transport capacity of the wash. Aggradation, the process of increasing land elevation due to the deposition of sediment, resulted in the rise of the wash channel such that a layer of tailings up to 5 m in depth was deposited in the channel, extending nearly 1 km downstream from the mine. The thickness of tailings in the wash decreased systematically further downstream such that 11 km from the mine, deposition no longer occurred and tailings were instead primarily transported (rather than deposited) throughout the lower segment of the wash. During this early phase of mining with uncontrolled release of tailings and very high sediment release, the upper segment of Fiddler Gulch became a repository for mine tailings.

In 1936, a tailings dam was built to collect tailings from the Randsburg stamp mills. Subsequently, sediment release to Fiddler Gulch decreased dramatically, resulting in incision and erosion of the tailings previously deposited in the upper 11 km of the wash. Erosion of the tailings continued until the base profile of the wash was reestablished to its pre-mining level. However, thick deposits of tailings remain in the narrow floodplain that borders each side of the wash. These tailings form relatively stable cliffs along the banks of the wash, and recent storm events are largely confined to the active channel. A video recording of one of these storm events in 2008 shows the relatively stable cliffs of mine tailings on either side of the active channel, which transports significant amounts of sediment and tailings.[31]

Fiddler Gulch therefore provides a record of the entire history of tailings transport, from uncontrolled tailings release and sedimentation in the upper part of the wash before 1936, to tailings control, incision/transport, and reestablishment of the pre-mining gradient in the wash. Ironically, the 1936 construction of a tailings dam at Randsburg resulted in a large release of tailings, previously stored in the upper segment of the wash to the lower part of the wash and ultimately to Koehn Playa as the natural wash gradient was reestablished.

At the Kelly Mine, tailings were deposited in the upper part of the alluvial fan from which the Red Mountain wash emanates. Uncontrolled release of tailings from the mine since its inception resulted in deposition of tailings in Red Mountain wash from the mine area downstream to Cuddeback Lake, a distance of about 16 km. The wash is now completely filled with tailings to a maximum depth of 1.25 m and is estimated to contain 35 000 m^3 of tailings. Tailings continue to be released from a breached tailings dam during storm events and are subsequently transported into Cuddeback Lake to the southeast, where they continue to accumulate.

Experimental method

Field sampling

Soil and sediment samples were collected from a number of locations in the western Mojave Desert, including numerous sites in the Randsburg Historic Mining District, and at the Ruth, Calico and Cactus Mines (Fig. 1a). All tailings and wash samples were collected by hand as single grab samples at each location using stainless steel trowels which were plunged into adjacent soils multiple times before sample collection to minimize contamination.

The surface enrichment of arsenic in soils surrounding mine tailings piles was determined by collecting samples at depths of 0–5 cm and 5–10 cm below the surface. The 0–5 cm sample interval was collected in order to include all tailings deposited in the upper 1 cm (maximum observed thickness of tailings) and to sample tailings that may have been transported downward into the topsoil layer through desiccation cracks and permeability of the soil. The 5–10 cm sample interval was selected because, based on empirical evidence, it provided a soil interval that did not contain significant contamination from tailings. Approximately 100 g of material were collected at each depth. Dry washes were sampled by collecting approximately 100 g of sediment at the center of the wash channel with minimal advance clearing of the sample area as necessary to remove significantly larger cobbles and organic material. Samples were collected within the washes at variable length intervals based on land access permissions. For samples collected directly on tailings piles, the top several cm of tailings were removed prior to collection of approximately 500 g of tailings from a single exposure. This was done to avoid sampling the most highly weathered material and to access unweathered material that is more representative of the entire pile.

Channel samples of natural exposures of gravel deposits and uncontaminated streambed sediments located away from the expected mine tailings contamination area (Fig. 1b, sites A through F) were collected to establish baseline arsenic levels for comparison with the contaminated washes and tailings piles. The Bureau of Land Management has targeted these locations as potential sources of cover material to aid in the capping and securing of tailings piles. Composite samples along the vertical transects were divided by natural breaks in the sedimentary layers, ranging from 0.5–1.0 m in thickness. Approximately 500 g of sample was collected for each portion of each channel sample to obtain a representative sample of the sediment.

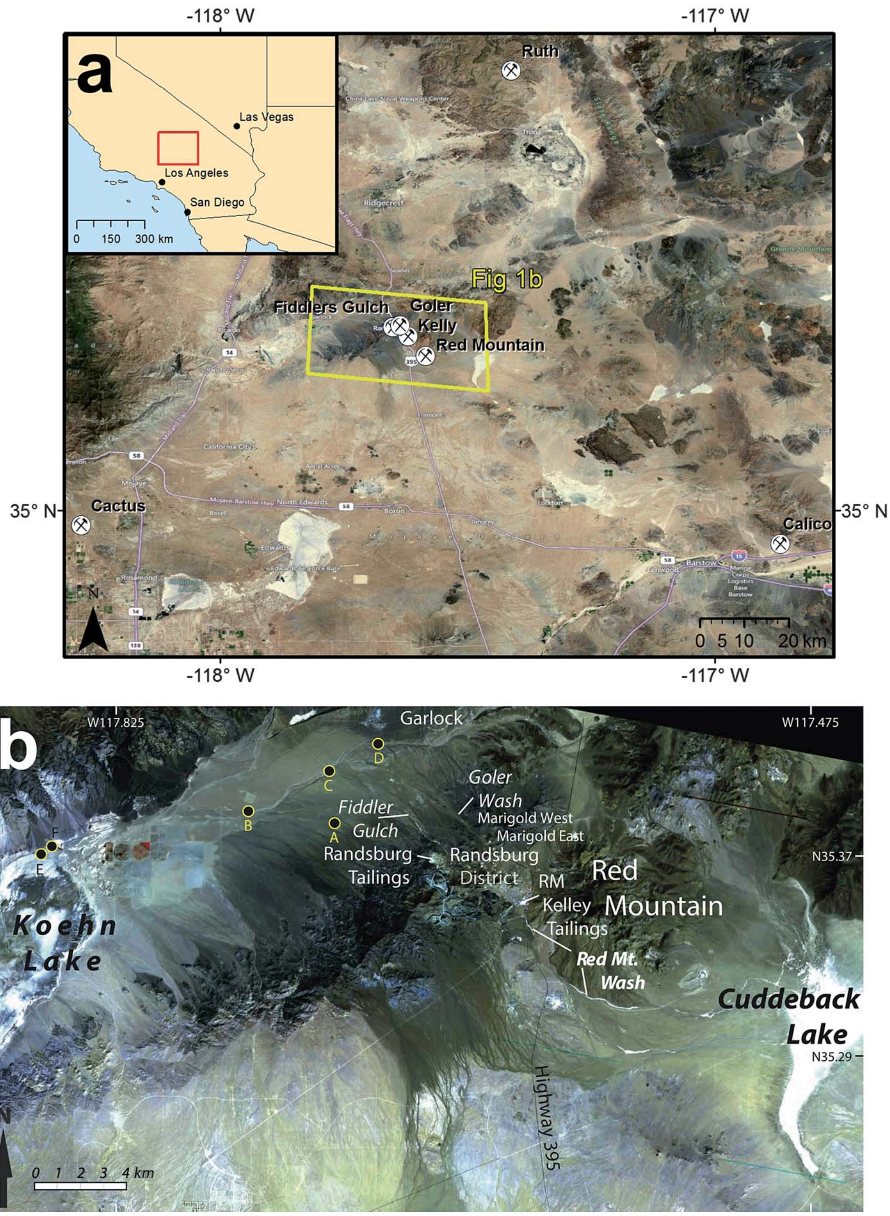


Fig. 1 (a) Aerial photograph of study area and mine/wash sampling locations; (b) ASTER (Advanced Spaceborne Thermal Emission and Reflection) image focusing in more detail on mines and washes within the Randsburg Historic Mine District. Circled points labeled A through F indicate locations where background uncontaminated material was sampled for comparison with mine-impacted sediments.

A brief but intense storm event that occurred during sampling of the Cactus Mine tailings pile provided a rare opportunity to analyze rainwater runoff at this site. Tailings and sediment samples were collected several months prior to the storm event along three parallel transects at ~150 m intervals; these transects traversed the tailings pile, an engineered channel designed to collect and direct runoff towards a nearby settling pond, and a natural wash that followed the general orientation of the pile (Figs. 2 and 3). By collecting adjacent samples of the tailings, channel, and wash every 150 m, differences in arsenic concentration and trends in fluvial tailings transport could then be assessed at each point of the parallel transects by calculating ratios of concentrations, *e.g.* channel : tailings, tailings : wash, channel : wash.

During the storm event, 750 mL samples of turbid rainwater runoff were collected in screw-capped 1 L HDPE bottles within the engineered channel at two locations corresponding to transect positions 4 and 6 (Fig. 2). A 50 mL aliquot from each sample was filtered using a 0.45 μm polycarbonate filter, half of which was subsequently filtered using a 0.2 μm polycarbonate filter. Both filtered aliquots were then acidified using small volumes of concentrated nitric acid until pH < 2. All samples were maintained under 4 °C refrigeration prior to subsequent analysis.

