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The Effects of Sediment and Mercury Mobilization in the South Yuba River and Humbug Creek Confluence Area, Nevada County, California: Concentrations, Speciation, and Environmental Fate–Part 1: Field Characterization

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U.S. Department of the Interior
U.S. Geological Survey

Cover top: Suction dredge test in the South Yuba River downstream of Humbug Creek, October 11, 2007; C.N. Alpers, USGS.
Cover bottom: South Yuba River just downstream of Humbug Creek during storm conditions, February 3, 2010; R. Humphreys, California State Water Resources Control Board.

The Effects of Sediment and Mercury Mobilization in the South Yuba River and Humbug Creek Confluence Area, Nevada County, California: Concentrations, Speciation, and Environmental Fate—Part 1: Field Characterization

Jacob A. Fleck, Charles N. Alpers, Mark Marvin-DiPasquale, Roger L. Hothem, Scott A. Wright, Kevin Ellett, Elizabeth Beaulieu, Jennifer L. Agee, Evangelos Kakouros, Le H. Kieu, Dennis D. Eberl, Alex E. Blum, and Jason T. May

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
Acre	4,047	square meter (m^2)
Acre	0.4047	hectare (ha)
Acre	0.004047	square kilometer (km^2)
square foot (ft^2)	929.0	square centimeter (cm^2)
square foot (ft^2)	0.09290	square meter (m^2)
square inch (in^2)	6.452	square centimeter (cm^2)
square mile (mi^2)	259.0	hectare (ha)
square mile (mi^2)	2.590	square kilometer (km^2)
	Volume	
gallon (gal)	3.785	liter (L)
gallon (gal)	0.003785	cubic meter (m^3)
gallon (gal)	3.785	cubic decimeter (dm^3)
cubic inch (in^3)	16.39	cubic centimeter (cm^3)
cubic inch (in^3)	0.01639	liter (L)
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
gallon per minute (gal/min)	0.06309	liter per second (L/s)
	Mass	
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)
ton, short (2,000 lb)	0.9072	megagram (Mg)
ton, long (2,240 lb)	1.016	megagram (Mg)
ton per day (ton/d)	0.9072	metric ton per day
ton per day (ton/d)	0.9072	megagram per day (Mg/d)
ton per year (ton/yr)	0.9072	metric ton per year

Pressure		
atmosphere, standard (atm)	101.3	kilopascal (kPa)
Bar	100	kilopascal (kPa)
inch of mercury at 60ºF (in Hg)	3.377	kilopascal (kPa)
Density		
pound per cubic foot (lb/ft^3)	16.02	gram per cubic centimeter (g/cm^3)
pound per cubic foot (lb/ft^3)	0.01602	gram per cubic centimeter (g/cm^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$°C = (°F - 32)/1.8$$

Horizontal coordinate information is referenced to North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

Specific conductance is given in micro Siemens per centimeter at 25 degrees Celsius (µS/cm at 25 °C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L), micrograms per liter (µg/L), or nanograms per liter (ng/L).

Acronyms, Abbreviations, and Chemical Notation

Acronyms

BLM, Bureau of Land Management

BRC, bedrock contact

CERCLA, Comprehensive Environmental Response, Compensation, and Liability Act (Superfund)

CSL, compact sediment layer

CVAFS, cold vapor atomic-fluorescence spectrometry

F1, fraction 1; sand, 0.063 to 1.0 millimeter

F2. fraction 2; fines, less than 0.063 millimeter, or silt plus clay

F3, fraction 3; sand plus fines, less than 1.0 millimeter

FCZ, first contact zone

GPR, ground-penetrating radar

HC, Humbug Creek

HDPE, high-density polyethylene

HMD, hydraulic mining debris

LOI, loss on ignition

NIST, National Institute of Standards and Technology

OBL, overburden layer

SEM, scanning electron microscope

SYR, South Yuba River

TSS, total suspended sediment

USEPA, U.S. Environmental Protection Agency

USFS, U.S. Forest Service

USGS, U.S. Geological Survey

WR–BRR, Western Region – Branch of Regional Research

XRD, x-ray diffraction

XRF, x-ray fluorescence

Abbreviations

cm, centimeter

cm^3, cubic centimeter

df, degrees of freedom

F, F-statistic

$F_{a,b}$, F-statistic with numerator and denominator degrees of freedom, a and b, respectively

g, gram

g/cm^3, gram per cubic centimeter

gal, gallon

HP, horsepower

hr, hour

Hz, hertz

kg, kilogram

km, kilometer

L, liter

m, meter

m^3/hr, cubic meter per hour

MHz, megahertz

mg, milligram

mg/hr, milligram per hour

mL, milliliter

mm, millimeter

µg, microgram

µg/g, microgram per gram (equivalent to part per million)

µg/kg, microgram per kilogram (equivalent to part per billion)

µL/L, microliter per liter (equivalent to part per million)

µm, micrometer

ng, nanogram

ng/g, nanogram per gram (equivalent to part per billion)

ng/L, nanogram per liter

p, p-value

ppm, part per million

R, correlation coefficient (Spearman Rank Order)

wt, weight

<, less than

%, percent

χ^2, chi-squared statistic

Chemical Notation

Al, aluminum

Al_2O_3, aluminum oxide

Au, gold

BrCl, bromine monochloride

Ca, calcium

CaO, calcium oxide

CH_3Hg^+, methylmercury (monomethylmercury)

CH_3OH, methanol

$CrCl_3$, chromium(III) chloride

F, fluorine

Fe, iron

$Fe(II)_{AE}$, acid extractable ferrous iron

$Fe(III)_a$, amorphous (poorly crystalline) ferric iron

$Fe(III)_c$, crystalline ferric iron

Fe_T, total measured iron ($Fe(II)_{AE}$ + $Fe(III)_a$ + $Fe(III)_c$)

fMeHg, filtered methylmercury (monomethyl mercury)

fTHg, filtered total mercury

H, hydrogen

HCl, hydrochloric acid

Hg, mercury

Hg(0), elemental mercury

Hg(II), (divalent) mercuric ion

$Hg(II)_R$, inorganic reactive mercury(II)

$Hg(II)_{R\text{-}SS}$, inorganic reactive mercury on the suspended sediment fraction

HgAu, mercury-gold amalgam

HNO_3, nitric acid

K, potassium

KOH, potassium hydroxide

MeHg, methylmercury (monomethylmercury)

Mg, magnesium

Na, sodium

O, oxygen

P, phosphorus

$pHg(II)_R$, particulate (water column) reactive mercury

pMeHg, particulate (water column) monomethylmercury

pTHg, particulate (water column) total mercury

Si, silicon

SiO_2, silicon oxide (quartz)

SO_4^{2-}, sulfate ion

$SnCl_2$, tin (stannous) chloride

THg, total mercury

THg_{SS}, total mercury of suspended sediment

Ti, titanium

TiO_2, titanium oxide

ZnS, zinc sulfide

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Abstract

Millions of pounds of mercury (Hg) were deposited in the river and stream channels of the Sierra Nevada from placer and hard-rock mining operations in the late 1800s and early 1900s. The resulting contaminated sediments are relatively harmless when buried and isolated from the overlying aquatic environment. The entrained Hg in the sediment constitutes a potential risk to human and ecosystem health should it be reintroduced to the actively cycling portion of the aquatic system, where it can become methylated and subsequently bioaccumulated in the food web. Each year, sediment is mobilized within these fluvial systems during high stormflows, transporting hundreds of tons of Hg-laden sediment downstream. The State of California and resource-management agencies, including the Bureau of Land Management (BLM) and the U.S. Forest Service, are concerned about additional disturbances, such as from suction gold dredging activities, which have the potential to mobilize Hg associated with buried sediment layers elevated in Hg that are otherwise likely to remain buried under normal storm conditions.

The BLM initiated a study looking at the feasibility of removing Hg-contaminated sediment at the confluence of the South Yuba River and Humbug Creek in the northern Sierra Nevada of California by using standard suction-dredge technology. Additionally, the California State Water Resources Control Board (SWRCB) supported a comprehensive characterization of the intended dredge site. Together, the BLM and SWRCB supported a comprehensive characterization of Hg contamination at the site and the potential effects of sediment disturbance at locations with historical hydraulic mining debris on downstream environments. The comprehensive study consisted of two primary components: field studies and laboratory experiments. The field component, described in this report, had several study elements: 1) a preliminary, small-scale, in-stream dredge test; 2) comprehensive characterization of grain size distribution, Hg speciation, and mineralogy of bed and suspended sediment; 3) a determination of the past and current sources of sediment in the study area; 4) an assessment of Hg bioaccumulation in the local invertebrate population; and 5) a comparison of potential Hg transport caused by natural storm disturbances with potential Hg mobilization caused by suction dredging as a method of Hg removal at the study site. The laboratory component of the study assessed the potential influence of the disturbance of Hg-contaminated

sediment through experiments designed to simulate in-stream transport, deposition, and potential methylation of Hg, described in a companion report (see Marvin-DiPasquale and others, 2011).

Results of the field studies indicate that the fine-grained fraction (silt-clay, less than 0.063 millimeters) contains the greatest concentration of Hg in contaminated sediment. Because the fine-grained fraction is the most susceptible to long-range fluvial transport, disturbance of Hg-contaminated sediment is likely to increase the concentration and load of Hg in downstream waters. The preliminary, small-scale dredge test showed an increase in the concentration of fine particles and Hg in the water column caused by the dredge activity, despite relatively low concentrations of fine particles and Hg (about 300 nanograms per gram) at the dredge site. Characterization of sediment from two test pits and other sites in the vicinity of the confluence of the South Yuba River and Humbug Creek revealed a highly variable distribution of fine- and coarse-grained sediment. The highest levels of Hg contamination (up to 11,100 ng/g) were associated with the fine-grained fraction of sediment from the bedrock contact zone of Pit 2, a horizon which also yielded grains of gold and gold-Hg amalgam.

A closed-circuit tank experiment with a venturi dredge at the base of Pit 1, in a gravel bar within the South Yuba River, resulted in fine-grained suspended sediment remaining in suspension more than 40 hours following the disturbance simulation. Although the volumetric concentration of Hg declined over time as particles settled out, the concentration of Hg on the suspended particles increased over time as the suspended material became finer grained, because Hg is preferentially adsorbed on to clay-sized particles. Mineralogical and chemical analyses indicated that the buried fine-grained material with the greatest Hg contamination was derived from hydraulic mining debris, which consist primarily of Eocene gravels mined in the Malakoff Diggins, North Bloomfield, and Lake City areas within the South Yuba River watershed. Coarse material and more recently deposited sediment were derived primarily from upstream sources on the South Yuba River.

The biota assessment indicated that invertebrate taxa collected from all sites on the South Yuba River in 2007, including lower Humbug Creek, had elevated concentrations of total mercury (THg) and methylmercury (MeHg) compared to a reference site on the Bear River, upstream of mining effects. Differences with the reference site were less pronounced in 2008 when a significant reduction in MeHg concentrations was observed in biota across all taxa from concentrations in 2007. It is possible that the inter-annual variation was related to the fact that suction dredging was active in the South Yuba River in 2007 but not in 2008 when a local moratorium was imposed by the BLM. There were significant variations among taxa for both THg and MeHg concentrations, with the water striders (Gerridae) having the highest concentrations of both THg and MeHg; variation among sites was not as strong as between years or among taxa. These results suggest that additional monitoring would be helpful to investigate the possible linkage between variations in MeHg bioaccumulation and levels of suction dredge activity in areas of historical gold mining.

Results from the field studies indicate that disturbance of the fine-grained Hg-contaminated sediment would likely lead to enhanced mobilization of Hg to downstream environments; therefore, the use of suction dredging to remove Hg at the South Yuba River and Humbug Creek confluence area would likely result in enhanced Hg transport downstream relative to natural conditions.

Introduction

Hydraulic mining left a profound mark on California's environment as hundreds of millions of tons of hydraulic mining debris (HMD) filled the river and stream channels of the Sierra Nevada (Gilbert, 1917; James, 1993). It is estimated

that about 10 million pounds of mercury (Hg) were lost to the environment during gold (Au) recovery placer mining operations using amalgamation methods, primarily during the mid- to late 1800s (Bowie, 1905; Averill, 1946; Churchill, 2000; Alpers and others, 2005a). This large-scale release of Hg to the environment resulted in Hg-contaminated sediment in Sierra Nevada rivers (Hunerlach and others, 1999, 2004), foothill reservoirs (Alpers and others, 2005b), and San Francisco Bay (Hornberger and others, 1999; Bouse and others, 2010). Hg was also lost to the environment from hard-rock Au mining and mineral processing activities, where amalgamation was used at stamp mills (Churchill, 2000). Hg-contaminated sediment associated with historical Au mining in Sierra Nevada watersheds continues to erode to this day and becomes periodically resuspended and transported downstream (James, 1993, 2005; Alpers and others, 2005b, 2006; Curtis and others, 2005, 2006; Hunerlach and others, 2004). Transport of Hg from mine wastes in the Sierra Nevada may represent a substantial ongoing source of Hg to downstream water bodies, such as the Sacramento–San Joaquin Delta, that are considered by the State of California to have impaired water quality (Wood and others, 2010).

The form or speciation of Hg in contaminated sediment associated with historical mining is important because it affects transport, reactivity, and bioavailability (Kim and others, 2003, 2004; Bloom and others, 2003, 2006). Liquid elemental mercury (Hg(0); quicksilver) has been observed in sediment within hydraulic sluice tunnels and in bed sediment of Sierra Nevada rivers draining historically mined regions (Hunerlach and others, 1999; Humphreys, 2005). Grains of Hg-Au amalgam have been observed macroscopically and microscopically in sediment from mining-affected areas such as Englebright Lake (Alpers and others, 2006) and the Yuba Goldfields (Hunerlach and others, 2004). The size of liquid Hg(0) droplets and Hg-Au amalgam particles has an important influence on the nature of their transport in flowing water; sand and gravel-sized particles ("nuggets") tend to move with the bedload, whereas silt- and clay-sized particles tend to be transported more readily in the water column as suspended sediment or wash load. Characterization of the grain size of Hg-rich particles in mining-contaminated sediment of the Sierra Nevada is an information gap that is addressed in this report.

Hg is a complex contaminant because of its unique physical and chemical properties and variable speciation. Although the elemental form (liquid Hg(0)) can be considered as relatively inert chemically, the divalent inorganic oxidized form (Hg(II)) and the organic, methylated form (CH_3Hg^+, monomethylmercury, abbreviated as MeHg) are more reactive and more bioavailable, posing the greatest risk to human and ecosystem health (Marvin-DiPasquale and others, 2009a, 2009b; Alpers and others, 2008). MeHg, a highly bioaccumulative form of Hg, is formed primarily by sulfate- and iron-reducing bacteria that are most active in environments where oxygen is limited and an energy source such as fresh organic matter is present (Compeau and Bartha, 1984; Gilmour and others, 1992; Marvin-DiPasquale and Agee, 2003). The formation of MeHg is also dependent on the availability of inorganic Hg(II). The U.S. Geological Survey (USGS) has developed an analytical method for operationally defined "reactive mercury" ($Hg(II)_R$) in sediment, by using exposure to a strong reducing agent for 15 minutes (Marvin-DiPasquale and Cox, 2007). This analysis of $Hg(II)_R$ provides a measure of the fraction of inorganic Hg that is most likely to be converted to MeHg if active communities of Hg(II)-methylating bacteria are present. Therefore, the environments where $Hg(II)_R$ is available and Hg(II)-methylating bacteria are active are the zones of most concern with regard to MeHg formation and effects. Wetlands can provide such an environment, particularly where there is an external supply of $Hg(II)_R$ to the wetland (Marvin-DiPasquale and Agee, 2003; Alpers and others, 2008; Marvin-DiPasquale and others, 2009a).

The historical Hg contamination of the Sierra Nevada associated with past Au mining activity poses a challenge to Federal, State, and local agencies that are responsible for managing public lands with regard to health and safety, as well as water quality and biota. At some Hg-contaminated Au-mine sites in the northwestern Sierra Nevada, site characterization has revealed Hg concentrations that are sufficiently high enough to warrant remedial actions (for example, Hunerlach and others, 1999; Alpers and others, 2005b). Clean-up efforts have been made under the Comprehensive Environmental Response, Compensation and Liability Act (CERCLA) by the U.S. Environmental Protection Agency (USEPA) in 2000 at the Polar Star Tunnel, Dutch Flat mining district (U.S. Environmental Protection Agency, 2000), by the U.S. Forest Service (USFS) in 2003 at the Sailor Flat mine (DeGraff, 2007), and by the Bureau of Land Management (BLM) in 2006 at the Boston Mine, Red Dog mining district (Key, 2006).