Chemical analysis

All samples collected for surface enrichment studies and from washes, tailings piles, gravel deposits, and streambed sediments

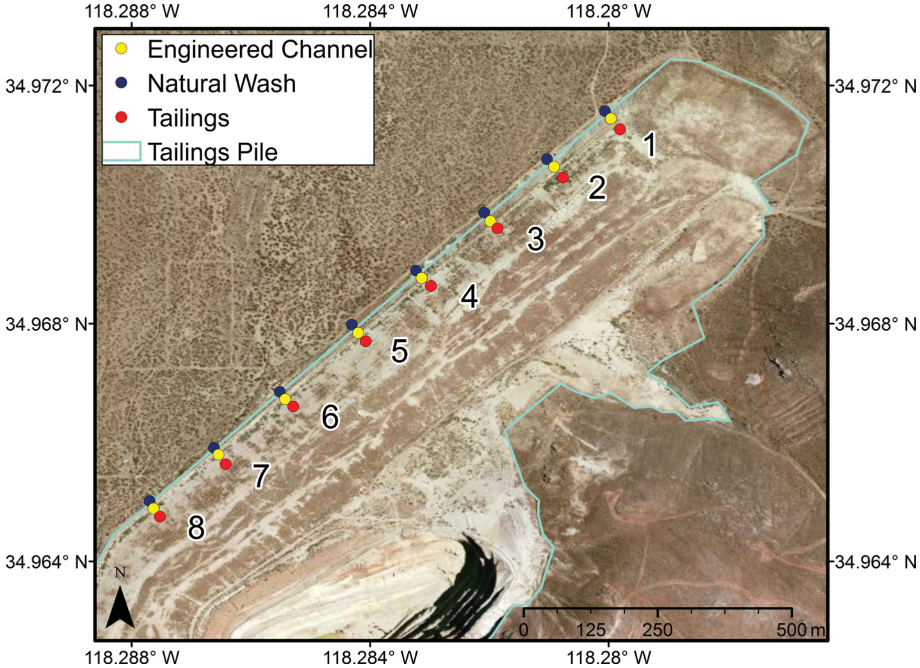


Fig. 2 Approximate sample locations at the Cactus Mine tailings pile. Two rainwater runoff samples were collected within the engineered channel at locations corresponding with sites 4 and 6.

were split and a 10 g aliquot sent to ALS Chemex, a private analytical laboratory, where samples were pulverized using a ring mill prior to digestion and analysis. Approximately 85% of the crushed samples passed through a 75 μm (Tyler 200 mesh) screen prior to digestion. A prepared split (0.250 g) of each sample was digested with concentrated $HClO_4$, HNO_3 and HF at 185 °C to near dryness and then further digested in a small volume of 11% HCl. The solution was brought up to a final volume of 12.5 mL with 11% HCl, homogenized, and analyzed for a suite of 49 elements either by inductively coupled plasma-mass spectrometry (ICP-MS) using a Perkin Elmer Elan 9000 spectrometer and/or by inductively coupled plasma-atomic emission spectroscopy

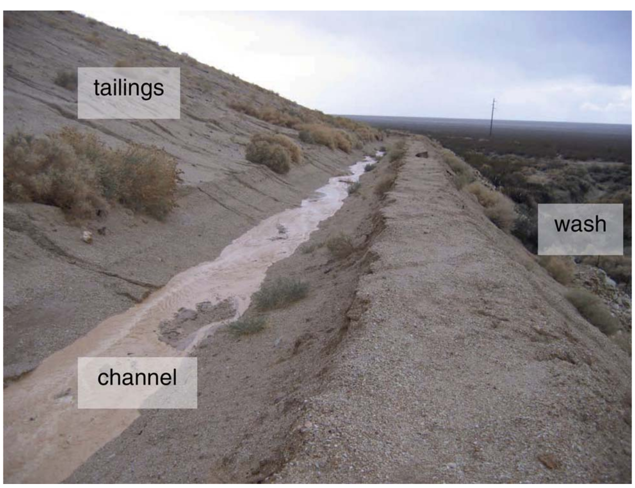


Fig. 3 Photo of tailings pile and engineered channel at the Cactus Mine immediately following storm event (natural wash is slightly visible to the right), demonstrating the retention of surface rainwater runoff within the channel.

(ICP-AES) using a Varian Vista-PRO/Vista-725ES, depending on the initial arsenic concentration in the sample. Arsenic concentrations of all solid samples are expressed in mg As per kg sample. The instrument detection limits and relative standard deviations for arsenic presented in this manuscript are 0.2 mg kg^{-1} and 12.0%, respectively. A series of two standards, one duplicate, and one blank were run within every 40 samples with standard and duplicate tolerances of 10% for quality control purposes.

Unfiltered and filtered rainwater runoff samples were analyzed by ICP-AES in USGS laboratories. Subsamples for metal(loid) determinations were first acid-digested with trace metal (Ultrex, J.T. Baker)-grade HNO_3, with all particles expected to be dissolved by this method. Duplicate water samples, blank samples, and USGS Water Resource Division standard reference waters were analyzed with the dataset. Arsenic, iron, and aluminum concentrations of all rainwater runoff samples are expressed in mg L^{-1}. The detection limit for arsenic using this method was 1 μg L^{-1}.

Data processing

Arsenic concentrations measured at 0–5 cm and 5–10 cm depth were used to establish the percentage surface enrichment in soils as follows:

$$\%\ \text{surface enrichment} = \frac{[\text{As}]_{0-5\text{cm}} - [\text{As}]_{5-10\text{cm}}}{[\text{As}]_{5-10\text{cm}}} \times 100 \quad (1)$$

Percentage surface enrichment, arsenic concentrations at 0–5 cm depth, arsenic concentrations at 5–10 cm depth, and arsenic concentrations in wash sediments were plotted geospatially using ArcGIS version 10.0. Scatter plots of transects and washes were also generated by plotting distance from the mine site against arsenic concentration, with distance calculated as the sum of the lengths of sequential line segments connecting two adjacent sample locations, fit to the course of the wash. Based on the distribution of concentrations within a given wash, samples were categorized and color-coded into three groups to aid viewing and analysis.

Data regressions were conducted to quantitatively model the arsenic concentration patterns observed with increasing distance from tailings point sources in transects across the alluvial fans and downstream in washes. For the washes, which generally featured more complex depletion and enrichment patterns throughout their lengths, a statistical model was developed to fit the dataset as a series of discrete segments representing multiple pulses of high-arsenic tailings, where each pulse is generally defined as a region of elevated arsenic concentrations possessing a local maximum, progressive decline with distance, and a local minimum. This more accurately represents the manner of tailings movement in semi-arid regions, where tailings are transported downstream and mobilized episodically by large storm events. Between 2 and 4 storm simulations were chosen for the model based on the stepwise shape of and the presence/frequency of local maxima and minima in the data. The entire model fit was then constructed as a linear combination of each of these piecewise segments. Each segment was separately and independently fit with a power law exponential decay function, reflective of the discrete nature of tailings transport occurring in semi-arid regions. Model equation coefficients were derived using the method of maximum likelihood fit on each segment, with the results combined to create the final fit. The modeled arsenic concentration using this method can be represented by the equation:

$$C_{x,i} = \frac{\sum_{i=1}^{n} a_i (x - x_i)^{k_i} I_i(x)}{\sum_{i=1}^{n} I_i(x)} \quad (2)$$

where $C_{\mathrm{x,i}}$ is the is the concentration of arsenic at distance x_{i}, n is the number of pulses (with power law decay character) that have occurred at a given location, a represents the power law coefficient, k represents the power law exponent, and x is the distance offset of the power function from the origin.

The indicator function $I_i(x)$ is represented as

$$I_i(x) = \begin{matrix} 1 & s_i \le x \le e_i \\ 0 & \text{Otherwise} \end{matrix}$$

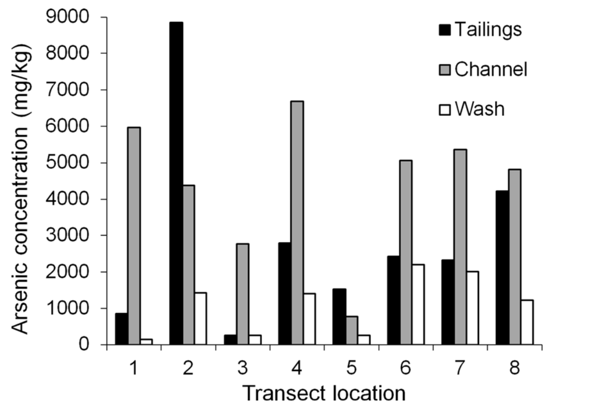


Fig. 4 Arsenic concentrations in the tailings, engineered channel, and natural wash adjacent to the Cactus Mine heap leach pad, with samples collected ~150 m apart.

where s_I and e_I represent the starting and ending cutoff distances for each of the segments.

Results and discussion

Cactus Mine transects and rainwater runoff

The Cactus Mine has a localized mine tailings source in the form of an engineered heap leach pad used during a period of mining that lasted from 1986–1996. Solid samples were collected along and adjacent to the leach pad and water samples were collected directly within the engineered channel at the base of the tailings pile during an intense rainwater runoff event. The samples represent the first-stage erosion and transport of tailings upstream of alluvial fan deposition. A plot of arsenic concentrations in the Cactus Mine tailings pile, engineered channel, and natural wash, collected at ~150 m intervals along the length of the pile, is shown in Fig. 4 with transect location number increasing in the downstream direction of the engineered channel (Fig. 2). Specific arsenic concentration values at all sample locations and concentration ratios between the channel and tailings, tailings and ravine, and channel and ravine are provided in Table 1.