The South Yuba River is one of California's rivers most affected by hydraulic mining, and there are numerous hydraulic mine sites located within its watershed. Oral reports from recreational suction dredgers working on the South Yuba River in the vicinity of the Humbug Creek confluence (hereafter referred to as the SYR-HC confluence) indicated that several kilograms of liquid Hg(0) have been found and removed. In addition, suction dredgers reported encountering a buried "slickens" (clay-rich) layer consisting of fine-grained sediment associated with Gold-Rush-era hydraulic mining and associated elevated concentrations of heavy minerals including Au, Hg-Au amalgam, and visible liquid Hg(0). These deposits constitute a particular risk to human and ecosystem health if they are reintroduced to the actively cycling portion of the aquatic system and enter the food web (Mason and others, 1995; Weiner and others, 2007). These oral reports led the BLM to pursue a possible CERCLA removal action in the area. The BLM was also interested in determining whether suction dredging could be used as an effective removal method for elemental Hg(0) at the SYR-HC confluence area, a site with difficult access for earth-moving equipment. Humbug Creek drains Malakoff Diggins (fig. 1B), one of the largest historical hydraulic mines in the Sierra Nevada Mountains, Calif., now preserved as Malakoff Diggins State Historic Park.

Purpose and Scope

This report documents the methods and results of field investigations during 2007 through 2009 in the region of the SYR-HC confluence, to 1) characterize Hg concentration and speciation in sediment of various size fractions, 2) characterize Hg and MeHg concentrations in local biota, and 3) assess the practicality and potential effects of using suction dredging as a method for Hg removal from an area contaminated with Hg.

The study scope includes five primary elements: 1) a preliminary suction-dredge test in the South Yuba River, 2) detailed site characterization of sediment in the SYR-HC confluence area, 3) assessment of Hg and sediment sources on the basis of mineralogy and chemical composition, 4) assessment of local MeHg bioaccumulation, and 5) determination of the likely influence of disturbances affecting Hg-contaminated sediment. This report documents the methods and results of the first four elements of the study. The results of elements 1 through 3 are then used to address element 5 with regard to enhanced inorganic Hg transport from disturbances. A companion report (Marvin-DiPasquale and others, 2011) addresses other aspects of element 5 by documenting methods and results of laboratory experiments on selected sediment samples to determine the likely effects of Hg transport resulting from disturbances. These experiments were designed to examine 1) changes in Hg speciation resulting from the mobilization of previously buried sediment into oxygenated overlying river water, and 2) the potential for MeHg production when the mobilized sediment is mixed with sediment collected from environments representative of common downstream depositional areas, such as streambeds, reservoirs, and wetlands.

The scope of the project was modified to accommodate concerns by the State Water Resources Control Board and California Regional Water Quality Control Board, Central Valley Region (CRWQCB-CVR), that the larger-scale test would result in a major and illegal discharge of Hg to the environment. The revised project scope replaced the planned full-scale suction-dredge test with study elements 2 and 3, which focused on a more complete assessment of sediment composition and Hg contamination and speciation as a function of grain size, as well as current and historical sources of contamination at the SYR-HC confluence site. The information generated in this study could prove helpful in determining the potential for Hg transport due to dredge activities through simulation calculations.

Site Description

The South Yuba River watershed is located in the northwestern Sierra Nevada geomorphic province (fig. 1A). Humbug Creek is part of the South Yuba River watershed and receives outflow from the Malakoff Diggins through the Hiller Tunnel and the North Bloomfield Tunnel, as well as some drainage from the Lake City Diggins and North San Juan Diggins through the Lake City Tunnel (fig. 1B). Additional, unidentified and undiscovered drainage tunnels in similar condition as these primary tunnels likely exist throughout the watershed. The tunnels were constructed in the 1870s and 1880s and were used to transport large quantities of HMD from the hydraulic mines. Contamination from Hg in the study area is likely to be extensive because historical reports estimate that as much as 30 percent (%) of Hg was lost (equal to approximately 30 lb of Hg per meter of tunnel were lost in the North Bloomfield sluiceway) each year during 1853–1884 (Bowie, 1905).

Malakoff Diggins is located in the North Bloomfield mining district and is one of the largest hydraulic mines in California. The mine processed 23 to 31 million cubic meters of auriferous gravels of Tertiary age using Hg-charged undercurrents for recovery of fine Au (Clark, 1970; Alpers and others, 2005a). The 170-m Hiller Tunnel was built between 1851 and 1856 to carry debris from the mine pit into Humbug Creek for transport off site. By 1872, the Hiller Tunnel was operating over capacity, so the 2,392-m North Bloomfield drain tunnel was built to replace the Hiller Tunnel as the primary outlet from Malakoff Diggins (*http://www.malakoffdiggins.org/?page_id=556*). The North Bloomfield tunnel bypassed much of the Humbug Creek canyon and discharged HMD onto and over an extensive series of Hg-laden undercurrents that eventually emptied into the South Yuba River. Although at present it is blocked, the North Bloomfield Tunnel currently discharges some drainage from the Malakoff Diggins hydraulic mine pit into Humbug Creek through its outlet (fig. 1B), but very little suspended sediment is transported through the tunnel because of the blockage.

The Lake City Tunnel was constructed to drain HMD from other hydraulic mines on the San Juan Ridge to the southwest of Malakoff Diggins. The Lake City Tunnel empties into Humbug Creek just upstream from the North Bloomfield Tunnel (fig. 1B). Although less HMD passed through the Lake City Tunnel than the North Bloomfield Tunnel, the Lake City Tunnel also contributed Hg to Humbug Creek. Compared to Malakoff Diggins, relatively little is known about the amount of Au-bearing gravel mined at the Lake City Diggins but the amount of Hg lost per cubic yard of gravel mined would have been similar. The Lake City Tunnel is also blocked and is believed to currently contribute only small amounts of sediment and drainage to Humbug Creek.

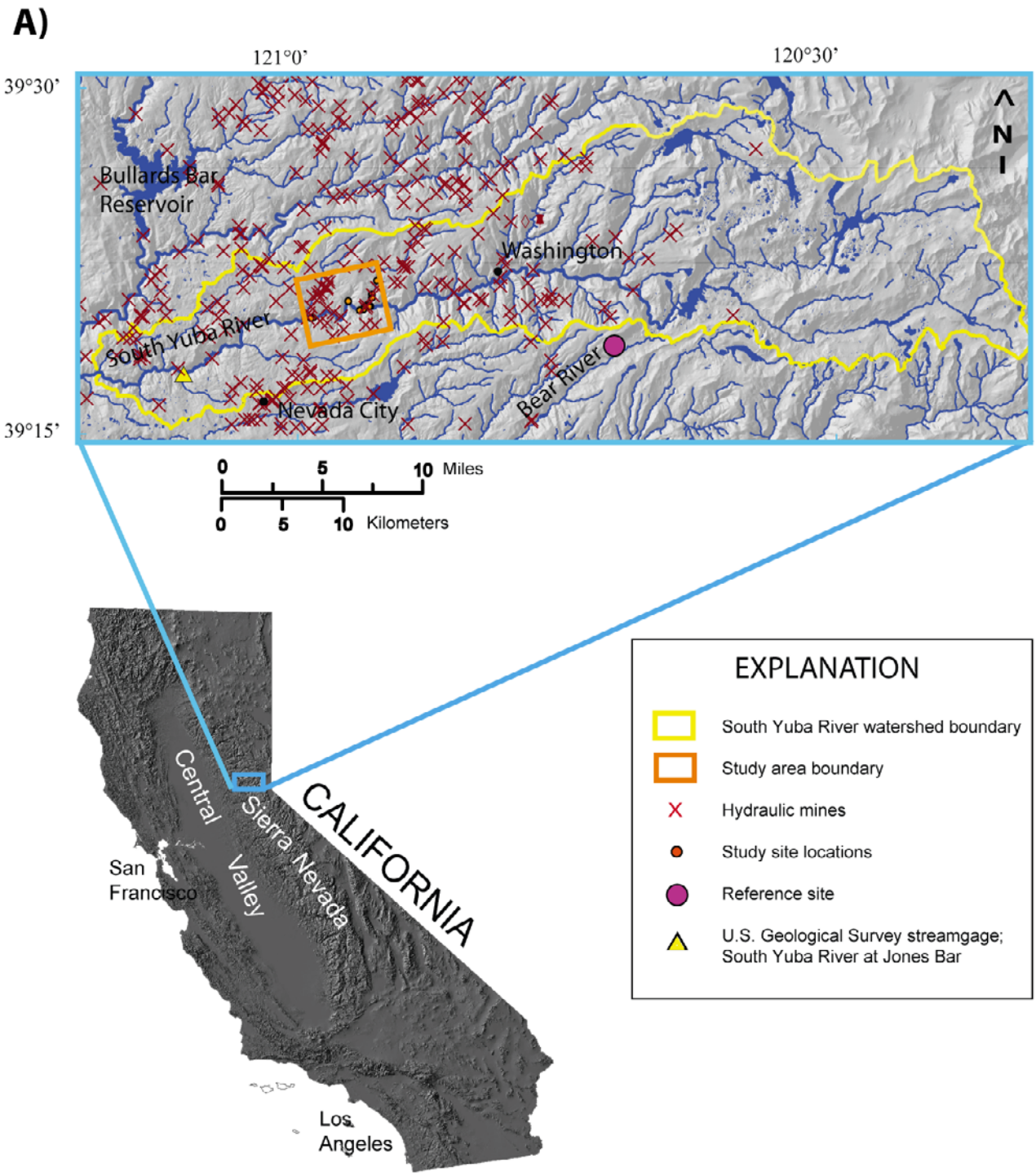


Figure 1. Maps showing location of (A) the South Yuba River watershed in California's Sierra Nevada, with a detailed view of the location of the study area and hydraulic mines within the South Yuba River watershed and (B) the locations of hydraulic pits (Yeend, 1974) and sampling sites within the study area, with a detailed view of the high-resolution aerial photo of the focused study area of the South Yuba River–Humbug Creek (SYR-HC) confluence. Source: MAS/MILS (Minerals Availability System/Mineral Information Location System) database compiled by the former U.S. Bureau of Mines, now archived by the USGS.

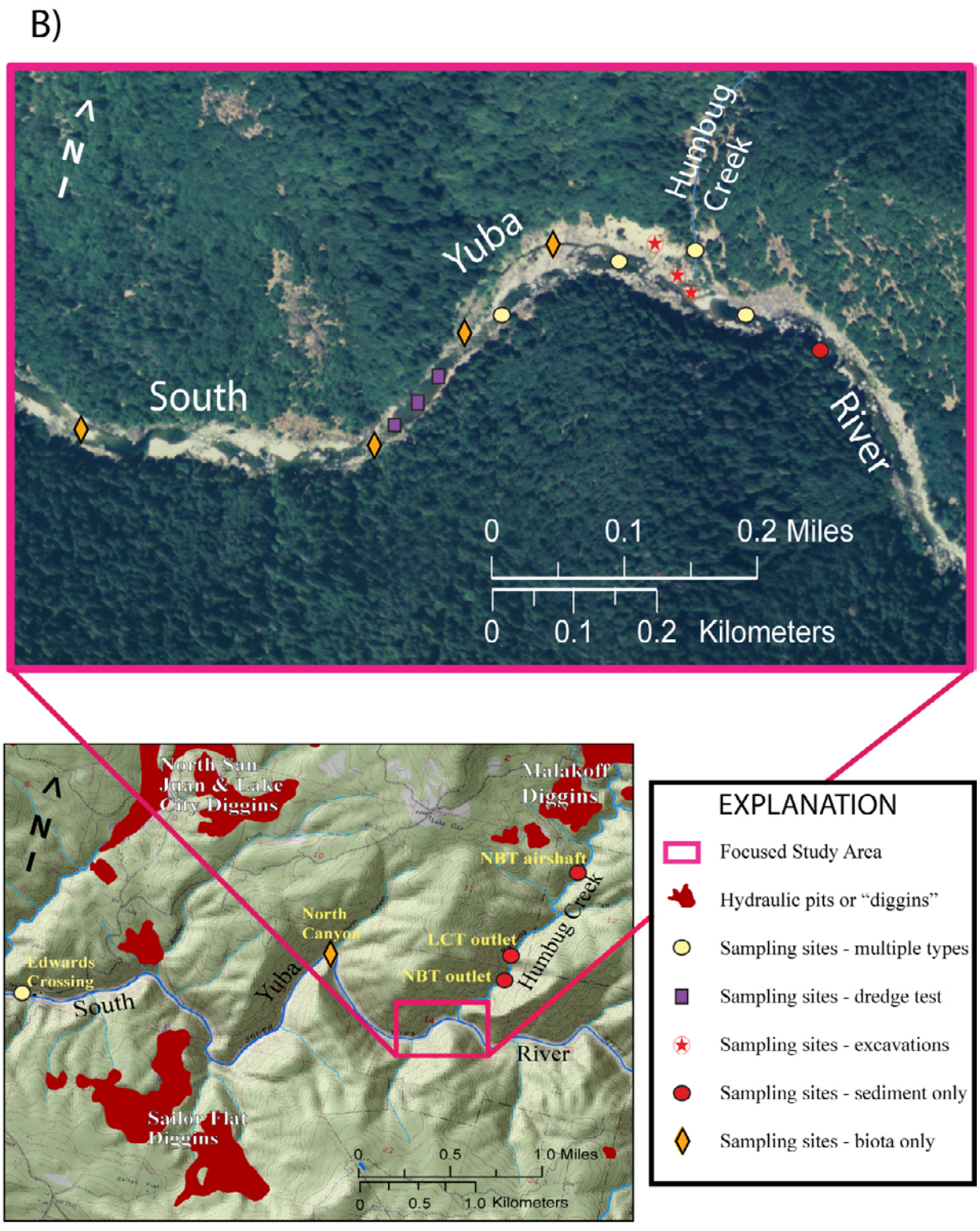


Figure 1.—Continued.

In 1884, the Sawyer Decision halted most major hydraulic mining operations in the Sierra Nevada (Sawyer, 1884). However, additional mining took place after that time. After the Caminetti Act of 1893, hydraulic mining was allowed in the Sierra Nevada, provided that HMD was kept out of navigable waterways and off other people's property by containing it behind debris dams. In the SYR-HC confluence area, at the height of hydraulic mining activity, there was up to 30 vertical meters of HMD filling the original steep-walled canyons of the South Yuba River and Humbug Creek. Since 1884, much of the HMD has been eroded away in the river channel, leaving relic cliffs composed of HMD exposed along the canyon walls. Conditions at the confluence site are currently still subject to erosion because of the instability of HMD that makes up a large portion of the canyon walls in this reach of the South Yuba River. The bed of Humbug Creek is predominantly bedrock, whereas the bed of the South Yuba River is largely armored with cobbles and boulders, with finer sediment in the deeper pools. According to some suction-dredge miners, the cobble layer overlays deeper, relic fine-grained "slickens" layers from the hydraulic mining era that are rich in Au, amalgam, and Hg. The extent and distribution of the historical "slickens" layer are unknown, but this layer has been the focus of previous suction dredge operations and continues to be sought out because it often contains substantial Au and Hg-Au amalgam.

Field Methods: Sample Collection and Processing

The breadth of field methodology used in this study is in part because of the change in the project scope brought about by concern from the CRWQCB-CVR that the planned full-scale dredge test would negatively affect water quality and violate regulatory statutes. The resulting complex set of study elements refocused the study efforts toward a multidisciplinary characterization of the SYR-HC confluence area. Because the resulting study contains a diverse range of methods, specific methods and results for each study element are presented in separate, parallel subsections of the report.

Preliminary Dredge Test

Sample collection methods and experiment logistics were tested in a preliminary test on October 11, 2007, prior to a larger suction-dredge test scheduled for 2008. A standard 3-in. (7.6-cm) diameter suction dredge operated for a total of 3 hours in the South Yuba River about 500 m downstream from the SYR-HC confluence (fig. 2). Two transects across the South Yuba River were established approximately 30 and 60 m downstream from the first dredging location, by using taglines (fig. 2, table 1). These transects were used as the locations for sampling of water quality and suspended sediment throughout the test. During the first 2 hours of the test, the riverbed was dredged at a location at the upstream end of a pool, just below a riffle zone. During the third hour of the test, the dredge was moved to a second location approximately 10 m downstream from the first location to increase the amount of suspended sediment at the sampling transects.