The figure and table both show that arsenic concentrations in the natural wash, although still elevated above background (Table 3), are consistently the lowest at each transect location (on

Table 1 Quantitative arsenic concentration values and averages/standard deviations in the tailings, channel, and wash. Ratios between the three locations are also provided at all sample positions

Concentrations				Ratios		
Transect position	Tailings (mg kg^{-1})	Channel (mg kg^{-1})	Wash (mg kg^{-1})	Channel : tailings	Tailings : wash	Channel : wash
1	852	5960	139	7.00	6.13	42.88
2	8850	4380	1430	0.49	6.19	3.06
3	254	2770	258	10.91	0.98	10.74
4	2790	6690	1410	2.40	1.98	4.74
5	1525	775	259	0.51	5.89	2.99
6	2430	5070	2200	2.09	1.10	2.30
7	2330	5360	2010	2.30	1.16	2.67
8	4220	4820	1225	1.14	3.44	3.93
Average	2906	4478	1116	3.35	3.36	9.16
Std. dev.	2694	1889	810	3.69	2.38	13.89

average between 3 to 4 times lower than the adjacent tailings concentrations and about 9 times lower than the corresponding channel concentrations, although considerable variability exists in the ratios), indicating that fluvial transport of tailings has been effectively controlled by the construction of the engineered channel.

At the majority of transect sample locations, the arsenic concentration measured in the engineered channel exceeds that of the concentration in the tailings pile (arsenic concentrations are on average between 3 to 4 times higher in the channel than in the tailings). One explanation for this difference is that finer-grained sediments are more prone to being mobilized in rainwater runoff and transported from tailings piles into their immediate surroundings. As mentioned earlier, the inverse relationship commonly observed between particle size and arsenic concentration in mine tailings[17] means that the finest-grained particles released tend to also contain the highest arsenic concentrations. The higher arsenic concentrations of the channel sediments compared to the tailings suggest that a larger proportion of fine-grained arsenic-enriched particles are preferentially eroded from the tailings pile and into the engineered channel. It also suggests that the arsenic concentrations of solid particles carried by surface runoff may be generally enriched compared to bulk tailings.

A plot of arsenic, iron, and aluminum concentrations in the unfiltered and two filtered (0.45 μm, 0.2 μm) rainwater runoff samples is shown in Fig. 5. Levels of iron and aluminum in the unfiltered samples average 147 and 97 mg L^{-1}, respectively, while filtration by either 0.45 μm or 0.2 μm filters removes ≥99% of the two elements from the runoff. This suggests that iron and aluminum exist almost entirely in the solid form, likely as Fe- or Al-(hydr)oxides, clays, silicates, or other common soil minerals. Arsenic concentrations in the unfiltered water samples are also highly elevated, averaging 91 mg L^{-1} and comparable to iron and aluminum concentrations. However, following filtration by either the 0.45 or 0.2 μm filters, significant levels of arsenic remain in the water (9.8 and 10.1 mg L^{-1}, respectively, 1000 times greater than the U.S. EPA drinking water standard of 0.01 mg L^{-1}) and representing only about 90% arsenic removal. These results indicate that both particulate, colloidal, and a significant fraction of dissolved arsenic are being mobilized from the tailings.

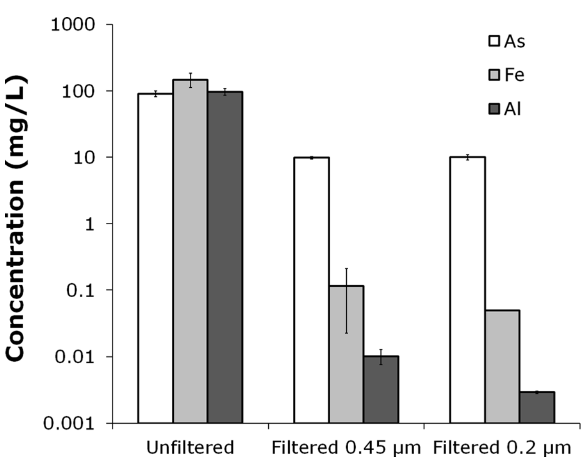


Fig. 5 Concentrations of total arsenic, iron, and aluminum in unfiltered and filtered (to 0.45 μm or 0.2 μm) rainwater runoff from Cactus Mine tailings. Data and error bars represent averages of two samples.

Preferential erosion and transport of fine-grained, arsenic-enriched mine tailings provides a framework to parameterize the potential distribution of arsenic from point sources (tailings) to more distant background regions. The minimal vegetation on the over-steepened slope of the tailings pile at the Cactus Mine (Fig. 3) is representative of most of the tailings piles present in the Mojave Desert where tailings and waste rock piles are typically devoid of vegetation.

Calico Mine

The tailings pile at the Calico Mine was deposited in the 1890s at the upper part of an alluvial fan. Since mining ended in 1896, the tailings have weathered and migrated downslope a distance of ~1500 m in several shallow washes on the alluvial fan and then into a playa. Three longitudinal transects extending roughly normal to the primary north-south trending wash were sampled by collecting surface enrichment samples (0–5 cm, 5–10 cm) to both the east and west of the tailings-filled wash at the upper, middle, and lower segments of the alluvial fan. An additional north-south transect was also collected down the middle of the primary tailings-filled wash. Fig. 6 shows the sample positions and arsenic concentrations of the 0–5 cm samples for the three transects and the primary wash and Fig. 7 shows plots of the 0–5 cm and 5–10 cm (Fig. 7a–c) and percentage surface enrichment data (Fig. 7d–f) of each transect as a function of distance from the center of the wash. Fig. 7g plots the arsenic concentration as a function of distance in the north-south direction down the primary wash.

The observed north-south arsenic concentration trend (Fig. 7g) along with the transect data (Fig. 7a–c) show that tailings from the pile have both migrated downslope and laterally outwards over time. Additionally, the three east-west transects exhibit slightly different trends in arsenic concentration as a function of distance. The uppermost transect, extending from either side of the tailings in the wash, reveals elevated arsenic concentrations across the tailings and considerably lower arsenic concentrations to both the east and west of the wash (averaging 6 mg kg^{-1}, equivalent to background concentrations) at both sample depths (Fig. 7a). This section of the tailings is in an incised channel (see topographic lines in Fig. 6) that effectively confines the tailings to the wash, with relatively little lateral migration observed.

A plot of the percentage arsenic surface enrichment along the upper transect with increasing distance from the tailings in the wash (Fig. 7d) is generally consistent with the trends observed in the absolute arsenic concentrations; surface enrichment is confined to a width of approximately 400 m and drops to zero at greater distances to the east or west. The trends in arsenic concentration can be adequately fit using a power-law exponential decay curve ($C = ax^{-k}$, where C = concentration, a = initial value, x = distance from origin, and k = decay rate constant), with R^2 values ranging from 0.47–0.59, consistent with other physical, biological, and man-made systems that follow a power-law relationship.[32–34]

A plot of arsenic concentrations across the middle transect at 0–5 cm and 5–10 cm soil depth with increasing distance from

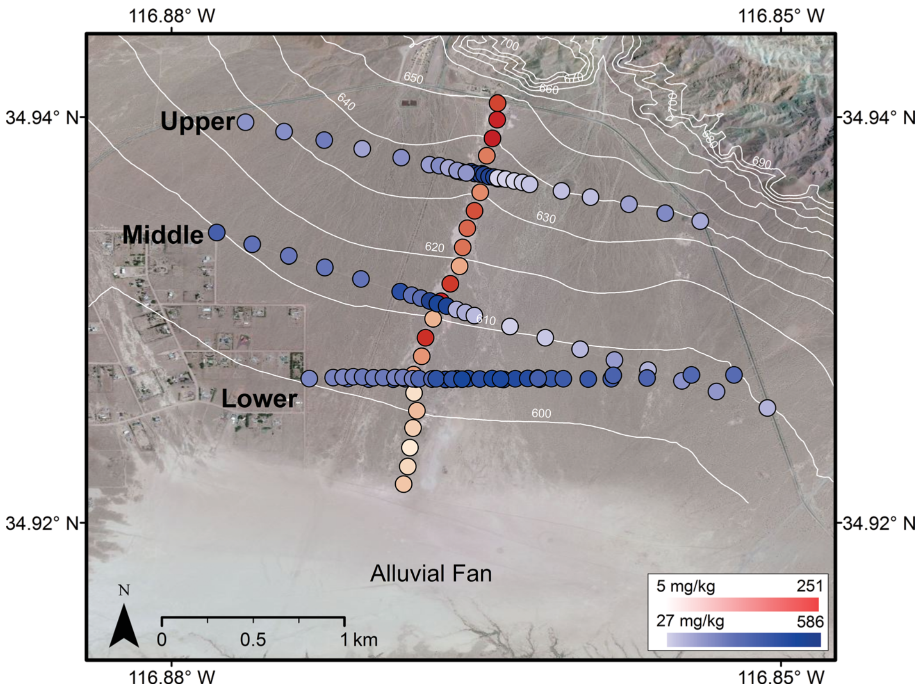


Fig. 6 Sample locations and arsenic concentrations in the 0–5 cm depth horizon at the Calico Mine. Different color scales are used for the primary tailings-filled wash (red) and the longitudinal transects (blue) to account for the different concentration ranges represented.

the tailings in the wash is shown in Fig. 7b. The middle transect also shows evidence of elevated arsenic concentrations close to the center of the tailings-filled wash, with concentrations declining asymmetrically with increasing distance in both the east and west directions (more abruptly to the east, and persisting at relatively elevated levels to the west even at a distance of 1 km from the wash). Surface enrichment also declines rapidly to both the east and the west (Fig. 7e), returning to background levels within the first 200 m in either direction from the center.