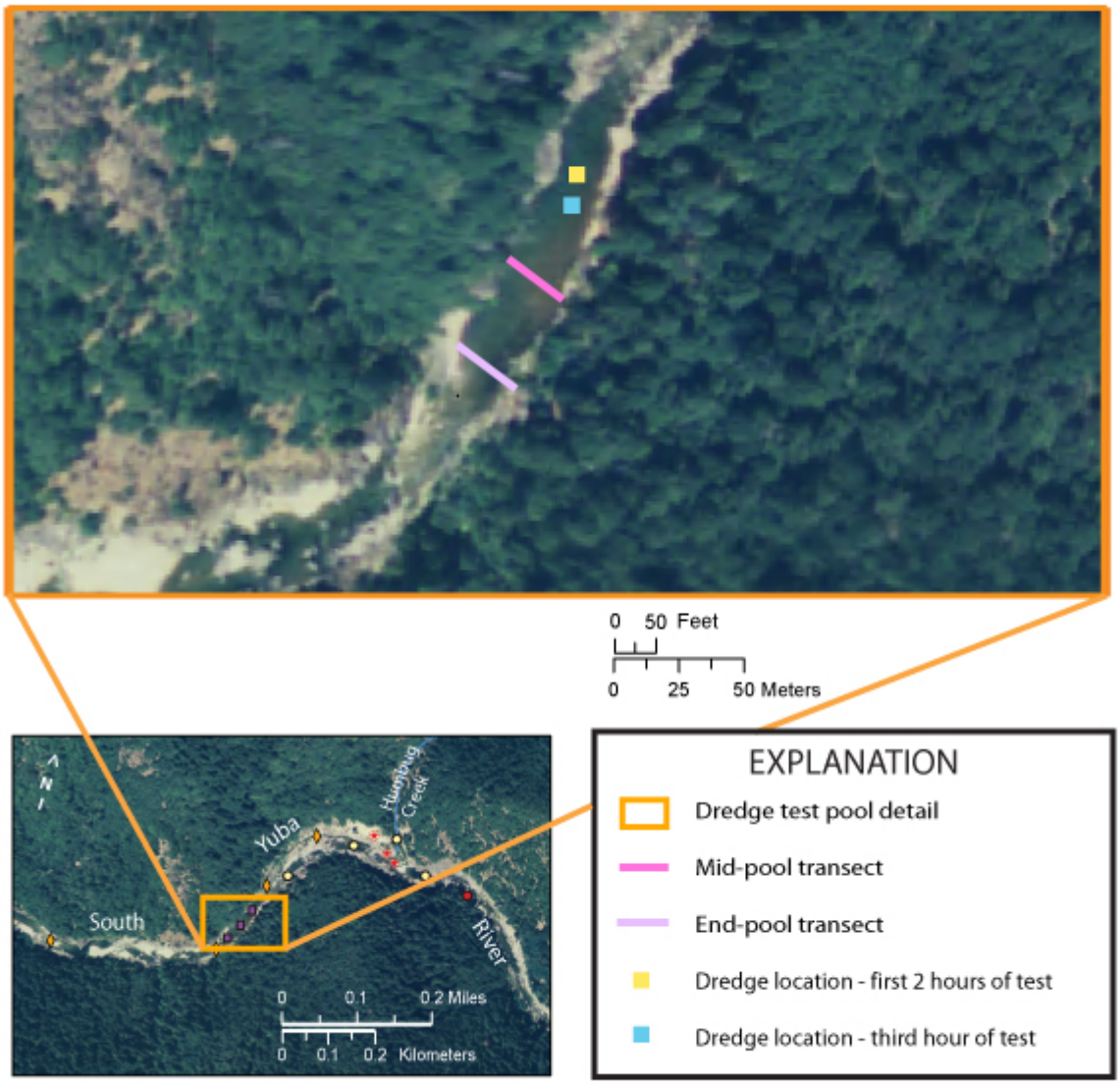


Figure 2. High resolution aerial photos showing (A) the location of the dredge test within the South Yuba River–Humbug Creek, California, confluence focused study area, and (B) locations of taglines and dredging site for the dredge test conducted on October 11, 2007.

Table 1. Location and brief description of sampling sites, South Yuba River and Humbug Creek, Nevada County, California.

[SYR, South Yuba River; HC, Humbug Creek; m, meter]

Location	Description	Site identifier	Latitude (degrees N)	Longitude (degrees W)	Type of sample	Study element
North Bloomfield Tunnel airshaft	Sediment deposits on edge of flooded airshaft next to Humbug Trail, "red shaft"	NB-RHA	39.356000	120.923000	Bed sediment	Source Assessment/ Provenance
Lake City Tunnel outlet	Mine tunnel outlet surface sediment	LC-MTO	39.346000	120.928000	Bed sediment	Source Assessment/ Provenance
North Bloomfield Tunnel outlet	Mine tunnel outlet surface sediment	NB-MTO	39.343366	120.927886	Bed sediment	Source Assessment/ Provenance
South Yuba River upstream of Humbug Creek	Integrated suspended sediment collector around 100 m upstream from the river bar	SYR-0	39.337878	120.929817	Integrated sediment collector	Source Assessment/ Provenance
South Yuba River upstream of Humbug Creek	River bed and bank samples around 100 to 300 m upstream from the river bar	SYR-0	39.337878	120.929817	Bed sediment	Source Assessment/ Provenance
South Yuba River – Humbug Creek confluence	Series of cracks in pools and on the edge of the river bar at the SYR-HC confluence	SYR-HC	39.338030	120.931467	Snipe	Detailed Sediment Characterization
South Yuba River upstream of Humbug Creek	Storm sampling access point upstream from the footbridge on the South Yuba River Trail	SYR-0a	39.338008	120.931400	Storm suspended sediment	Source Assessment/ Provenance
Humbug Creek at South Yuba River Trail footbridge	Site just below the South Yuba River Trail footbridge	HUM-1	39.338204	120.931733	Storm suspended sediment	Source Assessment/ Provenance
Humbug Creek at South Yuba River Trail footbridge	Integrated suspended sediment sampler upstream from footbridge	HUM-1	39.338272	120.931886	Integrated sediment collector	Source Assessment/ Provenance
Humbug Creek at South Yuba River Trail footbridge	Bed sediment upstream from footbridge in pools and under boulders	HUM-1	39.338272	120.931886	Bed sediment	Source Assessment/ Provenance

Table 1. Location and brief description of sampling sites, South Yuba River and Humbug Creek, Nevada County, California.

[SYR, South Yuba River; HC, Humbug Creek; m, meter]

Location	Description	Site identifier	Latitude (degrees N)	Longitude (degrees W)	Type of sample	Study element
Humbug Creek at South Yuba River Trail footbridge	Pools located around South Yuba River Trail footbridge	HUM-1	39.338500	120.932000	Biota	Biota Assessment
South Yuba River – Humbug Creek confluence	Pit 1 excavation and recirculation tank experiment on SYR-HC river bar	Pit 1	39.337946	120.931932	Bed sediment	Detailed Sediment Characterization
South Yuba River downstream of Humbug Creek, upstream of dredge site	Storm sampling access point	SYR-1b	39.337963	120.932137	Storm suspended sediment	Source Assessment/ Provenance
South Yuba River – Humbug Creek confluence	Riffles just downstream from confluence	SYR-1	39.338000	120.932167	Biota	Biota Assessment
South Yuba River – Humbug Creek confluence	Pit 2 excavation - four sediment layers collected	Pit 2	39.338026	120.932229	Bed sediment	Detailed Sediment Characterization
South Yuba River – Humbug Creek confluence	Hydraulic mining debris exposed cliff face below BLM picnic area	HMD-CF	39.338307	120.932645	Bed sediment	Detailed Sediment Characterization
South Yuba River side-cut diversion channel	Upsteam end of side-cut diversion	SYR-3	39.338000	120.934000	Biota	Biota Assessment
South Yuba River downstream of Humbug Creek, upstream of dredge site	Time-integrated suspended sediment sampler	SYR-1a	39.337411	120.934408	Integrated sediment collector	Source Assessment/ Provenance
South Yuba River downstream of Humbug Creek, upstream of dredge site	Bed and river bank sediment composite	SYR-1a	39.337411	120.934408	Bed sediment	Source Assessment/ Provenance
South Yuba River downstream of Humbug Creek, upstream dredge site	Riffle upstream from dredge test site	SYR-1a	39.337111	120.934461	Biota	Biota Assessment

Table 1. Location and brief description of sampling sites, South Yuba River and Humbug Creek, Nevada County, California.

[SYR, South Yuba River; HC, Humbug Creek; m, meter]

Location	Description	Site identifier	Latitude (degrees N)	Longitude (degrees W)	Type of sample	Study element
South Yuba River side-cut diversion channel	Downsteam end of side-cut diversion	SYR-2	39.337000	120.935000	Biota	Biota Assessment
South Yuba River Dredge Test Site	Location of suction dredging	SYR-DT	39.336424	120.935113	Suspended sediment	Dredge Test
South Yuba River Dredge Test Site	Upstream tagline (mid-pool) for dredge test	SYR-MP	39.336096	120.935313	Suspended sediment	Dredge Test
South Yuba River Dredge Test Site	Downstream tagline (end-pool) for dredge test	SYR-EP	39.335864	120.935505	Suspended sediment	Dredge Test
South Yuba River Dredge Test Site	Riffles just downstream from dredge test pool	SYR-4	39.335777	120.935617	Biota	Biota Assessment
South Yuba River 500 m downstream of dredge test site	First of three pools in series 500 m downstream from the dredge test site	SYR-5	39.335000	120.939583	Biota	Biota Assessment
South Yuba River downstream of North Canyon	Pool and riffle system off spur trail to North Canyon access to South Yuba River	SYR-6	39.341872	120.949894	Biota	Biota Assessment
South Yuba River at Edwards Crossing	About 100 m upstream from Edwards Crossing	SYR-7	39.330425	120.983141	Storm suspended sediment	Source Assessment/ Provenance
South Yuba River at Edwards Crossing	About 100 m upstream from Edwards Crossing	SYR-7	39.330393	120.983290	Integrated sediment collector	Source Assessment/ Provenance
South Yuba River at Edwards Crossing	About 100 m upstream from Edwards Crossing	SYR-7	39.329953	120.985108	Biota	Biota Assessment
South Yuba River downstream of Humbug Creek, upstream of dredge site	Series of cracks in pools downstream from the river bar at the SYR-HC confluence	SYR-1b	39.337983	120.932900	Snipe	Detailed Sediment Characterization

Table 1. Location and brief description of sampling sites, South Yuba River and Humbug Creek, Nevada County, California.

[SYR, South Yuba River; HC, Humbug Creek; m, meter]

Location	Description	Site identifier	Latitude (degrees N)	Longitude (degrees W)	Type of sample	Study element
South Yuba River upstream of Humbug Creek	Series of cracks in the large pool upstream from the river bar at the SYR-HC confluence	SYR-0a	39.337954	120.930500	Snipe	Detailed Sediment Characterization
Bear River at Highway 20	Reference control site located above historic hydraulic mining activitiy in the nearby Bear River watershed	BR-20	39.306390	120.679170	Biota	Biota Assessment

Water Sampling

Along each of the transects across the South Yuba River, a tagline was labeled with five stations for cross-sectionally integrated sampling of water quality during the dredge test using a clean 3-L Teflon® bottle equipped with a 3/8-in. (0.85-cm) Teflon® nozzle (U.S. Geological Survey, variously dated). The samples were collected by a person wading downstream from the tagline who raised and lowered the bottle through the water column at each station using a sampling pole. All sampling was performed using trace-metal clean techniques (U.S. Geological Survey, variously dated).

Water samples were collected at four time points: 1) before the dredge was started, 2) approximately halfway through the dredge operation (t=2 hrs, where t equals elapsed time after the start of dredging), 3) at the end of the operation (t=4 hrs), and 4) the following morning (t=24 hrs). Multiple samples were collected from each transect and composited in a 20-L Teflon®-lined churn for homogenization (Alpers and others, 2000). Aliquots of approximately 1 to 2 L were taken from the churn by using graduated cylinders, and were filtered in the field by using pre-combusted glass fiber filters (Whatman GF/F, 0.7 µm pore size) in Teflon® filter towers connected to glass vacuum flasks and a hand-operated vacuum pump. All glassware was acid-cleaned and double bagged in the laboratory prior to transport and use. The openings of the filter tower were covered with plastic bags during filtration to minimize particulate contamination from the atmosphere during the filtration procedure. Water passing through the filters was collected in the flasks and transferred to acid-cleaned Teflon® bottles, preserved with low-Hg hydrochloric acid (0.5% by volume final concentration), and placed on wet ice for storage prior to analysis of total mercury (THg) and MeHg. The filters were frozen in the field by using dry ice, and later were used for analysis of THg, $Hg(II)_R$, MeHg, and total suspended sediment (TSS). All samples were stored in coolers in the field, and were transported to the USGS mercury laboratory in Menlo Park, California, at the end of the day following the dredge test.

The concentrations of THg, $Hg(II)_R$, and MeHg analyzed on filters are expressed in volumetric units (for example, nanograms per liter) that are based on the mass of Hg recovered and the volume of water that passed through the filter. These concentrations are described as particulate THg (pTHg), particulate reactive mercury ($pHg(II)_R$), and particulate MeHg (pMeHg), respectively. The concentrations THg and MeHg in the filtrate are described as fTHg and fMeHg, respectively. Whole-water concentrations of THg or MeHg, equivalent to unfiltered samples, may be derived by summing the filtered and particulate concentrations for a given water sample.

In addition to the conventional environmental water sampling, measurements of suspended-sediment concentration and particle-size distribution were collected during the dredge test. A laser-diffraction particle-size analyzer (LISST-100X, Sequoia Scientific, Inc.) was deployed just upstream from each tagline during the dredge test. The LISST-100X instrument measured volumetric concentrations for 32 logarithmically spaced particle-size bins between 0.00125 and 0.250 mm at 5-minute intervals. In addition, a multisonde (model 6920, YSI Inc., Youngstown, Ohio) equipped with a turbidity probe was deployed upstream from the dredge site to verify that no major contributions of suspended sediment from upstream sources occurred during the dredge operation. A second multisonde was deployed throughout the dredge test approximately 6.8 km downstream at Edward's Crossing to observe any increases in turbidity downstream.

Bed-Sediment Sampling

Sediment traps (acid-washed plastic containers, 30 x 20 x 5 cm) were deployed at the centroids of each tagline to collect sediment deposited during the dredge test. The traps were deployed by hand and were weighed down using local stones to mimic the natural depositional conditions of the streambed. Following the final sampling of water quality along the taglines the day after the dredge test, the containers were recovered by removing the large stones holding the containers in place and snapping the lids in place with minimal disturbance prior to removal. Once the lids were securely in place, the traps were removed from the riverbed and transported back to the USGS laboratory in Sacramento, Calif., to quantify sediment deposition.

Dredged Materials

Samples of dredge material were collected from the suction dredge during a 3-hour test of active dredging operations in October 2007 to characterize Hg concentrations and speciation throughout the dredging activity (fig. 3). Because suction dredging requires numerous breaks for the removal of large cobbles, refueling, and safety precautions, it required more than 3 hours to obtain the equivalent 3 hours of active dredging. Materials collected between the suction-dredge intake hose and the sluice box are considered "heads" and materials processed through the sluice box and collected at the outlet of the sluice box are considered "tails." These samples were meant to compare the materials before and after the sluice box. Both heads and tails were sampled at 5-minute intervals over the 3-hour period of active dredging; composite samples were prepared representing each hour of dredging. Each 5-minute sample was collected by filling a 1-L wide-mouth high-density polyethylene (HDPE) bottle with sediment slurry material; the material was then transferred to a 5-gal (19-L) settling bucket. The heads and tails materials were collected with separate buckets and 1-L collection bottles. Samples were sieved in the field by using a 1.0 mm (#18 mesh) screen, and the finer material was retained. Because the dredge location was changed between hours 2 and 3, the material remaining in the sluice box, considered the "concentrate," was collected after the first 2 hours of the test and again after the final hour of the test. The concentrate was placed in a separate 19-L bucket for later processing.

Each bucket was allowed to settle for approximately 1 hour prior to removing the majority of overlying water, initially with the 1-L HDPE bottle used for sampling or a siphon hose, and finally by syringe. After decanting, the settled material was homogenized and subsampled for particle-size distribution analysis. Sediment samples were wet sieved in the field into multiple grain-size fractions—F1 = sand, 0.063 to 1.0 mm; F2 = fines, <0.063 mm, or silt plus clay; and F3 = <1.0 mm, or sand plus fines—and frozen for subsequent Hg speciation analysis. Additional sample splits were collected for particle-size distribution analysis (to determine, for example, percent F1 and percent F2). After sieving and preserving the F1 and F2 fractions for analysis of Hg speciation (THg, MeHg, and $Hg(II)_R$), the remaining material from each bucket was subsampled (0.5 to 1.0 kg) and panned in the field to isolate high-density materials, including Au, Hg(0), and Hg-Au amalgam. The panned concentrates were transferred in glass vials containing river water to the USGS scanning electron microscope laboratory in Menlo Park, Calif.