As the samples in the middle transect were collected directly in the middle of an unpaved access road, it is possible that a preferred east-to-west driving direction on this road may have resulted in the persistently elevated arsenic levels to the west of the wash. The history and purpose of this road is uncertain and there is a potential that significant disturbance may have occurred if the road were used to install a pipeline. Alternatively, during the early stages of tailings migration, and with a relatively gentle slope of the alluvial fan, tailings may have been preferentially distributed to the west through braided streams and wind dispersion. Again, the trend of arsenic concentration with distance in the sample data follows a roughly exponential decay pattern. Attempting power-law exponential decay regressions with this data subset yields comparable yet variable R^2 values ranging from 0.17 to 0.55. The lower-quality fit may support the artificial influence of vehicular traffic.

The lower transect (Fig. 7c), located the greatest distance from the original tailings source, is located along a dirt road that predates dispersal of the tailings so disturbances related to construction and use of the road are not expected to affect the arsenic dispersal pattern. The transect exhibits a very gradual decline in arsenic concentration with distance to the east (both 0–5 cm and 5–10 cm arsenic concentrations are still declining 1300 m from the source), although the decline is also decidedly asymmetrical with a much more abrupt drop in concentration to the west than to the east. The arsenic concentrations are also the most variable in the lower transect at both sampling depths, likely representing non-uniform mixing between tailings and background material. Indeed, the tailings along this transect are visibly dispersing and fanning out as they approach the dry lakebed, and the original incised wash channel in which the tailings were contained at its north end has flattened out. The elevated arsenic levels to the east of the tailings in the wash contribute to variable degrees of surface enrichment (Fig. 7f), while to the west surface enrichment is less commonly observed. The progressively lower topography to the east and the gradient on the alluvial fan may have favored the spread of material to the east at this stage of migration. Fits to the empirical data were best achieved using power-law decay behavior to the west and standard exponential decay to the east, resulting in R^2 values ranging from 0.23 to 0.57.

These data from the three transects crossing the wash in which the Calico Mine tailings have migrated provide an evolutionary view of tailings transport down an alluvial fan. Initially, sediment loads were very high as uncontrolled release of tailings occurred during large storm events. Subsequently, tailings deposition occurred in both the main wash and subsidiary channels as the wash became filled with tailings. The progressive broadening of the tailings width with downslope distance reflects alluvial fan development and demonstrates the potential for surface soil contamination on the order of kilometers from the original point source.

Since the end of primary production at the Calico Mine in 1893, 100 years of subsequent erosion gradually reduced the size

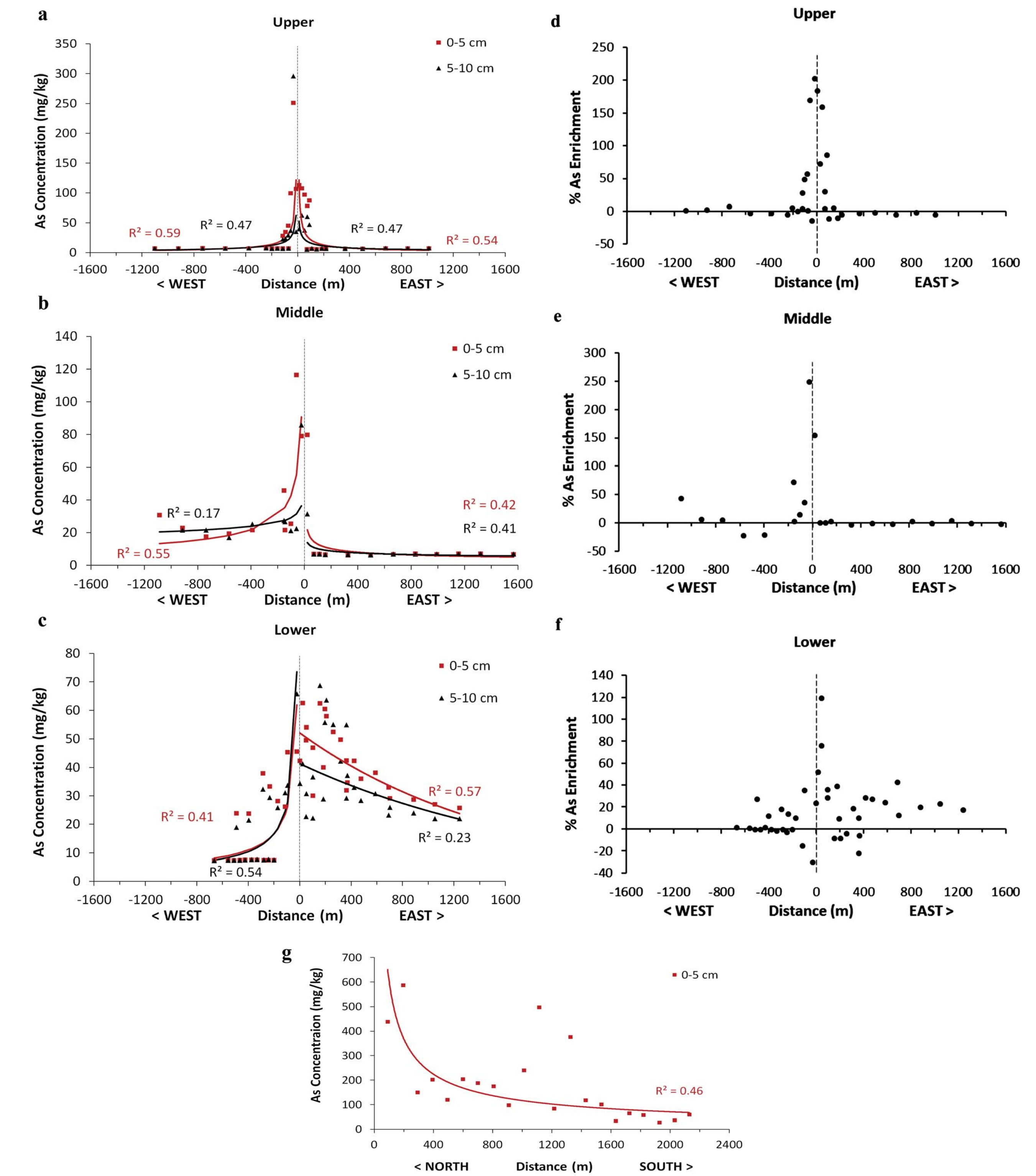


Fig. 7 Arsenic concentrations in surface and subsurface soil (a–c), percentage arsenic enrichment (d–f) as a function of distance from the center of the tailings-filled wash at Calico Mine, and arsenic concentration down the center of the tailings-filled wash (g). R^2 values correspond to power-law exponential decay fits to the 0–5 cm (gray) and 5-10 cm (bold data).

of the tailings pile and correspondingly the amount of tailings being released from the pile. This eventually resulted in the incision of tailings stored in the upper part of the wash as the natural slope gradient was reestablished, with these remobilized tailings transported farther down the alluvial fan. The presence of unpaved access roads crisscrossing the tailings also highlights the potential influence that human activity can have on the distribution of contaminated material.

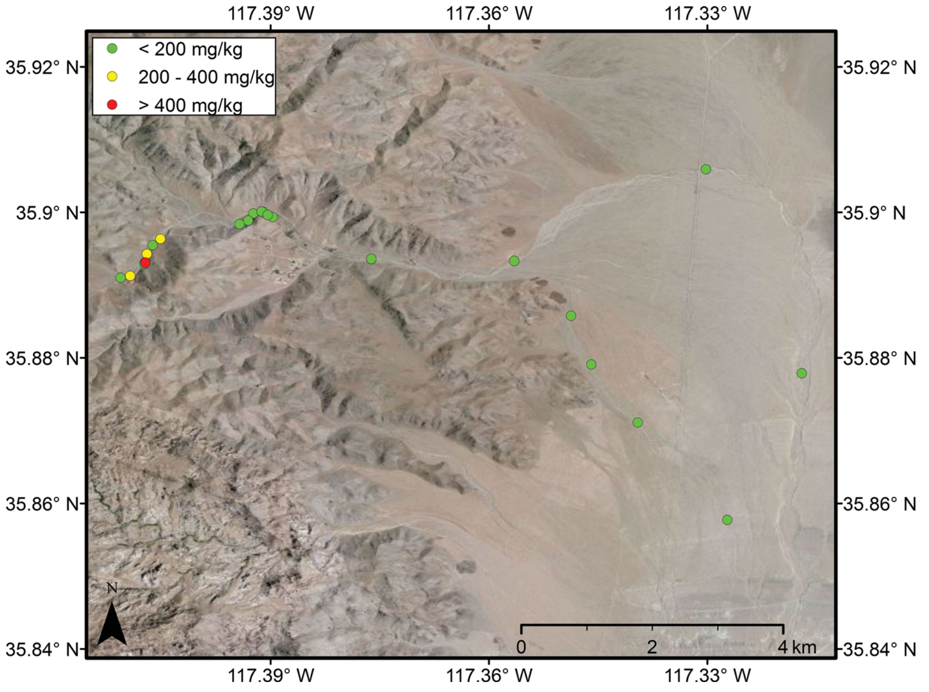


Fig. 8 Sample locations at Ruth Mine wash with arsenic concentrations indicated by color. Concentration category boundaries were defined by natural breaks in the dataset.