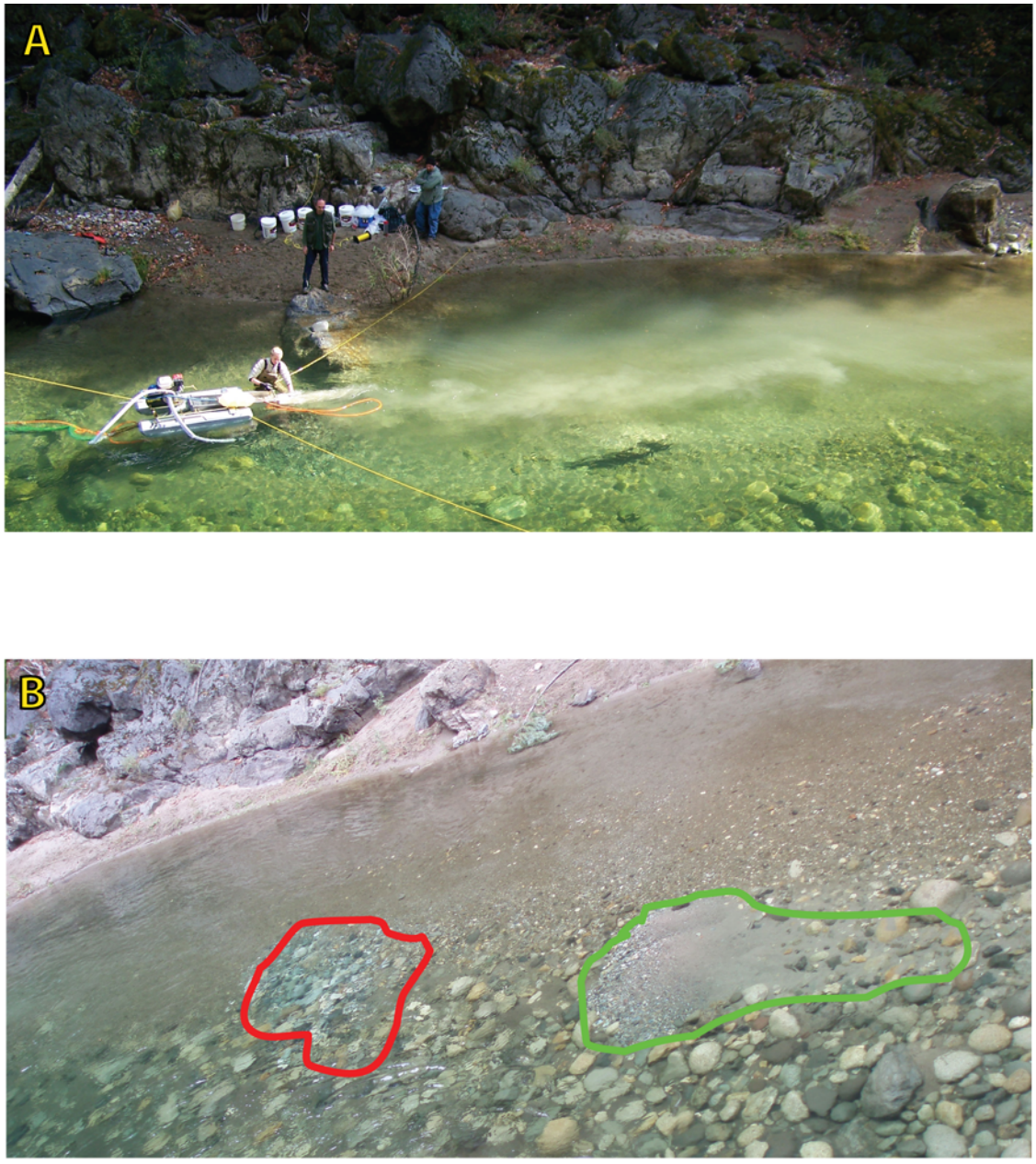


Figure 3. Photographs of dredge test in South Yuba River, California, on October 11, 2007. (A) Dredge in operation at first location (hours 0–2); plume of suspended sediment downstream of dredge is visible, (B) Streambed of second dredge location after 1 hour of dredging (hours 2−3), with the excavated 'dredged' streambed pit (outlined in red) and the pile of accumulated sediment 'tails' discharged from the sluice box (outlined in green) both visible.

Detailed Site Characterization

The concentrations and distribution of Hg in the vicinity of the SYR-HC confluence area were characterized in detail to verify anecdotal reports that this location is particularly contaminated with Hg (Hg "hotspot"). The site characterization included four different study elements: 1) sediment mapping with ground-penetrating radar (GPR); 2) sediment excavation and detailed characterization of particle-size distribution, Hg concentration and speciation, and associated geochemistry in the confluence area; 3) a recirculation-tank experiment to determine potential for use of this

method to achieve on-site suspended-particle settling prior to the release of water used in dredging; and 4) a "sniping" assessment of heavy minerals to qualitatively assess the extent of Hg contamination in the SYR-HC confluence area by using a common approach to Au-seeking that employs focused dig and pan methods in cracks and other features where heavy minerals such as Au and Hg are most likely to collect. This multi-tiered approach to the site assessment provides a diverse combination of qualitative and quantitative methods to assess the level of Hg contamination in the sediment at the SYR-HC study site. Sampling locations for the various aspects of the sediment assessment are detailed in table 1 and shown in figure 4.

Ground-Penetrating Radar

Prior to the sediment excavation, GPR was used to survey the exposed cobble and gravel bar located in the South Yuba River main channel at the SYR-HC confluence (fig. 5) by using a PulseEKKO 100 system (Sensors and Software Inc.) to better target potential sampling locations (especially those containing a defined subsurface "slickens" layer). The objectives of the GPR survey were two-fold: (1) to determine if GPR is a viable method for identifying the historical "slickens" layers and determining the depth to bedrock beneath a cobble surface layer; and (2) to guide the selection of candidate sites for the manual sediment excavation (should the method prove effective).

GPR surveying is analogous to seismic reflection profiling, in that pulses of energy are emitted into the ground to image the subsurface through the analysis of subsequent arrivals of energy at receivers on the ground surface. The GPR energy source consists of high-frequency radio waves, typically 10-1,000 megahertz (MHz), for which the propagation, reflection, and attenuation of energy depends on the dielectric permittivity of the subsurface. Contrasts in dielectric permittivity arising from variations in saturation level, sediment type, and bedrock geology have made GPR an effective method for mapping soil and rock stratigraphy in a variety of settings since the 1970s (Davis and Annan, 1989). The effectiveness of GPR surveying through a cobble surface layer is uncertain, however, owing to poor ground coupling for the transmission pulse and a high degree of scattering and attenuation that is likely to occur from the cobble surface layer. In response to this uncertainty, preliminary tests were first conducted at the California State University, Sacramento campus, to evaluate the GPR response over a cobble surface layer. Results suggest that reflection profiling with 200-MHz center frequency antennas would not provide adequate penetration, but 100-MHz antennas might be effective at resolving target reflectors to several meters depth below the cobble layer.

On the basis of these preliminary findings, the South Yuba River Bar was surveyed by using bistatic GPR with 100-MHz antennas with a separation of 1 m between the transmission and receiver antennas and a station spacing of 20 cm. The antennas were placed atop a movable wooden board track that was laid over the cobble surface and leveled prior to data collection at each station (fig. 6). A total of 12 north-south trending transect lines were surveyed with a separation interval of 5 m between each line to span the entire exposed surface of the cobble bar and provide a three-dimensional image of the bedrock surface and the target "slickens" layer. The lengths of each survey line varied from about 7 to 18 m according to the geometry of the bar (fig. 5).

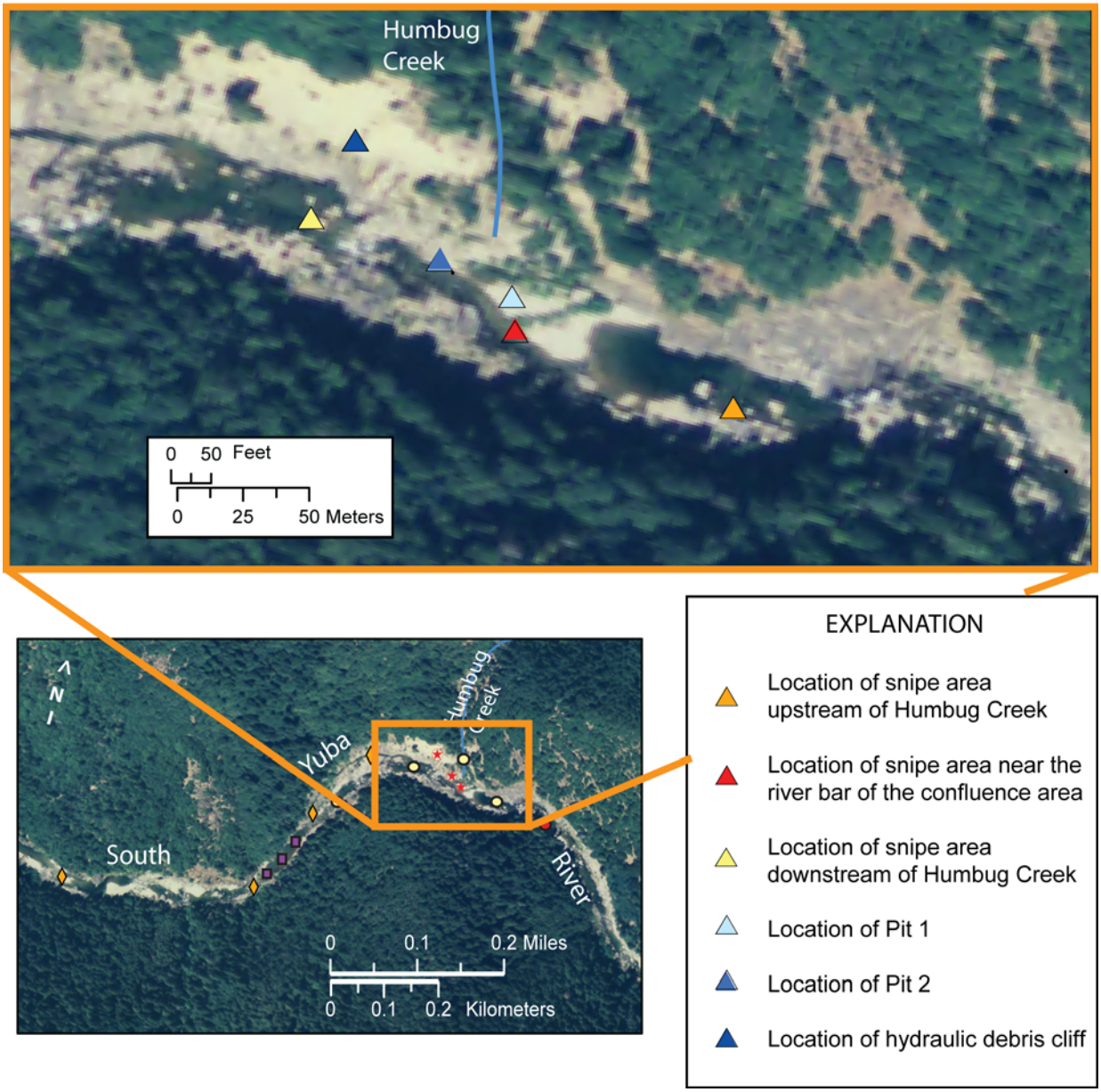


Figure 4. High resolution aerial photo showing the locations where the various elements of the September 2008 detailed site characterization were performed, South Yuba River and Humbug Creek, California. (Site descriptions and types of samples collected are given in table 1.)

Data processing included high-pass filtering of each trace to suppress a slowly decaying, low-frequency component observed in the data that is commonly induced by the transmit signal in GPR systems (the so-called “wow” effect). A total of 64 traces were collected at each station location and averaged (“stacked”) to increase the signal-to-noise ratio to reduce the effect of random noise on the signal. A variety of signal gains were also applied during data processing to enhance the detection of coherent reflectors.

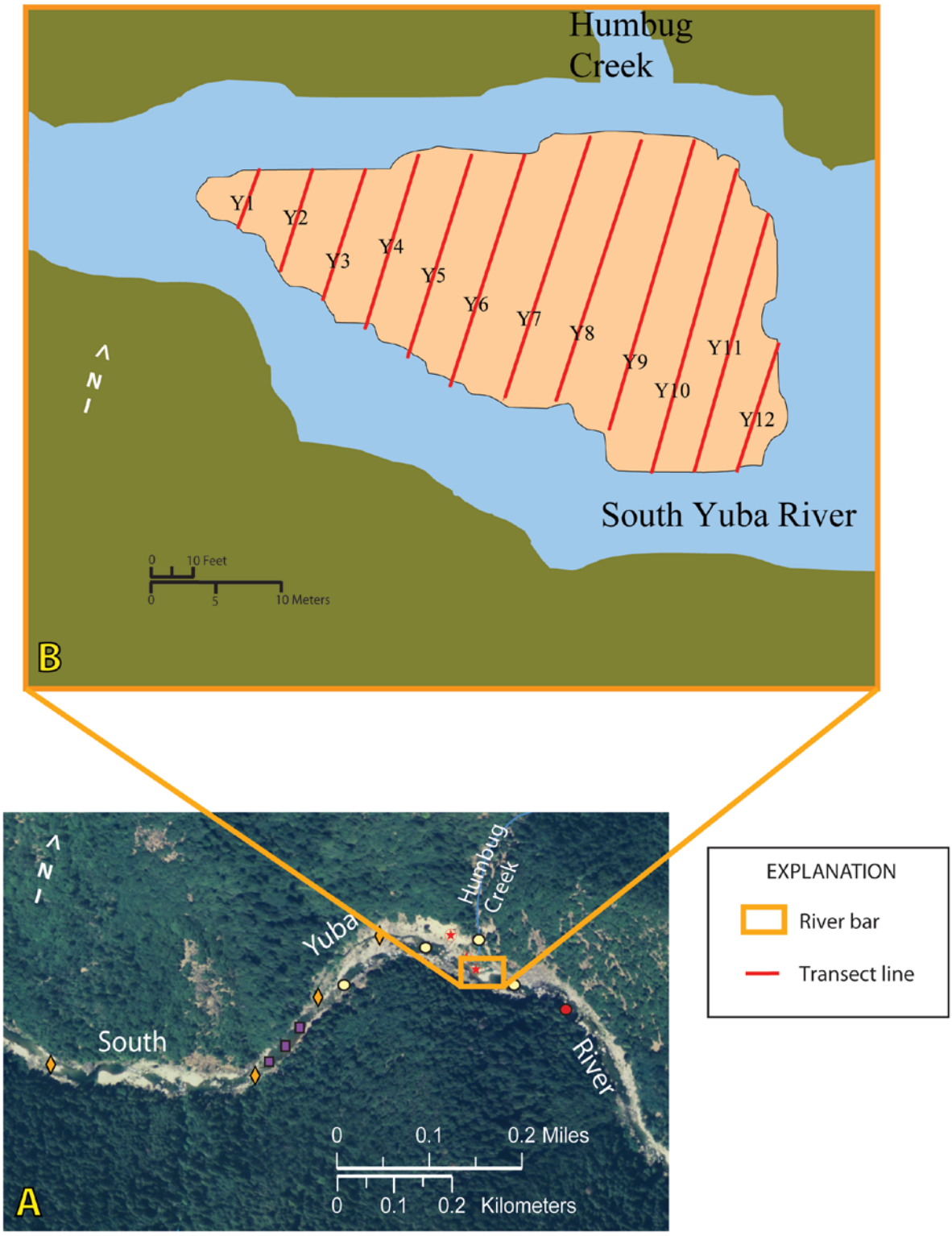


Figure 5. (A) High resolution aerial photo showing location of the ground-penetrating radar (GPR) survey within the South Yuba River and Humbug Creek, California, focused study area, and (B) diagram showing the GPR-survey transects on the river bar of the South Yuba River–Humbug Creek confluence area in July 2008. Grid transects Y1 through Y12 are shown in red.

Figure 6. Photograph showing moveable wooden board track used during ground-penetrating radar data collection atop the cobble surface layer, South Yuba River, California.

Sediment Excavation

Sediment was excavated at three different locations within the SYR-HC confluence area (fig. 4). Large quantities of sediment were collected from each of the locations and processed on-site. The details of sample collection differ between locations, depending on the unique characteristics of each location.

Sediment Pit 1 was excavated by hand on September 16, 2008. Detail of the location and dimensions of Pit 1 are provided on figure 7. The excavated sediment was then processed according to the flow chart shown in figure 8. All excavated materials were weighed in the field by using a high-capacity scale with a resolution of 0.5 kg. Large cobbles were first removed by hand and weighed individually; smaller cobbles and large gravels were placed into 19-L buckets and weighed. When the cobble layer armoring the surface of the gravel bar was effectively cleared away, material consisting of gravel and finer-grained sediment was shoveled into 19-L buckets. These finer-grained samples were dry sieved at 6 mm (¼-in. or #4 mesh). The material greater than 6.3 mm was composited into buckets and weighed. A total of 3,936 kg of material greater than 6.3 mm was excavated, including hand-weighed cobbles and buckets of gravel. The total dry weight of material less than (<) 6.3 mm from Pit 1 was 497 kg, or 11.2% of the bulk material (table 2), and approximately half of this fraction (266 kg, or 54%) was further processed by wet sieving.