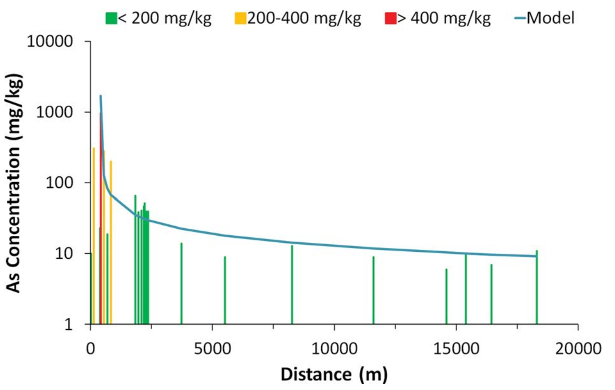


Fig. 9 Arsenic concentration plotted over distance downwash from the mine pile at Ruth Mine wash. Blue line represents best fit curve to the data starting at the point of highest arsenic concentration, created from a single power-law exponential decay curve.

Ruth Mine wash

A map showing the locations of samples collected within the Ruth Mine wash is shown in Fig. 8 and a chart displaying the arsenic concentrations in the wash sediments with increasing distance is shown in Fig. 9. Sample points and bars on the figures are color-coded to indicate the measured arsenic concentration range in each sample, with category boundaries defined by natural breaks in each dataset. The Ruth Mine wash is a highly confined, incised, steep stream channel that winds through considerable topography until it exits Homewood Canyon into a broad alluvial fan system to the east (Fig. 8). The Ruth Mine tailings are spatially confined to a small area that effectively provides a single input source of arsenic-enriched tailings into the wash (represented by the highest recorded wash sediment concentration of 976 mg kg^{-1} at a distance of 409 m from the most upstream sample collected). Where the wash exits the incised canyon, it splits into a braided segment of washes that eventually enter a playa lake, with tailings dispersed widely and diluted across the alluvial fan. The conditions for tailings transport at the Ruth Mine are therefore relatively simple, and the data exhibit a continuous decline in arsenic concentration and a high quality fit of the data with a single power law exponential decay regression (Fig. 9), resulting in an R^2 value of 0.80.

Goler Wash

A map showing the locations of samples collected within Goler Wash and a chart displaying the arsenic concentrations in the wash sediments with increasing distance are shown in Figs. 10 and 11, respectively. Goler Wash is a relatively linear, gently sloping wash that traverses a region with multiple mine tailings inputs, specifically the Marigold East and Marigold West Mines identified on Fig. 10. These inputs can be observed in Fig. 11, where arsenic concentrations increase abruptly at distances of ~500 and 880 m downstream from the first collected sample. The relative influences of the two mines on arsenic sediment concentrations in the wash are considerably different. The input of the Marigold East mine tailings into Goler Wash causes a single spike in arsenic concentration that cannot be detected only 50 m further downstream, while the input of the Marigold West mine tailings into the wash results in elevated arsenic concentrations over the next 1 km downstream. We interpret this pattern to indicate that the capacity (total sediment load that can be carried) of the stream has not yet been exceeded at the point of the Marigold East input, meaning that the tailings

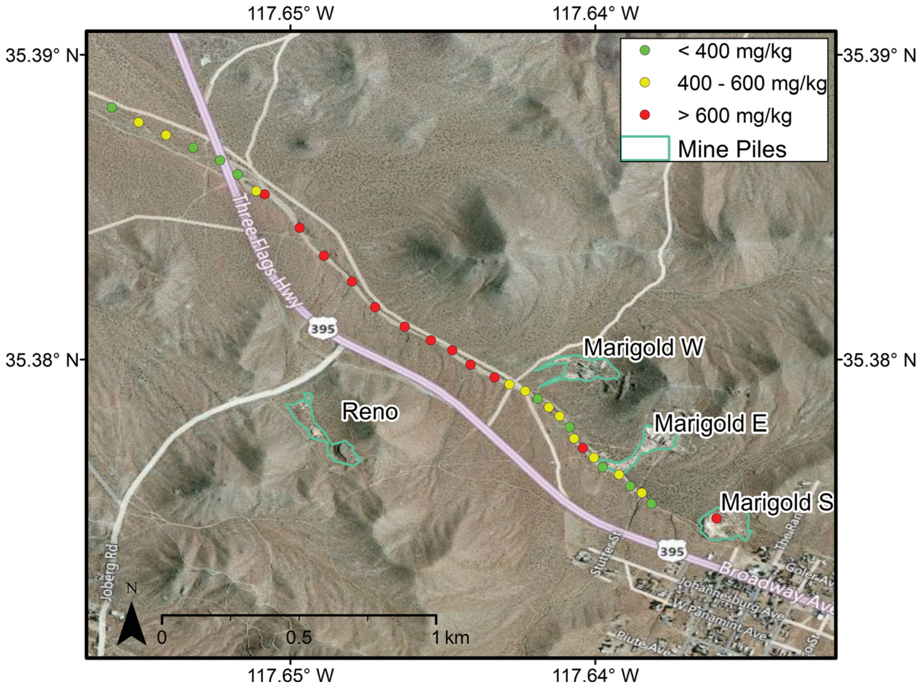


Fig. 10 Sample locations at Goler Wash with arsenic concentrations indicated by color. Concentration category boundaries were defined by natural breaks in the dataset. Potentially contributing tailing piles are outlined and labeled.

contributed at this point are primarily transported downstream. The addition of the Marigold West input, presumably enough to exceed the stream's capacity, results in deposition of Marigold West tailings (along with some of the transported Marigold East tailings) down the wash to a compensation point (change from sediment deposition back to sediment transport) about 1 km from the point of initial deposition.

The input from another tailings pile further upstream, identified in Fig. 10 as the Marigold South pile (located on privately owned land and thus not accessible for extensive sampling), and the relatively high arsenic concentrations persistent among all samples in the wash suggest that the entirety of the sampled wash region has been contaminated with tailings material, with additional tailings inputs along its length producing the more complex pattern observed. This is further supported by samples collected in the background region surrounding each mine tailings pile at 5–10 cm depth (not shown), containing arsenic concentrations near the Marigold East and West mines averaging 213 mg kg^{-1} ($n = 7$) and 92 mg kg^{-1} ($n = 8$), respectively, both below the lowest arsenic concentration value in the wash of 328 mg kg^{-1}. In contrast, arsenic concentrations in the tailings at the mines themselves exceed these background levels by well over an order of magnitude, averaging 5300 mg kg^{-1} ($n = 59$) and 4000 mg kg^{-1} ($n = 42$) for the Marigold East and West mines, respectively.

The relative arsenic concentrations of the background regions, tailings piles, and wash sediments indicate that a fraction of the wash sediments sampled are composed of eroded mine tailings, with background sediments from both the regions surrounding

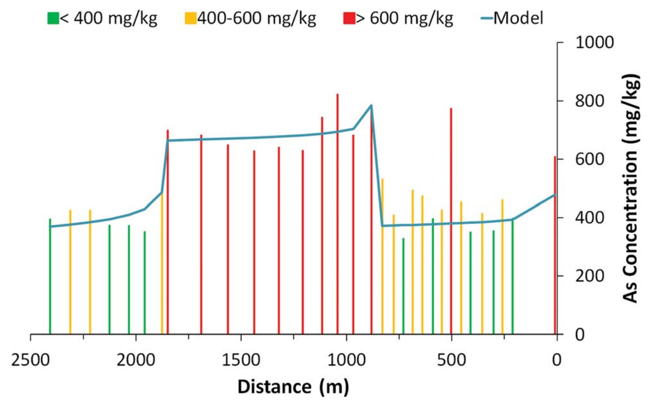


Fig. 11 Arsenic concentration plotted over distance downwash from the mine pile at Goler Wash. Blue line represents best fit to the data, created from a series of power-law exponential decay curves.

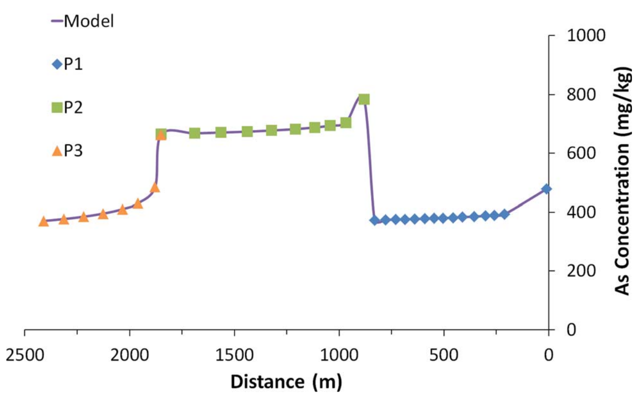


Fig. 12 Modeled arsenic concentration plotted over distance downstream at Goler Wash. The data could be adequately modeled using a series of three discrete pulses (P1–P3) with power-law exponential decay behavior.