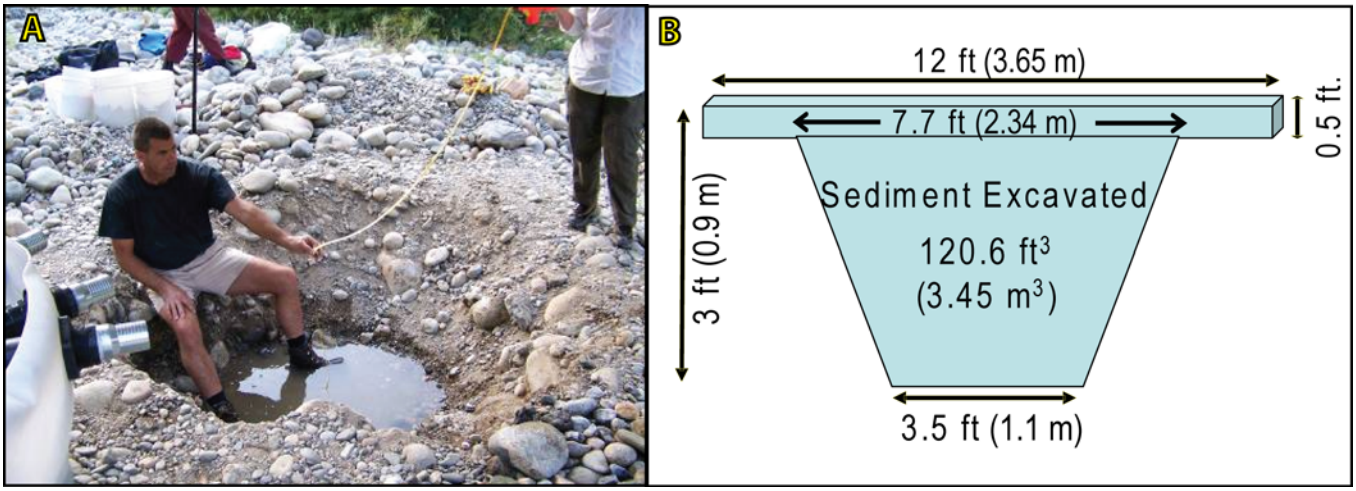


Figure 7. Details of Pit 1 excavation, South Yuba River and Humbug Creek, California. (A) Photograph showing completed excavation of Pit 1 prior to recirculation-tank experiment, and (B) Diagram showing the final dimensions of Pit 1 prior to recirculation-tank experiment.

Table 2. Particle-size distribution and mass of excavated materials, South Yuba River and Humbug Creek, Nevada County, California.

[Note: Mass less than 6.3 mm calculated from particle size distribution in processed materials and multiplied by total mass weighed. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; >. greater than; <, less than; kg, kilogram; mm, millimeter; %, percent; nd, not determined]

Sample identifier	>6.3 mm		1.0 - 6.3 mm		0.25 - 1.0 mm		0.063 - 0.25 mm		<0.063 mm		Total	
	kg	% of total	kg	% of total	kg	% of total	kg	% of total	kg	% of total	kg	% of total
Pit 1 (0 to 3 feet)	3,936	88.8	411.1	9.3	82.2	1.9	2.4	0.05	1.3	0.03	4,433	100.0
Pit 2 OBL	977	77.0	207.2	16.3	65.3	5.1	6.5	0.51	13.1	1.0	1,269	100.0
Pit 2 FCZ	150	63.6	70.2	29.7	11.9	5.0	1.0	0.42	3.0	1.3	236	100.0
Pit 2 CSL	503	66.0	140.7	18.5	85.8	11.3	17.0	2.2	15.5	2.0	762	100.0
Pit 2 BRC	52	48.6	33.0	30.8	16.0	15.0	3.0	2.8	3.0	2.8	107	100.0
HMD-CF	nd	nd	8.0	61.5	3.7	28.5	0.9	6.9	0.4	3.1	13	100.0

The material <6.3 mm was wet sieved (using river water) through a series of three screen sizes, 1.0 mm (#18 mesh), 0.25 mm (#120 mesh), and 0.063 mm (#230 mesh), by using rectangular, plastic storage containers to retain the rinse water. All containers used for the wet sieving were acid-washed with dilute hydrochloric acid prior to use. All rinse water was retained in the <0.063 mm size fraction so that the finest particles, including colloids, would be included. The volume of water used for sieving was recycled in the sieving process to minimize the volume centrifuged.

Sample splits (approximately 0.5 kg) from all excavation sites and all size fractions, except the finest fraction (<0.063 mm), were transferred into acid-cleaned plastic containers and maintained at ambient (river water) temperature until transport back to the USGS mercury laboratory in Menlo Park, Calif. Subsequently, sediment from each plastic jar was homogenized under an oxygen-free environment (in a nitrogen-flushed glove bag) and subsamples (about 15 cm^3) for Hg speciation analysis were collected and stored frozen for further analysis. The remaining sediment was stored refrigerated for analysis of organic content, bulk density, and water content (percent dry weight).

The <0.063 mm fraction (“fines slurry”) was collected in 8-L stainless-steel soda kegs for transport to the USGS mercury laboratory in Menlo Park, Calif., where the fines were centrifuged (1,700 revolutions per minute for 25 minutes) in 250 milliliter (mL) aliquots. The resulting solids were composited by site and depth interval into acid-cleaned glass jars, which were subsampled and preserved in a similar manner as the other size fractions. The recovered solids had particle diameters greater than 0.0004 mm and up to 0.063 mm based on Stokes’ Law and an assumed grain density of 2.7 grams per cubic centimeter (g/cm^3). If any particles of Hg(0) were present (density 13.5 g/cm^3), the particles retained would be greater than 0.00015 mm in diameter.

Sediment in the coarse-sand (0.25 to 1.0 mm) and fine-sand (0.063 to 0.25 mm) size fractions were further processed in the field by using a standard Au pan to concentrate minerals of high grain density, including Hg, Au, and Hg-Au amalgam. The panned concentrates were transferred to glass vials filled with river water and later were weighed and examined using a scanning electron microscope (SEM) at the USGS SEM laboratory in Menlo Park, Calif.

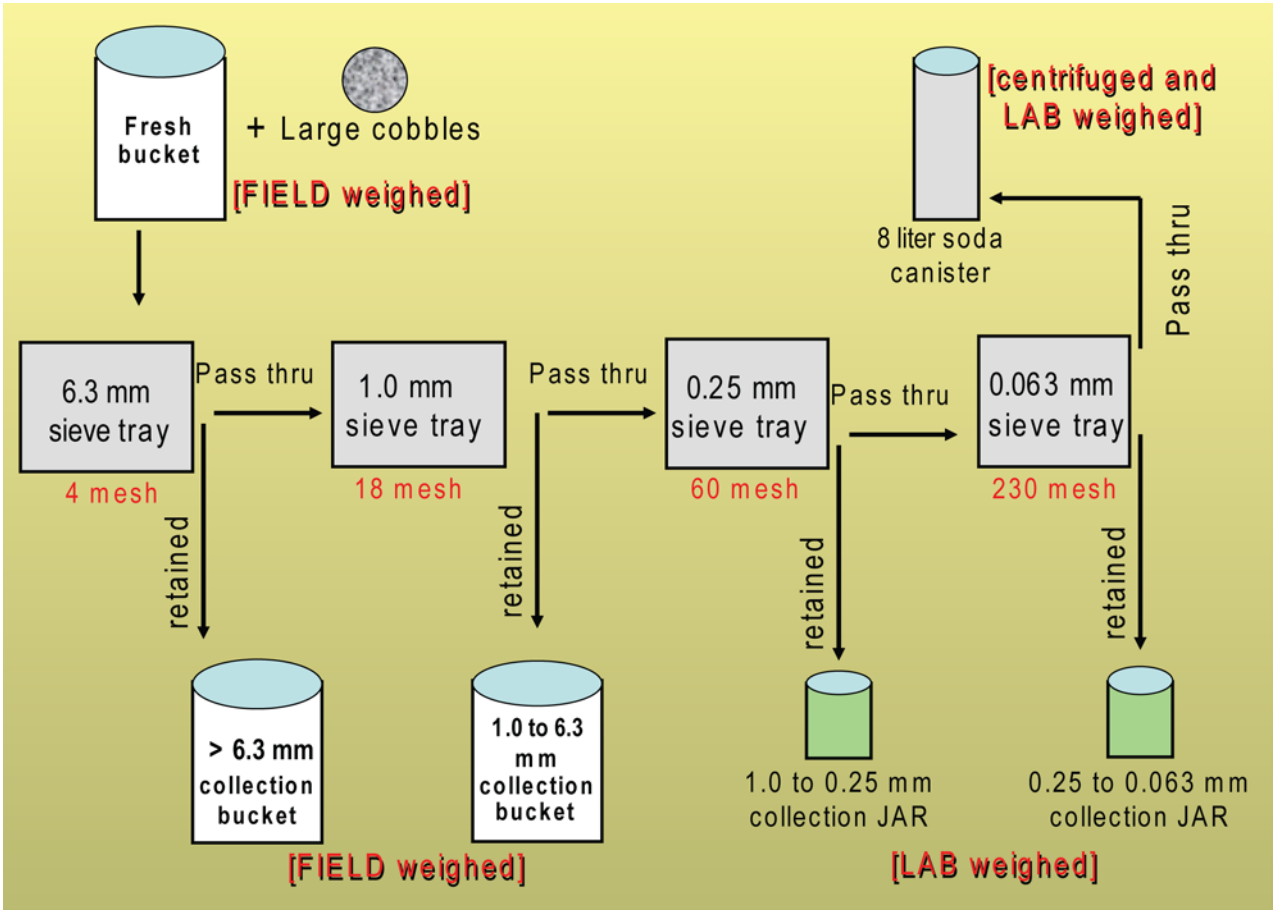


Figure 8. Flowchart showing processing methods for excavated sediment samples.

Pit 2 was excavated on September 17, 2008, in a manner similar to Pit 1 except that the pit material was separated into four different samples according to different strata identified in the field (fig. 9). The strata were based on field observations of differences in color, dominant grain size, and degree of consolidation. The four strata differentiated in Pit 2 were the Overburden layer (OBL), First Contact Zone (FCZ), Compact Sediment Layer (CSL), and Bedrock Contact (BRC).

The OBL was cobble-rich material very similar to the material excavated in Pit 1. The FCZ material was distinguished from the OBL by smaller grain size and a color change from light brown-gray to orange-brown. The CSL was highly compacted, not quite as hard as a ferricrete but requiring more effort to disaggregate than the other layers. The BRC was not a true sediment layer but consisted of materials remaining after the CSL material had been removed, representing mostly sediment recovered from fractures in the bedrock. The BRC materials were separated from the CSL because bedrock surfaces are known to concentrate Au and Hg, making the contact materials potentially very different from the overlying sediment. Because of this propensity to be enriched in Au, Hg, and amalgam, the CSL and BRC are the zones that are frequently targeted by suction dredgers. Each of the strata from Pit 2 was processed in separate containers, using the same methods that were used for the sediment from Pit 1.

Figure 9. Details of Pit 2 excavation, South Yuba River and Humbug Creek, California. (A) Photograph of Pit 2 area prior to excavation, (B) photograph of Pit 2 after excavation, and (C) schematic cross section showing layers differentiated as separate sediment samples.

HMD was sampled from a cliff face below the BLM picnic area by excavating four vertical channels spaced horizontally at approximately 7.5-m intervals over a 30-m horizontal section of the cliff (fig. 10). Each vertical channel was approximately 0.6 to 1 m long, 5 cm deep, and 15 cm wide. Taken together, the four vertical channels represent 3 vertical meters of the stratigraphic section. This represented about one-third of the vertical extent of the exposed cliff face. The upper 6 m of the cliff exposure were not accessible for sampling because of safety considerations. Samples were collected by using a clean plastic trowel and a 19-L bucket. The material sampled consisted of poorly consolidated, poorly sorted sediment.

Large cobbles and all gravels greater than 1/4 in. (6.3 mm) in diameter were removed and weighed for mass calculations but were not further processed until arrival at the USGS mercury laboratory in Menlo Park, Calif.

Figure 10. Photograph showing sediment sampling of the hydraulic mining debris along the cliff face below the Bureau of Land Management picnic area, South Yuba River, California.

Recirculation-Tank Experiment

Following the excavation of Pit 1, a 3-in.-diameter (7.5-cm) suction hose was attached to a HDPE recirculation tank (fig. 11). The tank was filled with river water pumped from a location near the excavation site. The hose was set up with a venturi-style suction-nozzle head supplied with recirculated water from the tank. By recycling water in a closed loop, so that there was no net discharge of water from the tank to the river, the venturi successfully excavated sediment from the bottom of Pit 1. The venturi was operated for about 30 minutes, resulting in approximately 1 yd^3 (about 0.75 m^3) of gravel-rich sediment transferred to the tank (fig. 11). Normally, a sluice box would be attached to the dredge for recovery of valuable heavy minerals, but no sluice box was attached during this test because the goal was to analyze water quality and suspended particulate settling within the tank rather than to attempt recovery of heavy minerals.

Figure 11. Photographs of recirculation-tank experiment. (A) Filling with water from South Yuba River and taking "tank blank", (B) taking "first flush" sample, (C) using venturi pump to extract sediment from bottom of Pit 1, and (D) tank after approximately 40 hours of settling.

At the start of the tank experiment, a water sample was collected from the South Yuba River for a baseline measurement of TSS and THg concentration of the source water. In addition, a baseline water sample was collected from the tank, after it had been filled with river water and prior to dredging, to determine any contribution to TSS or THg from the tank itself from previous use or dust that may have accumulated during storage or transportation to the site. Water samples were collected during the initial pulse of sediment at the beginning of the venturi pump operation (the "first flush"), as well as 16 hrs and 40 hrs after the venturi dredge activity had stopped. The tank was covered with plastic sheeting to reduce any potential contamination of the tank water from atmospheric sources and to eliminate any wind-driven resuspension of particles during the settling period.

Sniping Assessment

The presence or absence of localized Hg hotspots in bed sediment within a river reach gives an indication of the general level of Hg contamination for the reach. Sniping is a method used by recreational Au miners to search for Au and other minerals of high grain density in bedrock fractures and other natural hydraulic traps on the river bottom.

Ten sites were chosen along the South Yuba River, within, upstream, and downstream from the SYR-HC confluence, to assess the presence of Au, Hg(0), and Hg-Au amalgam in riverbed sediment (fig. 4, tables 1 and 3). The sniping was performed by experienced miners from Pro-Mack Mining, under contract with the BLM through TetraTech, Inc. At each site, sediment was excavated using hand tools, and heavy minerals were concentrated by standard Au panning techniques. After approximately 10 to 30 minutes working at each site, the volume of black sands, clean Au, Hg-Au amalgam, and liquid Hg(0) recovered by panning were semi-quantitatively assessed using a four-level scale ranging from “0” indicating no visible Hg or Au in panned sediment and “3” indicating “abundant Hg or Au.” The ratio of Hg to Au at each site was then assessed using the observed abundance of Au, Hg, and Hg-Au amalgam.

Table 3. Description of sniping locations, South Yuba River, California, near Humbug Creek confluence.

[SYR, South Yuba River; HC, Humbug Creek; ", inches; ', feet]

Snipe number	Site identifier	Snipe location	Description
1	SYR-HC	Near river bar at South Yuba River – Humbug Creek confluence	Crack on gravel bar side of river, parallel to flow, facing downstream, 4" x 27"
2	SYR-HC	Near river bar at South Yuba River – Humbug Creek confluence	Crack not on gravel bar side of river, 3-4' of bank 0.5' - 2' water depth, 30˚ to flow, 6" to 12" wide
3	SYR-HC	Near river bar at South Yuba River – Humbug Creek confluence	Crack below gravel bar, perpendicular to flow, outlet facing upstream, 4"x18"
4	SYR-HC	Near river bar at South Yuba River – Humbug Creek confluence	River left, perpendicular to flow, 2' deep, crack, 3"x18"
5	SYR-1b	South Yuba River downstream from Humbug Creek	River center, 8"x2" crack perpendicular to flow, 6" deep, appeared undisturbed compacted sediments
6	SYR-1b	South Yuba River downstream from Humbug Creek	Near #5, crack of pyrite vein, 4"x1.5", 1.5" deep, compacted gravel
7	SYR-0a	South Yuba River upstream from Humbug Creek	Bowl swept bedrock, 18" water below small waterfall, 12" deep sediment
8	SYR-0a	South Yuba River upstream from Humbug Creek	4' long bedrock crack parallel to flow, tapered 12" wide at top to 3" at bottom
9	SYR-1b	South Yuba River downstream from Humbug Creek	Low spot in river center, parallel to flow, 5'x2"x1'
10	SYR-1b	South Yuba River downstream from Humbug Creek	River center, 20' downstream of #5, 15'x1.5" crack perpendicular to flow, 1' deep

Sediment Source Assessment

The source assessment has three primary goals: 1) to determine a wider distribution of Hg contamination in the surficial deposits of the SYR-HC confluence area, 2) to determine whether the amount of current transport of Hg suggests a continuing deposition of Hg at the SYR-HC confluence that precludes a clean-up effort, and 3) to characterize representative current and historical sources of sediment that may be related to the Hg contamination of the SYR-HC confluence area.

Sediment Collection

Bed and suspended sediment were collected at several locations in the SYR-HC confluence area by using various methods during 2008 and 2009, to characterize sediment transport and sources (fig. 12). During October 2008 and January 2009, bed-sediment samples were collected from the streambed surface (0 to 5 cm depth), the banks of Humbug Creek, and the South Yuba River upstream from the confluence (fig. 12). Surface (0 to 5 cm depth) sediment samples were also collected from the outlets of two sluice tunnels that drain into Humbug Creek (the North Bloomfield Tunnel and the Lake City Tunnel), as well as from a discharge area associated with an air shaft connected to the North Bloomfield Tunnel, located adjacent to the Humbug Trail (fig. 1B, table 1). Suspended-sediment samples from Humbug Creek and the South Yuba River were collected by using two methods. The first method used time-integrating samplers, described by Phillips and others (2000), deployed for approximately 10 weeks at three locations—within Humbug Creek near the mouth, and on the South Yuba River immediately upstream and downstream from the SYR-HC confluence. The time-integrating samplers consisted of 1-m-long aluminum tubes approximately 10 cm in diameter with 4-mm inlet and exhaust nozzles located axially on each end. Water continuously passes through the sampler from inlet nozzle to exhaust nozzle, trapping sediment as it settles along the length of the sampler, mimicking the natural settling environment. These units were secured below the water surface approximately 5 cm above the river bottom by using rebar stakes. Prior to deployment, the inner surface of the tubes was coated with Teflon®, triple-rinsed with dilute hydrochloric acid, and then triple-rinsed with deionized water to minimize Hg contamination of the samples. The time-integrating samplers were deployed on January 13, 2009, and retrieved on March 27, 2009 (fig. 13).

Composite grab samples of raw water were collected near peak streamflow during a storm event on May 5, 2009. The collection of cross-sectional and depth-integrated samples was not possible because of safety and infrastructural limitations at the study site. A total of 6 L of raw water was collected using a 3-L Teflon® bottle attached to a telescoping rod at the same locations that the time-integrated samplers had been deployed.

The daily average streamflow for the date of the storm sampling event was 217 m^3/s at the South Yuba River at Jones Bar, approximately 15 km downstream from the SYR-HC confluence (USGS streamgage 11417500, fig. 1B). The peak streamflow (280 m^3/s) was similar to the daily average for that day, and was annual peak discharge for the water year. This annual peak discharge was exceeded only 17 of the previous 59 years. Thus, the storm samples represent sediment and Hg mobilization conditions that occur fewer than once every 3 years, on average, in the South Yuba River.

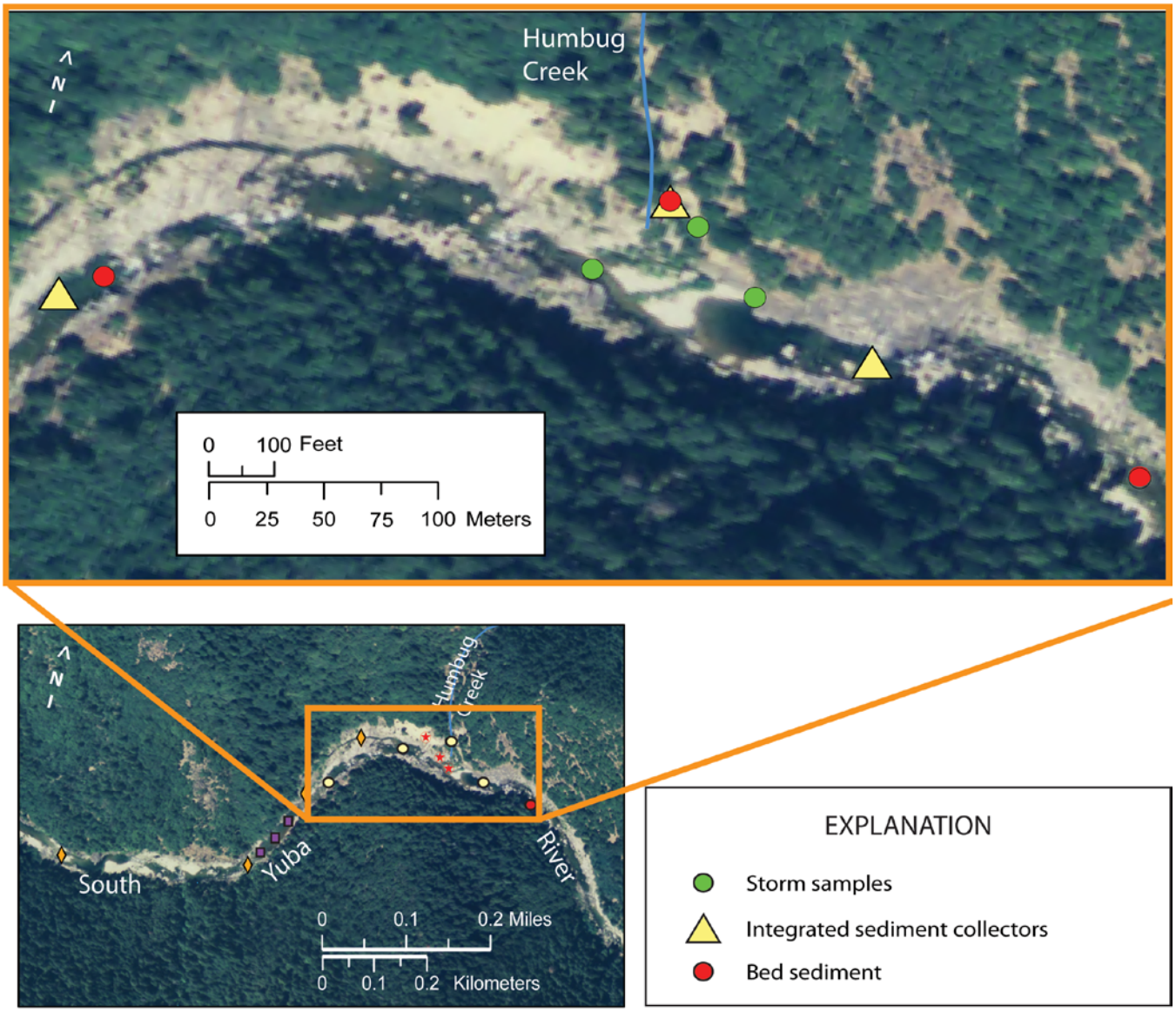


Figure 12. High resolution aerial photo showing the location of the study elements associated with the South Yuba River–Humbug Creek, California, Source assessment performed between October 2008 and May 2009.

During the period that the time-integrating samplers were deployed, small to moderate flood flows occurred on the South Yuba River (fig. 13). Despite the relatively moderate flows during the deployment, the performance of the samplers was mixed. The sampler in the South Yuba River downstream from the SYR-HC confluence worked as planned; however, the others did not. The sampler in Humbug Creek became dislodged but remained in the creek near the original deployment location. The sampler in the South Yuba River upstream from the SYR-HC confluence remained in place but the downstream end-cap became detached from the tube. The sampler still worked to some degree because sediment had collected in the tube even without the downstream end-cap; however, this certainly resulted in the loss of fine-grained sediment from the tube. Despite these problems, the time-integrating samplers provided useful information, described in the Results section.

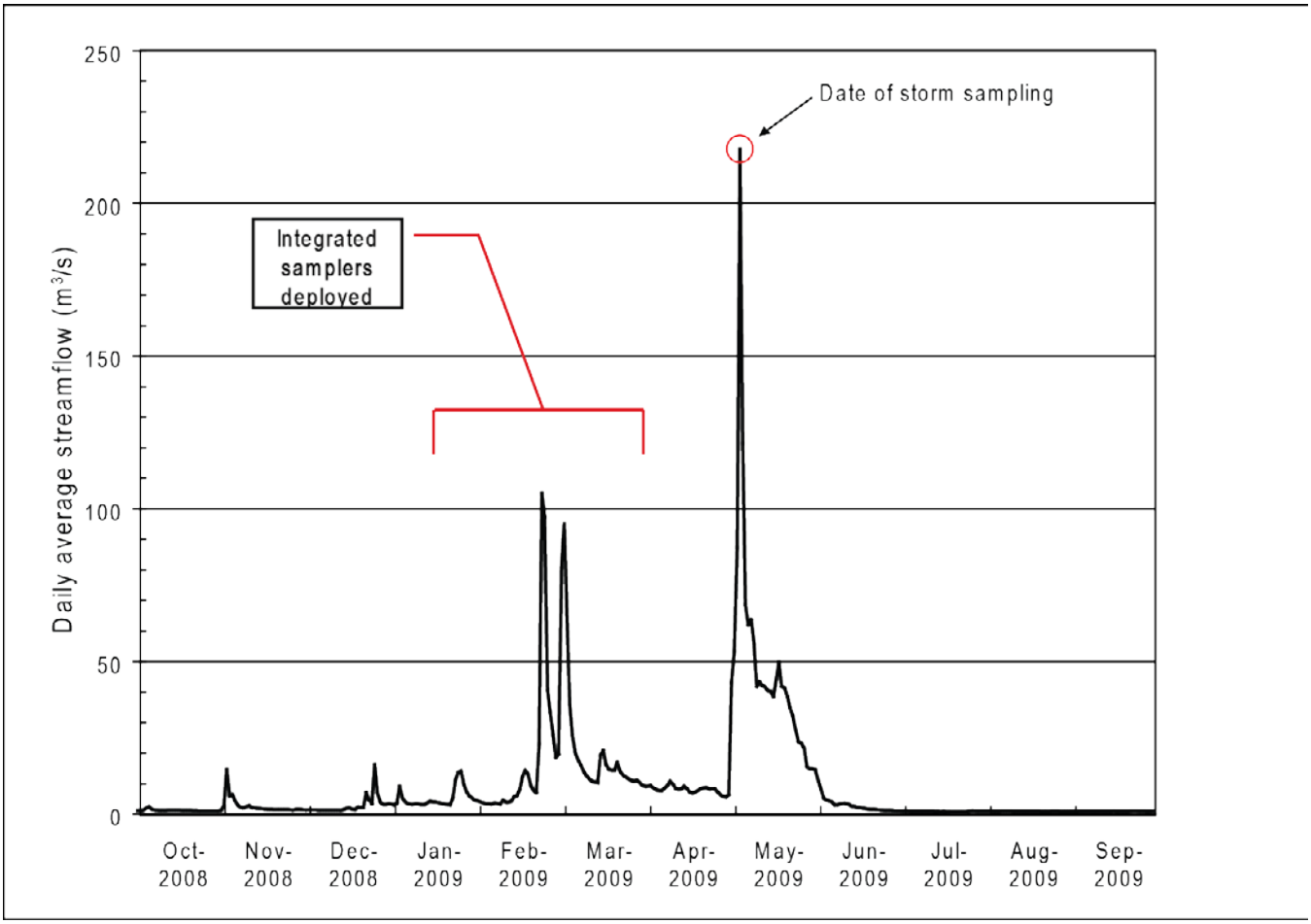


Figure 13. Water-year 2009 hydrograph for the South Yuba River at Jones Bar, California (U.S. Geological Survey streamgage 11417500), showing the time period of integrated sampling and the date of storm sampling.

Biota Assessment

Aquatic invertebrates can serve as excellent bioindicators of metal contamination (for example, Cain and others, 1992). The target macroinvertebrates (Merritt and Cummins, 1995) for this study were predatory or filter-feeding insects, depending on their abundance and availability at sampling sites.

Macroinvertebrates collected during September 2007 included larval stoneflies (Order Plecoptera, family Perlidae), larval caddisflies (Order Trichoptera, family Hydropsychidae), larval dragonflies (Order Odonata, Suborder Anisoptera, families Gomphidae and Libellulidae), and adult water striders (Order Hemiptera, family Gerridae). The three taxa of predaceous invertebrates collected in this study were water striders (Gerridae), stoneflies (Perlidae), and dragonflies (Gomphidae and Libellulidae). Caddisflies are filter-feeding insects that have been used extensively in surveys of THg and MeHg in river environments (for example, Slotton and others, 1997; Weiner and others, 2007). The same macroinvertebrates were collected during September 2008, with the exception that no dragonflies of the family Libellulidae were collected.

Invertebrates were collected from all biota sites (table 1, fig. 14) by using dip nets and by hand and placed in zip-lock plastic bags with native water by using clean techniques when possible (Olson and DeWild, 1999; U.S. Environmental Protection Agency, 2001a). Samples were kept in a cooler on wet ice and allowed to depurate (release impurities) in native water for 4 to 24 hours to minimize external sources of contamination before they were processed. Individuals were sorted by family and placed in disposable dishes by using Teflon®-coated forceps or by hand while wearing disposable powder-free latex gloves. Individual organisms were thoroughly rinsed with deionized water, patted dry with a clean paper towel, and composited by family. Composites were placed in chemically cleaned glass jars with Teflon®-lined lids, and the mass of each composite sample was determined using an electronic balance (± 0.01 g). Where possible, insects from each taxon that were similar in size were combined, assuming that size was a predictor of age and thus exposure to Hg and MeHg contamination. The goal was to obtain a minimum of 1 g of wet biomass per sample. Samples, consisting of 3 to 150 individuals (0.34 –1.84 g total mass), were stored frozen for 2 to 3 weeks prior to shipment to the Brooks Rand Laboratory in Seattle, Wash., for analysis of THg and MeHg concentration.

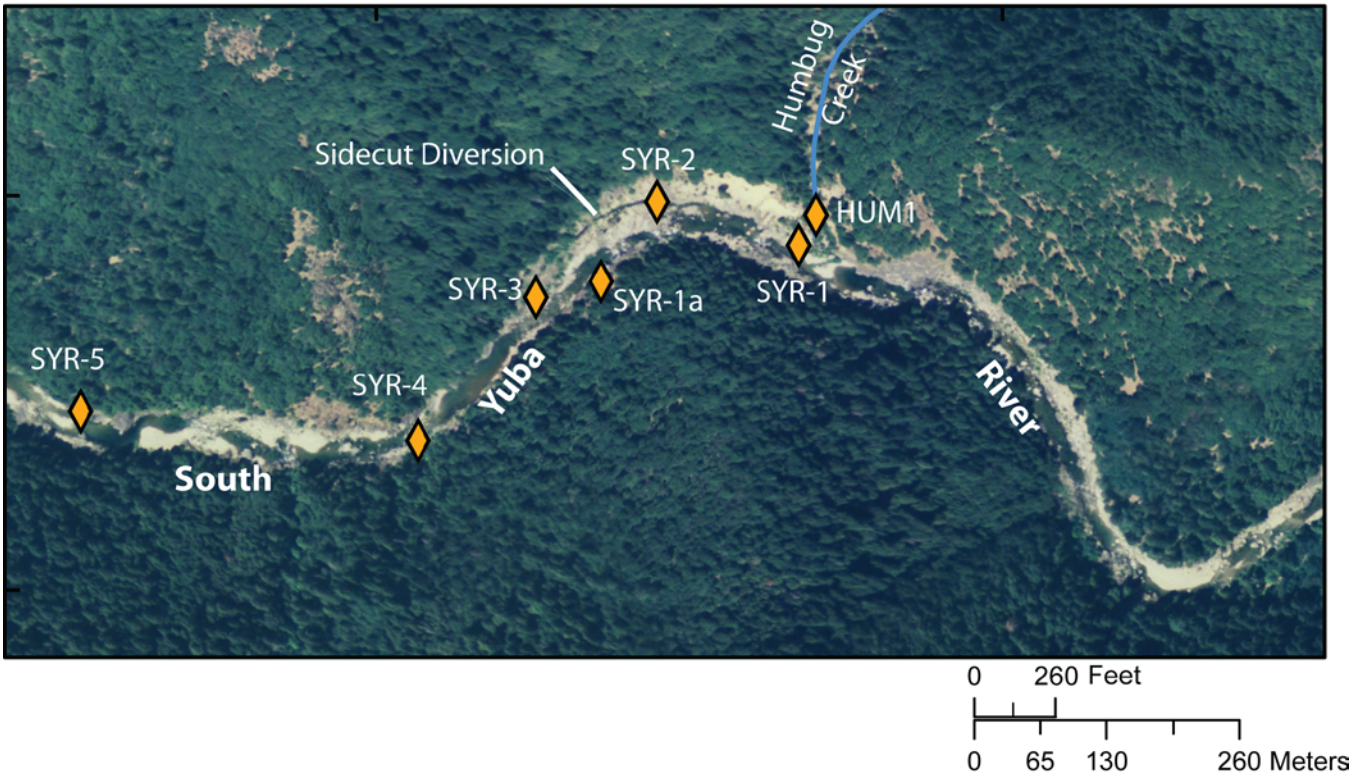


Figure 14. High-resolution aerial photo showing the location of biota collection sites within the South Yuba River–Humbug Creek, California, confluence study area. Additional downstream sampling sites were located at North Canyon and Edwards Crossing on the South Yuba River (sampling locations and descriptions are given in table 1).