Table 2 Variable values for the discrete pulses at each wash site, determined by linear combination fitting and represented as series of power-law exponential decay curves

	P1	P2	P3	P4
Fiddlers Gulch				
k	7027.3	5789.7	7618.1	6080.2
a	−0.109	−0.004	−0.052	−0.179
x-start (m)	10	1213	2982	5051
x-end (m)	765	2355	3574	7369
Goler				
k	478.28	784.17	662.97	—
a	−0.037	−0.024	−0.092	—
x-start (m)	10	882	1850	—
x-end (m)	967	1850	2410	—
Red Mountain				
a	4137.7	6668	2713.5	1887
k	−0.408	−0.369	−0.032	−0.411
x-start (m)	626	845	4879	12 050
x-end (m)	789	1255	11 272	18 174
Ruth				
a	1709.9	—	—	—
k	−0.534	—	—	—
x-start (m)	409	—	—	—
x-end (m)	18 296	—	—	—

the piles and the alluvial fan serving to dilute the tailings in the stream to the sample concentrations observed. By using the average arsenic concentrations of the background and tailings material at each mine as endmembers, we can estimate their relative proportions at any point in the wash downstream from the tailings input by the following equation:

$$[\mathrm{As}]_{\mathrm{wash}} = \frac{\left[(1-p)[\mathrm{As}]_{\mathrm{bkgd}} + p[\mathrm{As}]_{\mathrm{tailings}}\right]}{2} \quad (3)$$

where p represents the percent contribution of tailings and $(1 - p)$ represents the percent contribution of background sediments to the sediment wash sample. Using this equation and empirical data, the relative contributions of tailings at the point of greatest arsenic concentration enhancement downstream from each mine's input are 22% and 37% for the Marigold East and West mines, respectively.

With the presence of multiple source inputs, fitting the data through the entire wash with a single exponential decay function yields an unsurprisingly poor fit and is not appropriate. However, fitting the decline in arsenic concentration at the end of the wash region sampled and using the peak value at ~1850 m as the starting point, a power law exponential decay function fits the data with an R^2 value of 0.75. Power law decay functions were similarly fitted to upstream segments of the Goler Wash sediment data using distance ranges determined by local concentration minima and maxima, with the resulting combination of power law functions superimposed on the empirical data in Fig. 11 and shown separately in Fig. 12. The fitted variables determined from this method for the Goler and other washes are listed in Table 2. The general quality of the fit along with the historical storm data mentioned earlier provides validation for this approach to fitting long-range wash sediment data as a series of pulses of arsenic-contaminated mine tailings which migrate downstream as discrete, discontinuous entities.

Red Mountain wash

A map showing sample locations collected within the Red Mountain wash and a chart displaying the arsenic concentrations in the wash sediments with increasing distance are shown in Fig. 13 and 14, respectively. The Red Mountain wash covers the greatest distance of all of the washes in this study and empties into Cuddeback Lake to the east (Fig. 1b), where sediment depth profiles in the playa lake have indicated substantial enrichment of arsenic in the surface sediments from wash-transported tailings. In the first 1200 m of the wash the samples consist essentially entirely of tailings, while in the lower part of the wash tailings still predominate but also include a significant component of sediment from the alluvial fan. A data gap between 1200 and 3800 m exists due to the relatively recent overprinting of sediments from an alluvial fan not associated with the Red Mountain mine tailings (visible in the upper left corner of Fig. 13). Nevertheless, the data can still be adequately modeled by assuming multiple discrete pulses of arsenic-enriched mine tailings, each of which exhibits power-law exponential decay behavior (Fig. 15). Fit quality suffered in the region immediately following the data gap, perhaps because the possible introduction of an additional tailings pulse is obscured by the newer alluvial fan sediments; accordingly, fits were omitted from this portion of data and restarted at the next local maximum.

Notably, the local arsenic concentration decay rates of the first two pulses within the first 1500 m are much more rapid than those that characterize sediment arsenic concentration trends starting around 5000 m, suggesting that the pulses nearest the initial mine tailings source originated through recent storm events that were relatively short in duration, while the older pulses represent a much longer timeframe of transport and downstream migration.

Fiddler Gulch wash

A map showing the locations of samples collected along the Fiddler Gulch wash and a chart displaying the arsenic concentrations in the wash sediments with increasing distance are shown in Fig. 16 and 17, respectively. Originating in the town of Randsburg and traversing parallel with the Descarga tailings pile (the largest quantity of tailings (~800 000 tons) from the Randsburg mining operations), the Fiddler Gulch wash eventually empties into Koehn Lake to the southwest (Fig. 1b). The tailings being distributed down Fiddler Gulch contain the highest arsenic concentrations of any wash investigated due to their origin from the Randsburg Au–Ag mine. Similar to the Red Mountain wash, a rapid and relatively spatially constrained decline in arsenic concentration characterizes the wash sediments closest to the tailings pile (within the first 800 m), suggesting that this pulse of mine tailings began traveling as a result of recent, brief storm events. Elevated arsenic concentrations persist farther downstream and begin to decline noticeably after 5000 m. These measurements can again be modeled with multiple pulses of tailings, showing a reasonably good fit to the data by proposing a total of four pulses, each exhibiting power-law exponential decay behavior (Fig. 18).

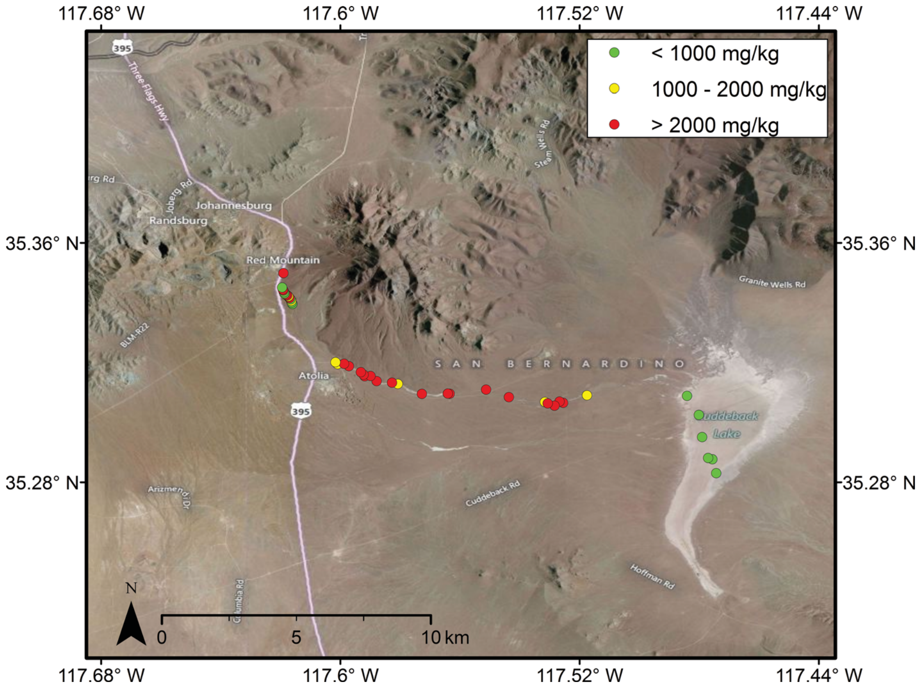


Fig. 13 Sample locations at Red Mountain wash with arsenic concentrations indicated by color. Concentration category boundaries were defined by natural breaks in the dataset.

Non-contaminated regions

Arsenic concentrations collected from non-impacted nearby alluvial fan sediments are tabulated in Table 3, with sample locations indicated in Fig. 1b. Measurements show that alluvial fan sediments in these background samples range from 2.6 to 62.7 mg kg^{-1} arsenic, considerably lower than the concentrations observed in tailings-impacted washes and comparable to concentrations in sediments adjacent to tailings piles such as those observed in the transects across the Calico Mine (Fig. 6). The alluvial fan sediments that receive material from the mineralized portion of the Randsburg area feature arsenic concentrations an order of magnitude greater than alluvial fan sediments derived from the El Paso Mountains (Fig. 1b, sites E and F) where no mineralization is present. However, the generally low concentrations observed in all samples suggest that these materials could be used for cover and fill material in future remediation strategies, such as the stabilization and capping of existing tailings piles.

The ability to track the distribution of tailings within washes by identifying a compensation point marking the transition between the incision/transport of upstream tailings and the deposition of tailings pulses out to a defined distance is not applicable to sediments on alluvial fans. Tailings are often manually piled above surface topography as in the Red Mountain and Fiddler Gulch washes, generating over-steepened, unvegetated slopes that then erode rapidly with tailings transport, extending downslope and spreading laterally with increasing distance from the original source. Alluvium also

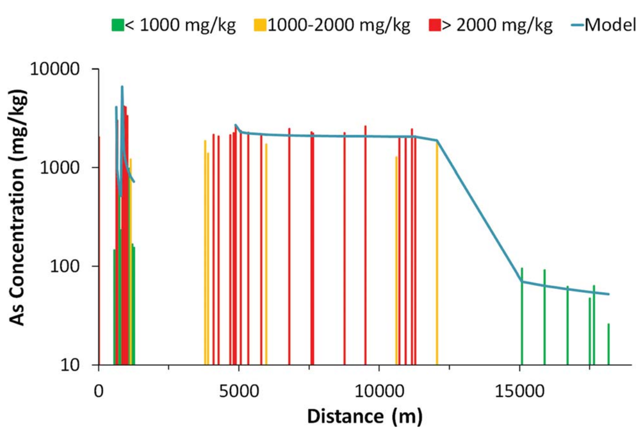


Fig. 14 Arsenic concentration plotted over distance downwash from the mine pile at Red Mountain wash.