Twenty-three composite samples of aquatic macroinvertebrates were collected from 8 sites during September 2007 and 33 composite samples from 6 sites during September 2008. Lower Humbug Creek (HUM-1) was sampled both years, as were sites SYR-1, SYR-4, SYR-6, and SYR-7. Three sites (SYR-2, SYR-3, and SYR-5) were only sampled during 2007, and SYR-1a was only sampled during 2008 (table 1). At least one composite of adult water striders and larval stoneflies were collected from all the sites except for the two diversion sites (SYR-2 and SYR-3). Dragonfly larvae were less available in 2007 than in 2008. Gomphidae larvae were collected only from HUM-1 and SYR-7 in 2007, but they were collected from all six sites during 2008. Larval Libellulidae were collected only from the two diversion sites (SYR-2 and SYR-3) during 2007. Caddisfly larvae were collected from each of the five mainstem sites on the South Yuba River both years, but were not collected from the two diversion sites during 2007 or from Humbug Creek (HUM-1) either year.

Laboratory Methods

The details of laboratory methods are separated into sediment, water, and biota to address the unique details associated with each sample type. Sediment and water analyses for Hg speciation were performed at the USGS mercury laboratory in Menlo Park, Calif. Mineralogical and geochemical analyses were performed at the USGS mineralogy laboratory in Boulder, Colo. Biota analyses were performed at Brooks Rand Laboratory in Seattle, Wash. Data quality-assurance and quality-control measures for all types of mercury analysis done for this study are summarized in *appendix 1*.

Sediment

Laboratory analyses included in the sediment section are for bed sediment, excavated sediment, and dredged materials. Methods related to suspended sediment are discussed in the water-column section immediately following the sediment-methods discussion.

Particle-Size Distribution

The detailed particle-size distribution of three excavated sediment samples (Pit 1, Pit 2 BRC, and HMD-CF) were analyzed at the USGS mercury laboratory in Menlo Park, California, by using laser diffraction to obtain continuous particle-size distributions (Eshel and others, 2004). A Beckman LS230 laser-diffraction particle-size analyzer was used to quantify particle-size distribution for subsamples that had previously been separated by sieving into the following three size fractions: coarse sand (0.25 to 1.0 mm), fine sand (0.063 to 0.25 mm), and silt-clay (<0.063 mm). The results of the particle-size distributions for each of the sieved sediment-size fractions were combined to create a single particle-size distribution for the full range of sediment greater than 0.063 mm.

In addition, the particle-size distribution within the size fraction less than 0.063 mm was determined in the laboratory by using a LISST-100X (Sequoia Scientific) laser-diffraction particle-size analyzer for selected samples from the time-integrated sediment collectors, the May 5, 2009, storm event, selected bed and bank sediment, and selected pit-excavation samples. A small amount of dried sediment was mixed with water, disaggregated through vigorous shaking, and placed into a small mixing chamber enclosing the 5-cm laser path. Typically, measurements were made in triplicate, with each measurement lasting approximately 1 minute while scanning at 1 hertz (Hz) intervals. The data were then evaluated for consistency and averaged to obtain a single size distribution for each sample. The LISST results were then combined with the data from the larger grain-sized fractions to create a single particle-size distribution from 0.001 mm to 1.0 mm for these three samples.

Mercury Speciation

Sediment samples were assayed at the USGS WR-BRR mercury laboratory in Menlo Park, California, by using dual amalgamation, purge and trap, and cold vapor atomic-fluorescence spectrometry (CVAFS) as described by Olund and others (2004), with the following modified sample-digestion procedures: After thawing, approximately 0.1 g of sediment (exact weight measured) was digested initially with aqua regia (2 mL concentrated HNO_3 and 6 mL concentrated HCl) in a Teflon® bomb overnight at room temperature. Subsequently, 22 mL of 5% BrCl were added to each sample and heated overnight to 50 ^{o}C in an oven. Once cooled, a 5 mL subsample was transferred into a pre-combusted glass container. The digestate was analyzed by using an Automated Mercury Analyzer (Tekran Model 2600, Tekran, Inc., Canada) according to USEPA Method 1631, Revision E (U.S. Environmental Protection Agency, 2002).

Sediment samples collected in the field, subsampled in the laboratory, and preserved frozen (-80 °C) for subsequent $Hg(II)_R$ quantification were assayed at the USGS mercury laboratory in Menlo Park, California, as described by Marvin-DiPasquale and Cox (2007). Sediment $Hg(II)_R$ is methodologically defined as the fraction of total Hg(II), which has not been chemically altered (for example, digested, oxidized, or chemically preserved apart from freezing), that is readily reduced to Hg(0) by an excess of stannous chloride ($SnCl_2$) over a defined (short) exposure time. This operationally defined parameter was developed as a surrogate measure of the fraction of inorganic Hg(II) that is most likely available to the bacteria responsible for MeHg production (Marvin-DiPasquale and others, 2009b).

Size-fractioned sediment (heads, tails, and sluice-box concentrates) collected and frozen in the field during the October 2007 suction-dredge test were assayed for MeHg at the USGS mercury laboratory in Menlo Park, California, by using distillation, ethylation, purge and trap, gas chromatography (GC) separation, and pyrolysis with CVAFS detection, as described in Niessen and others (1999).

Sediment Percent Dry Weight and Organic Content

Sediment percent dry weight and organic content (loss on ignition) were analyzed in sequence from a single sediment subsample, as previously described by Marvin-DiPasquale and others (2009a). Quality control consisted of analyzing a subset of samples in duplicate. The average relative percent difference was 0.43% (n = 2) for percent dry weight and 7.8% (n = 2) for organic content.

Quantitative Mineralogy by X-Ray Diffraction and X-Ray Fluorescence

Sediment samples collected from Pit 1, Pit 2, the HMD cliff face, and from various locations within Humbug Creek and the South Yuba River were analyzed for mineralogy using powder X-ray diffraction (XRD) and for major-element chemistry using X-ray fluorescence (XRF) at the USGS mineralogy laboratory in Boulder, Colo. For most samples, three different particle-size fractions were analyzed separately: coarse sand (0.25 to 1.0 mm), fine sand (0.063 to 0.25 mm), and silt-clay (<0.063 mm).

Mineralogy samples were analyzed using a Siemens D500 XRD system. Samples were prepared in a uniform manner, first by grinding for 5 minutes in a McCrone mill, then by shaking for 10 minutes in plastic vials with three plastic balls and a small amount of Vertrel®, a hydrofluorocarbon (2,3 dihydrodecafluoropentane) with trans-1,2-dichloroethylene

and methanol, followed by sieving (0.25 mm), to minimize preferred orientation (see Eberl, 2003). Whole-pattern fitting to known mineral standards was used to determine quantitative mineralogy, by using the RockJock program (Eberl, 2003).

Geochemical samples were analyzed by XRF using a Siemens SRS 300 AS instrument. Lithium borate flux was added to samples during combustion (925 °C), which were then fused into disks using a Phoenix fusion machine. Geochemical data were used to derive correlations with mineralogy and Hg concentrations to aid in determining sediment and Hg sources.

Sediment-Source Determination (Provenance)

Local sources of sediment were determined by assuming that samples collected in a particular upstream or upslope area are representative of specific sediment source types to the depositional area within the SYR-HC confluence. The sample of unconsolidated sediment collected from the cliff exposure during September 2008 (HMD-CF) was chosen to represent historical HMD because the cliff deposits are remnant HMD deposited during the gold-rush era that has been largely undisturbed since deposition; however, they also represent current sources to downstream locations. Bed sediment collected at the mouth of Humbug Creek during January 2009 was chosen to represent current sources of sediment to Humbug Creek. Sediment collected from the shoreline of the South Yuba River upstream from the SYR-HC confluence during September 2008 was used to represent current upstream sources on the South Yuba River. The mineralogy and geochemistry of each grain-size fraction was considered separately for the provenance calculations. Correlation analysis using MinUnMix (Eberl, 2004) was applied to the mineralogical data from the RockJock program (Eberl, 2003) to determine whether the composition of other sediment samples, such as the samples excavated from Pit 1 and the various strata from Pit 2, could be composed of mixtures of the three assumed source materials.

Microscopic Examination of Heavy Minerals

Heavy-mineral concentrates from the 2008 excavations and the 2007 dredge test were examined by using an optical microscope and the LEO 982 field-emission SEM at the USGS scanning electron microscope laboratory in Menlo Park, California. Semi-quantitative, energy-dispersive spectrometry (EDS) on the SEM was used to determine the relative concentrations of Au and Hg in the heavy minerals.

Water Column

Samples of suspended sediment in the water column from the October 2007 dredge test, the September 2008 recirculation-tank experiment, and the May 2009 storm samples were analyzed for TSS concentration and Hg speciation. The pre-weighed filters loaded with suspended sediment in the field were removed from frozen storage, freeze-dried, placed in a dessicator, and reweighed. The original weight of the filter was subtracted from the final weight and divided by the volume of water filtered to obtain a volumetric measurement of TSS concentration (in milligrams per liter). For the October 2007 dredge test, three filters were collected for each sample, whereas for the September 2008 and May 2009 samples, only two filters were collected. Once TSS values were calculated, the TSS samples were analyzed for Hg species and normalized to the volume of water filtered. One loaded filter for each site was analyzed for THg using the method described by Olund and others (2004) and reported as pTHg (in nanograms per liter). The second filter was analyzed for $Hg(II)_R$ using the method

described by Marvin-DiPasquale and Cox (2007) and reported as $pHg(II)_R$ (in nanograms per liter). For the October 2007 dredge test, a third filter, when present, was analyzed for MeHg using the method described by Niessen and others (1999) and reported as pMeHg (in nanograms per liter).

Water passing through the filters (filtrate) was collected and preserved in the field for THg and MeHg analysis during the October 2007 dredge test only. Samples for THg in the filtrate were analyzed according to USEPA Method 1631 Revision E (U.S. Environmental Protection Agency, 2002), with quantification using CVAFS on a Model 2600 Automated Total Mercury Analyzer (Tekran, Inc., Canada) and reported as fTHg (in nanograms per liter). Filtrate MeHg was analyzed by distillation followed by ethylation (DeWild and others, 2002) with subsequent quantification by using CVAFS detection on a MERX automated MeHg analyzer (Brooks Rand Laboratories, Seattle, Wash.) and reported as fMeHg (in nanograms per liter).

Biota

THg in biota was analyzed according to USEPA Method 1631 Revision E (U.S. Environmental Protection Agency, 2002) by digesting homogenized samples in nitric acid (HNO_3) and sulfuric acid (H_2SO_4), and then further oxidizing with bromine monochloride (BrCl). Samples were analyzed with stannous chloride ($SnCl_2$) reduction, single Au trap amalgamation, and CVAFS detection using a BRL Model III CVAFS Mercury Analyzer.

MeHg in biota was analyzed using a modified version of USEPA method 1630 (U.S. Environmental Protection Agency, 2001b). MeHg extraction was carried out by potassium hydroxide (KOH) methanol (CH_3OH) digestion. The resulting extract was then analyzed by aqueous phase ethylation, Tenax trap collection, GC separation, isothermal decomposition, and by CVAFS using a BRL Model III CVAFS Mercury Analyzer.

All concentrations are presented on a wet-weight basis; however, for the 2008 samples, percentage moisture was used to calculate concentrations on a dry-weight basis as well; percent moisture was not analyzed in the 2007 samples. To determine the percent solids, an aliquot of homogenized sample was measured into a pre-weighed vessel, dried in an oven overnight, and then reweighed. The percent of dried solid material was calculated on the basis of the moisture loss according to standard method SM 2540G (Eaton and others, 2005).

Statistical Analyses

For the biota data, a mixed-effects analysis of variance model (hereafter “mixed ANOVA”) was used to analyze variations in total and methyl Hg (hereafter Hg and MeHg) concentrations among taxa and years as fixed factors, including year by taxa interactions, and among sites as a random blocking factor (Littell and others, 1996; Neter and others, 1990). Taxa were analyzed at the Order level, which in most cases was equivalent to analyzing at the Family level, because there was usually one Family represented per Order. The Odonata order, which had two families (Gomphidae, Libellulidae) pooled together, was the only exception. In 2008, some sites were sampled more than once for certain taxa, and these multiple samples were averaged by using geometric means prior to analysis. The data were transformed using the natural log function in order to meet the assumptions of normality and homoscedasticity (that is, constant variances) required in standard ANOVA models. All mixed ANOVAs were fit using the methodology of restricted maximum likelihood, and all estimates and tests were calculated by using least squares means and the Satterthwaite approximation for degrees of freedom, denoted

df, by using SAS software (SAS Institute, 2007; Littell and others, 1996). F statistics were computed in order to test all fixed effects, and these test statistics are reported as $F_{a,b}$ where a and b represent the numerator and denominator df of the test, respectively. The significance of each F test statistic was measured using a p-value, denoted p, where any effects with $p<0.05$ were considered to be statistically significant. Where statistically significant effects were found, specific years or taxa were further compared and tested while applying a Tukey-Kramer adjustment to the p-value in order to limit the potential for spuriously significant results among the multiple comparisons. Likelihood chi-square test statistics, denoted χ^2 were computed for the random site effect, in an analogous manner as the F test statistics for the fixed effects.

Results

The results presented cover a diverse set of data and collection methods used to characterize the SYR-HC confluence area. Results for each study element are presented in separate sections, with the organizational structure based primarily on the type of data and its application and secondarily on chronological order. Within each section, results are further divided by sample type or experiment.

Preliminary Dredge Test

A preliminary dredge test on October 11, 2007, used a standard 3-in. suction dredge in the South Yuba River downstream from the SYR-HC confluence area (fig. 2). The test was designed to evaluate sample-collection methodology and logistical issues related to the remote study site. It is important to note that the results presented here do not represent a full-scale dredge operation nor can the results be scaled-up quantitatively. The results of the test should be evaluated as valuable information regarding the proof of concept rather than a quantitative evaluation of the effects of suction dredging on water and sediment in the South Yuba River.

Water Column

Laboratory analyses of suspended-sediment concentration collected on filters were consistent with the field measurements of particle concentration by using the LISST (fig. 15). Suspended-sediment concentrations increased by 150% to 300% during the dredge test relative to the samples collected pre-dredge operation (October 10, 2007) and the following day (October 12, 2007) (fig. 15). LISST data show short-term increases in suspended particle concentrations during and immediately following the dredge test (fig. 15). The intermittent concentration spikes in the LISST data reflect the intermittent activity of the dredge and poor cross-sectional mixing of the dredge plume past the LISST deployment location. Breaks in the dredge activity were related to boulder and cobble removal, changes in dredge operators, dredge refueling, and equipment checks.

The LISST measurements also indicated higher concentrations at the upstream (mid-pool) tagline as compared to the downstream (end-pool) tagline. It is difficult to ascertain if these mid-pool and end-pool differences represented deposition along the flow path between the two taglines, because these spatial differences also persisted during non-dredging periods. Deposition during non-dredge periods may be attributed to deposition across the riffle-pool complex following the rainfall event that occurred the night prior to the dredge test. However, the apparent deposition may alternatively be related to the fact that the LISST measurements were made at two discrete points, and while efforts were made to place the two LISST

instruments in similar environments (mid-channel, near the bed), some of the spatial differences in TSS concentration observed during non-dredging periods may reflect hydrologic variability within the cross section and along the stream reach studied.

The proportion of suspended sediment in the clay-size fraction (<0.002 mm) measured in-situ by the LISST increased dramatically during the dredge test at both the mid-pool and end-pool tagline locations (fig. 16). The proportion of suspended sediment in the clay-sized fraction (<0.002 mm) reached maxima around 27% at the mid-pool location and 47% at the end-pool location (fig. 16). It should be noted that the LISST measures any particle in suspension that diffracts light, including microbubbles that may have been introduced during the dredging activities. Thus, while it is likely that the reported spikes represent suspended particles because they were measured by both instruments, the composition of these very fine particles is unknown.

Concentrations of pTHg increased in a similar manner as TSS, with concentrations during the suction dredging two times the pre-dredging concentration and three to four times the concentration of the samples collected the following day (fig. 17). The consistency of the relation is because of the similar Hg concentration in the suspended sediment across samples. The dry-mass-normalized Hg content of the suspended material (Hg_{SS}) remained at approximately 300 ng/g throughout the test (fig. 18). This concentration is similar to that measured in sediment from the San Francisco Bay estuary (Bouse and others, 2010) and the fine-grained (<0.063 mm fraction) sediment excavated from Pit 1, a gravel-cobble bar on the South Yuba River, during September 2008 (discussed in a later section of this report).

Concentrations of fTHg in the South Yuba River during the dredge test were similar to those in the field blanks (table 4). The elevated concentration of the field blank compared to the laboratory blank water may have been caused by multiple sources of background contamination affecting field equipment and the filtration process. Efforts were made to keep equipment and blank water clean by using multiple layers of plastic bags, but the difficulty of site access and exposure to the weather increased the potential for equipment and blank-water contamination.