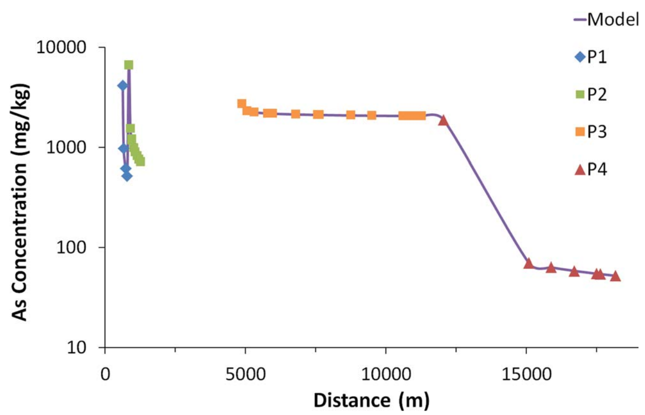


Fig. 15 Modeled arsenic concentration plotted over distance downwash from the mine pile at Red Mountain wash. The data could be adequately modeled using a series of four discrete pulses (P1–P4) with power-law exponential decay behavior.

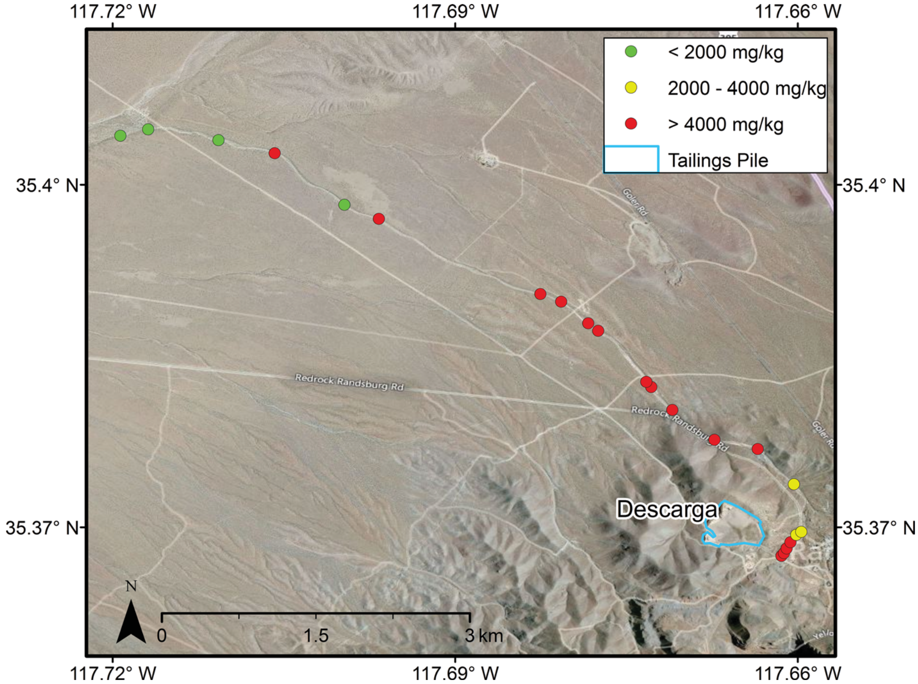


Fig. 16 Sample locations at Fiddler Gulch wash with arsenic concentrations indicated by color. Concentration category boundaries were defined by natural breaks in the dataset.

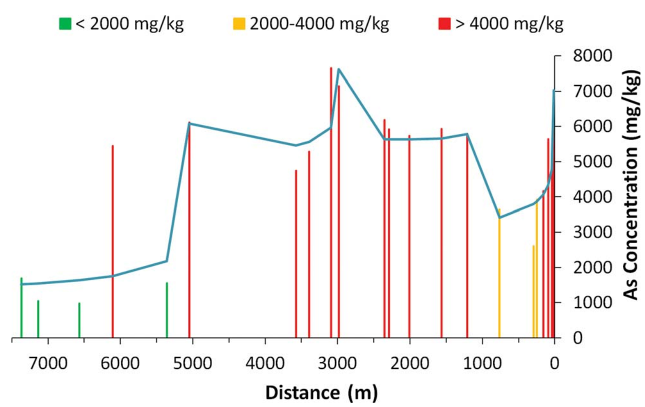


Fig. 17 Arsenic concentration plotted over distance downwash from the mine pile at Fiddler Gulch wash.

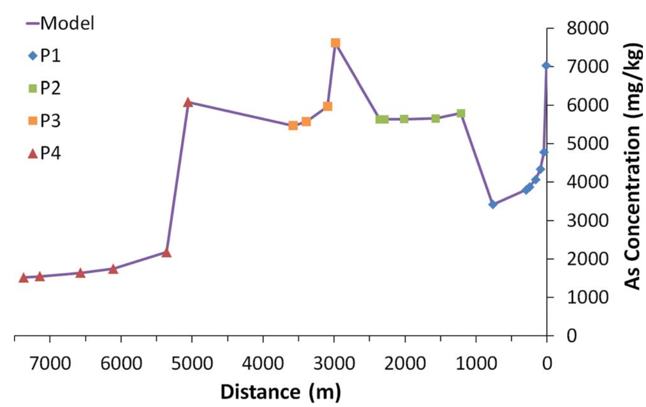


Fig. 18 Modeled arsenic concentration plotted over distance downwash from the mine pile at Fiddler Gulch wash.

Table 3 Locations, arsenic concentration ranges and arsenic concentration averages of uncontaminated alluvial fan sediments near mines in the Randsburg Historic Mine District (see Figure 1bfor locations)

Site/Sample Name (# of samples)	Range in As concentration (mg kg^{-1})	Average As concentration (mg kg^{-1})
Fremont Valley		
A (6)	51.5–62.7	56.4
B (2)	25.7–55.0	40.4
C (4)	14.6–55.5	32.6
D (3)	41.6–52.7	45.7
All sites (15)		45.8
El Paso Mountain		
E (8)	3.8–6.7	4.7
F (10)	2.6–8.8	4.9
All sites (18)		4.8

spreads in a classic fan shape with distance; however, in contrast to tailings, it creates natural surface topography with slopes that do not persist above angles of repose, consistent with its size distribution and featuring slower erosion/transport of sediment.

Conclusions

Monitoring the erosion and fluvial transport of arsenic-enriched Au–Ag mine tailings in a semi-arid environment demonstrates that significant movement of arsenic-bearing sediments occurs in washes located on alluvial fans, with contaminated sediments able to travel several kilometers from their sources into playa lakes. Understanding the enrichment of arsenic in sediments originating from mining sources is critical to assessing and monitoring the scope of environmental contamination associated with both historic and recent mining activity. While the general mechanism of tailings migration through fluvial and windborne means is relatively obvious, a more detailed characterization of the rates, extents, and future potential of tailings movement is needed in order to inform more effective remediation strategies. Based on observations of erosion and tailings transport from several mining regions, a conceptual model can be constructed to explain the fluvial migration of mine tailings in semi-arid environments. During rare but intense precipitation events, erosion of fine-grained particles causes them to be preferentially released over coarser particles from the tailings piles. Because arsenic concentration generally increases in the finer grain size fraction of the tailings, the suspended sediment in the runoff is highly enriched in arsenic with most of the arsenic bound to particles, although a significant fraction can also be transported in the dissolved state.

Tailings released from tailings piles increases the sediment load to the upper part of the washes, where transport capacity is exceeded and tailings are deposited in the bed of the wash. Successive storm events continue to release tailings that deposit in the washes and extend downstream as discrete pulses. The thickest tailings are located at the head of the wash and become progressively thinner and more diluted with uncontaminated sediment downstream. Since the tailings continue to move during successive storm events, the compensation point (change from sediment deposition to transport) shifts downstream as the gradient in the upper part of the wash decreases. Tailings in the upper part of the wash eventually become thick enough such that flows extend laterally onto adjacent surfaces, where tailings are also deposited. Where the wash is not highly incised into the alluvial fan, transport of tailings occurs as sheet wash on the alluvial fan and in the smaller channels that extend on either side of the main wash. In this phase of uncontrolled release, tailings are initially stored in the upper part of the wash and can progressively fill the entire wash to the playa lake if the sediment loads released from tailings piles are sufficient to continue to exceed the capacity of the wash.

The behavior of tailings in washes can change if the sediment load to the wash decreases in the following ways: (a) the initial tailings pile eventually erodes to the point where the sediment release becomes minimal; (b) controls on tailings release are implemented by the construction of a tailings dam; or (c) remediation results in removal of the tailings pile. With such a reduction in sediment release in any of these cases, the transport capacity of the wash increases, with high flows during storm events eroding the tailings in the upper part of the wash and progressively removing tailings from the active channel. The incision of the wash into the stored tailings will continue until the original pre-mining gradient is restored. Through this process, a significant volume of tailings can be released and transported towards and into a playa lake.

This conceptual model suggests that any remediation of historic mine sites that contain both tailings at the mine site and in the wash that drains it needs to address both problems concurrently. Control of tailings release at a mine site without addressing the stored arsenic-enriched sediment in the wash will lead to eventual erosion of these stored sediments and transport to the lower part of the wash and eventually the playa due to the decreased sediment load at the mine site. Removal of tailings from washes and alluvial fans is more challenging than remediation at mine sites, but the consequences of dealing with these problems separately may lead to unintended release of tailings, ineffective remediation efforts, and longer-term contamination.

The identification of negative exponential (power-law) decay behavior in arsenic concentrations with distance from tailings sources at several mine sites is consistent with more generalized studies on sediment transport[35] and best represents the distribution of arsenic-enriched tailings downstream/downslope through natural erosion and fluvial transport processes. The transport of mine tailings in washes as discrete pulses that migrate and broaden during large storm events can explain the relatively complex patterns in arsenic concentration with distance in multiple washes in the Randsburg Historic Mining District and other mining districts in the western Mojave Desert. A quantitative model of arsenic concentrations in wash sediments as a series of overlapping sediment pulses, each with exponential power-law decay behavior, results in adequate fits to the field data.

Certainly, this approach has shortcomings, including the need to arbitrarily define the operational length of each pulse (*i.e.* the starting and ending location of the pulse), as well as the degree of overlap with earlier/later pulses. The usage of local maxima and minima in arsenic concentration is an acceptable way to establish these variables, but does not represent the only way in which these patterns may be simulated. Another simplification occurs when conducting linear regression fits to the pulses individually instead of simultaneously. Simultaneous fitting of all pulses was attempted but could not be resolved due to the large number of degrees of freedom in such a fit as well as the discontinuous nature of the function used to describe the entirety of the wash sediment arsenic concentration trends.

Despite these assumptions and simplifications, the proposed quantitative model is satisfactory in reproducing the arsenic concentration patterns observed in the washes. It can also serve as a mechanism to model future trends in down-wash arsenic concentrations with a degree of reliability, providing a tool to help predict contaminant fate and transport under similar settings. The collection and modeling of datasets in a given wash at different time points would further improve the capacity to predict tailings migration over time. Alternatively, predictive models could be defined as a function of the number of large storm events that are likely to be responsible for the majority of fluvially derived tailings movement in semi-arid regions. The future variability in such events as a result of climate change may significantly impact the migration of contaminated tailings, particularly if the frequency or severity of storm events increases.

Continued improvements to such modeling efforts, aided by larger datasets and greater resolution of these datasets, will improve the effectiveness of the monitoring, management, and long-term remediation of mining-impacted areas. Furthermore, a detailed site-specific understanding of the mining history, tailings production and emplacement, and historical regional weather patterns is necessary in order to refine forecasts of the mobilization of arsenic and other toxic elements through fluvial transport processes.

Acknowledgements

This work was supported by USGS-MRERP (USGS award number 06HQGR0181) and NSF-CAREER (Award ID 0847811) grants. The authors wish to thank Dick Forester (Bureau of Land Management) for coordinating field sampling efforts and site permissions, Paul Lamothe (USGS) for assistance with chemical analyses, Dr Cyril Rakovski (Chapman University) for fruitful discussions and assistance with modeling of field data, Daniel Goldstein (USGS) for help with sample database management and editorial feedback, and past and present members of the Environmental Geochemistry Lab at Chapman University for their enthusiastic participation in field sampling.

References

1 J. J. Rytuba, A. Foster, C. S. Kim, A. Slowey, R. Forester and D. Lawler, *Geological Society of America Abstracts with Programs*, Denver, CO, 2007.
2 J. J. Rytuba, C. S. Kim and D. N. Goldstein, *Review of Samples of Tailings, Soils and Stream Sediment Adjacent to and Downstream from the Ruth Mine, Inyo County, California*, U.S., Geological Survey Open-File Report 2011-1105, http://pubs.usgs.gov/of/2011/1105/.
3 J. J. Rytuba, C. S. Kim and D. N. Goldstein, *Review of Samples of Sediment, Tailings, and Waters Adjacent to the Cactus Queen Gold Mine, Kern County, California*, U.S., Geological Survey Open-File Report 2011-1034, http://pubs.usgs.gov/of/2011/1034/.
4 K. A. Hudson-Edwards, H. E. Jamieson and B. G. Lottermoser, *Elements*, 2011, **7**, 375–379.
5 R. Eisler, in *Reviews of Environmental Contamination and Toxicology*, 2004, vol. 180, pp. 133–165.
6 J.-Q. Chen, Z.-X. Wang, X. Wu, J.-J. Zhu and W.-B. Zhou, *Trans. Nonferrous Met. Soc. China*, 2011, **21**, 642–651.
7 Y.-G. Wu, Y.-N. Xu, J.-H. Zhang and S.-H. Hu, *Trans. Nonferrous Met. Soc. China*, 2010, **20**, 688–694.
8 U.S. Fish and Wildlife Service, *Revised Recovery Plan for the Mojave Population of the Desert Tortoise (*Gopherus agassizii*)*, U.S. Fish and Wildlife Service, Pacific Southwest Region, Sacramento, California, 2011.
9 M. D. Seltzer and K. H. Berry, *Sci. Total Environ.*, 2005, **339**, 253–265.
10 J. M. Azcue and J. O. Nriagu, *J. Geochem. Explor.*, 1995, **52**, 81–89.
11 R. L. Hooke, *Geol. Soc. Am. Bull.*, 2000, **112**, 1778–1786.
12 W. A. Marcus, G. A. Meyer and D. R. Nimmo, *Geology*, 2001, **29**, 355–358.
13 J. R. Miller and P. J. Lechler, *Environ. Geol.*, 2003, **43**, 315–325.
14 Y. Sivry, M. Munoz, V. Sappin-Didier, J. Riotte, L. Denaix, P. de Parseval, C. Destrigneville and B. Dupre, *Eur. J. Mineral.*, 2010, **22**, 679–691.
15 J. R. Miller, J. Rowland, P. J. Lechler, M. Desilets and L. C. Hsu, *Water, Air, Soil Pollut.*, 1996, **86**, 373–388.
16 I. Razo, L. Carrizales, J. Castro, F. Diaz-Barriga and M. Monroy, *Water, Air, Soil Pollut.*, 2004, **152**, 129–152.
17 C. S. Kim, K. M. Wilson and J. J. Rytuba, *Appl. Geochem.*, 2011, **26**, 484–495.
18 J. R. Miller, K. A. Hudson-Edwards, P. J. Lechler, D. Preston and M. G. Macklin, *Sci. Total Environ.*, 2004, **320**, 189–209.
19 O. Gonzalez-Fernandez, L. Rivero, I. Queralt and M. Viladevall, *Water, Air, Soil Pollut.*, 2011, **221**, 45–61.
20 O. Gonzalez-Fernandez, I. Queralt, M. L. Carvalho and G. Garcia, *Water, Air, Soil Pollut.*, 2011, **220**, 279–291.
21 C. N. Kien, V. N. Noi, N. D. Bang, L. T. Son, S. Tanaka, Y. M. Kang, K. Sakurai and K. Iwasaki, *Water, Air, Soil Pollut.*, 2009, **197**, 75–89.
22 E. I. B. Chopin and B. J. Alloway, *Water, Air, Soil Pollut.*, 2007, **182**, 245–261.
23 S. M. Allen-Gil, J. Ford, B. K. Lasorsa, M. Monetti, T. Vlasova and D. H. Landers, *Sci. Total Environ.*, 2003, **301**, 119–138.
24 Y. Wu, Y. Xu, J. Zhang, S. Hu and K. Liu, *Environ. Earth Sci.*, 2011, **64**, 1585–1592.
25 J. Hettler, G. Irion and B. Lehmann, *Miner. Deposita*, 1997, **32**, 280–291.
26 D. L. Gardner, *California Division of Mines*, Bulletin 118, 1954, pp. 549–550.
27 J. J. Rytuba in *Geology and Ore Deposits of the American Cordillera*, ed. A. R. Coyner and P. L. Fahey, Geological Society of Nevada Symposium Proceedings, Reno/Sparks, Nevada, 1996, pp. 803–822.
28 C. E. W. Bateson, *Trans. Am. Inst. Min. Metall. Eng.*, 1906, **37**, 160–177.
29 A. R. Blaske, T. J. Bornhorst, J. M. Brady, T. M. Marsh and S. A. McKitrick, *Econ. Geol. Bull. Soc. Econ. Geol.*, 1991, **86**, 1646–1656.
30 *U.S. Geological Survey Bulletin 1693*, ed. D. P. Cox and D. A. Singer, 1986, p. 379.
31 HighDesertNews, Flash flood 7-16-08 (Part 1), http://www.youtube.com/watch?v=aq4-OAsposI.
32 A. Clauset, C. R. Shalizi and M. E. J. Newman, *SIAM Rev.*, 2009, **51**, 661–703.
33 M. E. J. Newman, *Contemp. Phys.*, 2005, **46**, 323–351.
34 N. E. Humphries, N. Queiroz, J. R. Dyer, N. G. Pade, M. K. Musyl, K. M. Schaefer, D. W. Fuller, J. M. Brunnschweiler, T. K. Doyle, J. D. Houghton, G. C. Hays, C. S. Jones, L. R. Noble, V. J. Wearmouth, E. J. Southall and D. W. Sims, *Nature*, 2010, **465**, 1066–1069.
35 J. D. Stock, K. M. Schmidt and D. M. Miller, *Geol. Soc. Am. Bull.*, 2008, **120**, 619.