Dredging appeared to have no major effect on pMeHg concentrations in the South Yuba River during the dredge operations. Concentrations of pMeHg in environmental samples were approximately twice those in the field blanks (table 4) but did not change over time at the end-pool site (approximately 0.006 ng/L). Only one sample collected at the mid-pool site was analyzed for pMeHg as part of this methods-testing exercise, so no trend could be evaluated at that site. Concentrations of fMeHg were all below the method detection limit (MDL) of 0.040 ng/L except for one sample that was just above the MDL at 0.041 ng/L; however, this variation may not have been directly attributable to the dredge operations. Similarly, all samples for $pHg(II)_R$ analysis were below the MDL (table 4).

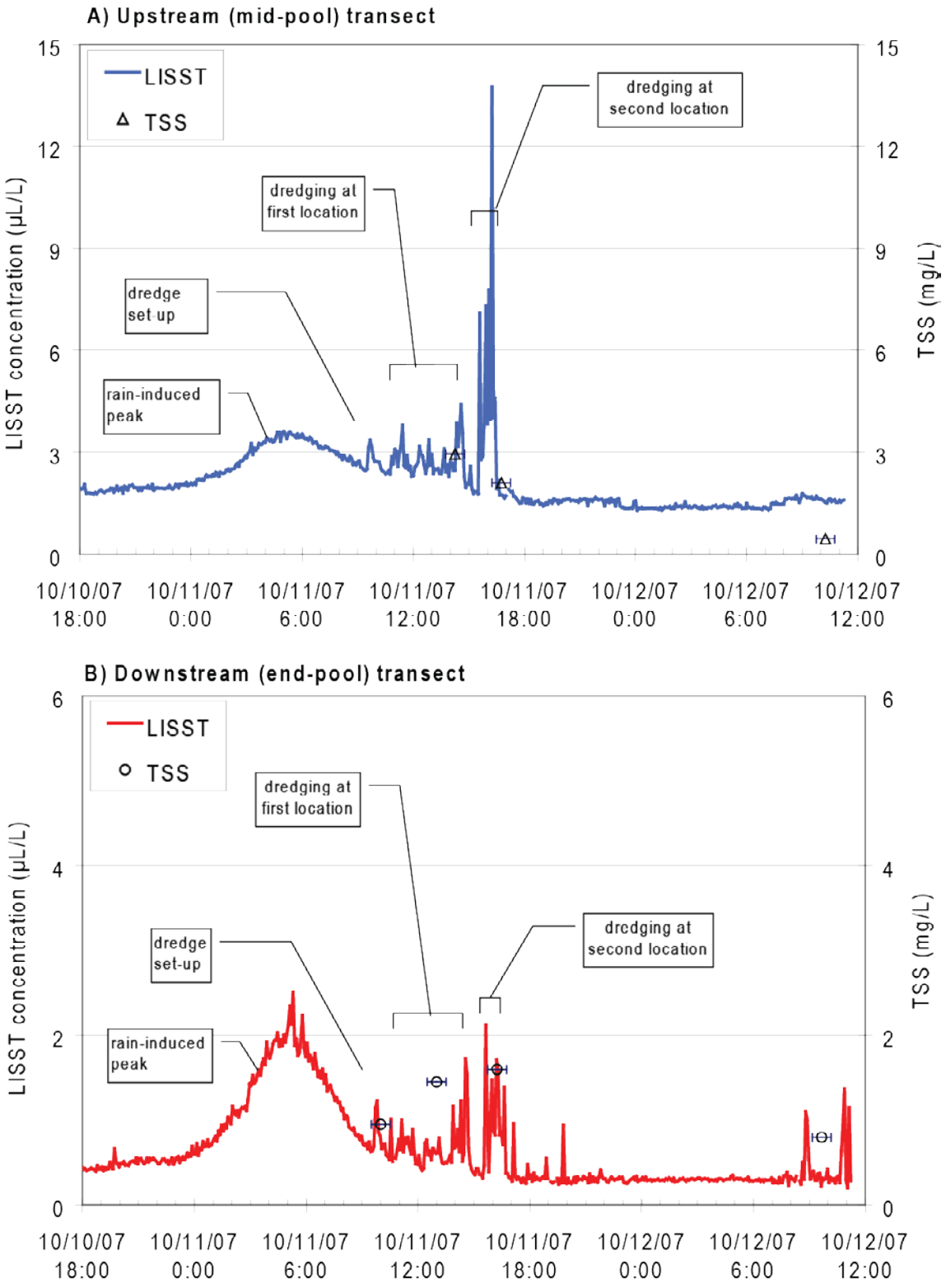


Figure 15. Suspended-sediment concentrations throughout the October 2007 dredge test in the South Yuba River, California, measured in-situ with the LISST-100X laser particle size analyzer and in the laboratory (measured as total suspended sediment or TSS) on samples collected at the transects at the (A) mid-pool, and (B) end-pool locations.

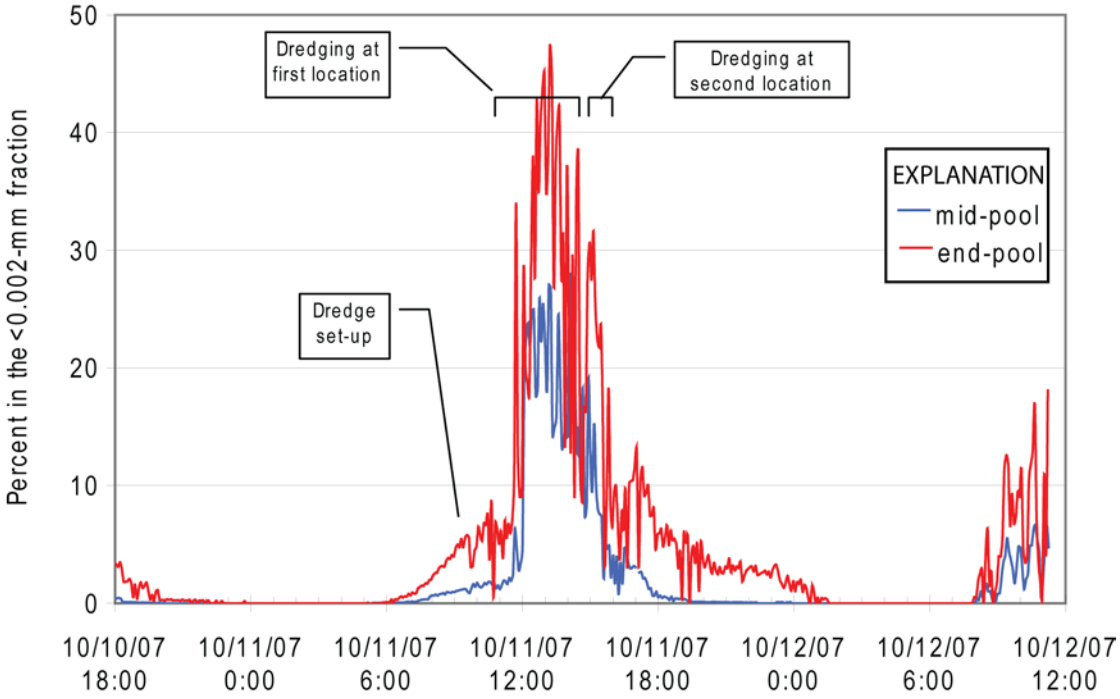


Figure 16. LISST data depicting the percentage of suspended sediment in the clay-size fraction at the South Yuba River, California, dredge site at the upstream (mid-pool) and the downstream (end-pool) tagline during the October 2007 dredge test.

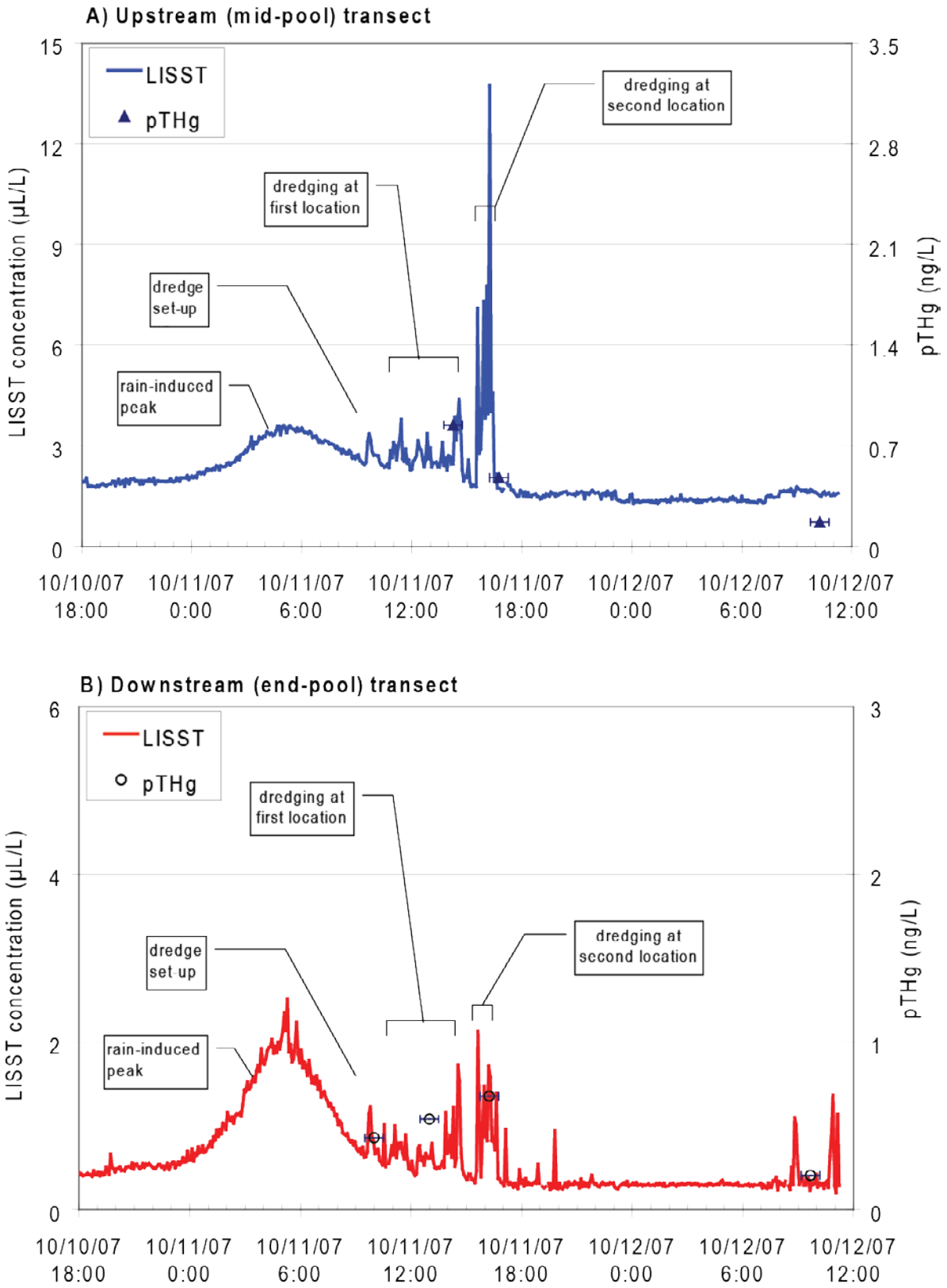


Figure 17. Time course line graphs depicting the LISST concentrations and particulate total mercury at (A) the mid-pool, and (B) end-pool transects throughout the October 2007 dredge test on the South Yuba River.

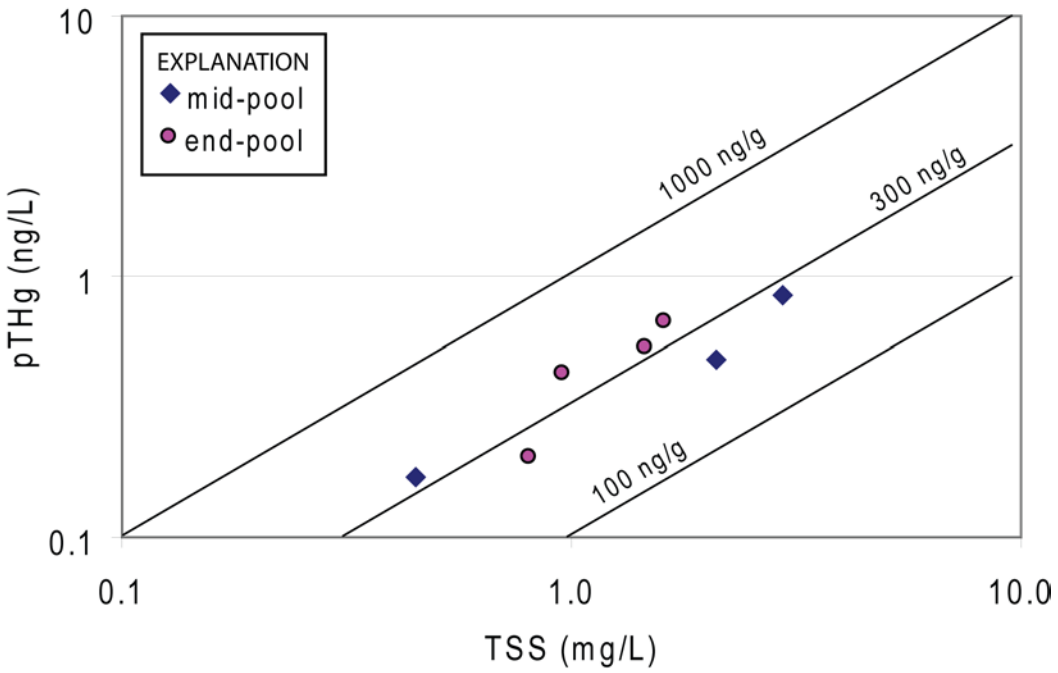


Figure 18. Log-log plot showing the relation between concentrations of total suspended sediment (TSS) and particulate total mercury (pTHg) at the mid-pool (blue symbols) and end-pool (pink symbols) sites during the October 2007 dredge test on the South Yuba River, California. Lines represent mass-based pTHg concentration.

Table 4. Mercury concentrations in water samples collected during the October 2007 dredge test, South Yuba River, California.

[MP, mid-pool; EP, end-pool; hrs, hours; µm, micrometer; THg, total mercury; MeHg, methylmercury, $Hg(II)_R$, reactive mercury (II); $Hg(II)_{R\text{-}SS}$, reactive mercury concentration of suspended sediment; TSS, total suspended sediment; p, particulate; f, filtered; ng/g, nanogram per gram (or part per billion); %, percentage; ng/L, nanogram per liter; mg/L, milligram per liter; $MeHg_{SS}$, methylmercury concentration of suspended sediment; MDL, method detection limit; <, less than; nd, not determined]

Site	Collection Date	Time relative to start of dredging (hours)	THg_{SS} (ng/g)	pTHg (ng/L)	fTHg (ng/L)	$MeHg_{SS}$ (ng/g)	pMeHg (ng/L)	fMeHg (ng/L)	$Hg(II)_{R\text{-}SS}$ (ng/g)	% $MeHg_{SS}$	% $Hg(II)_{R\text{-}SS}$	TSS (mg/L)
Field blank	11-Oct-07	-1	<MDL	<MDL	0.67	nd	nd	<MDL	<MDL	nd	nd	0.1
Field blank	12-Oct-07	24	<MDL	<MDL	0.38	nd	nd	<MDL	<MDL	nd	nd	0.0
SYR-MP	11-Oct-07	1.5	421	0.84	nd	nd	nd	0.015	<MDL	nd	nd	3.0
SYR-MP	11-Oct-07	3	440	0.48	0.57	5.2	0.012	0.021	<MDL	1.2	nd	2.1
SYR-MP	12-Oct-07	24	670	0.17	nd	nd	nd	0.041	<MDL	nd	nd	0.5
SYR-EP	11-Oct-07	-1	717	0.43	0.53	14.2	<MDL	<MDL	<MDL	2.0	nd	1.0
SYR-EP	11-Oct-07	1	338	0.54	0.47	8.4	<MDL	0.012	<MDL	2.5	nd	1.5
SYR-EP	11-Oct-07	3	510	0.68	0.53	5.9	<MDL	0.011	<MDL	1.2	nd	1.6
SYR-EP	12-Oct-07	24	410	0.20	1.08	13.3	<MDL	0.008	<MDL	3.2	nd	0.8

Bed-Sediment Deposition

Measureable amounts of sediment were not collected in any of the sediment traps deployed along the taglines. Most of the sediment that passed through the dredge sluice was coarse sand or larger in size and was deposited within 10 m of the sluice tail outlet, as can be seen in the photo of the dredge hole and waste pile (fig. 3). The grain-size distribution of bed sediment in the area of the study was dominated by particles of sand size or larger (>0.063 mm). The remaining suspended sediment in the clay and silt fractions did not settle within the dredge pool, because these fine-grained particles require longer time periods and low-velocity, quiescent conditions to settle out of the water column. These silt- and clay-size, fine particles are visible in the photo of the dredge plume, which also shows poor mixing of the plume in the channel cross section (fig. 3). Although the LISST data suggest some deposition of fine sand between the mid-pool and end-pool taglines, the amount was too small to capture using the methods employed.

Dredged Material (Mobilized Sediments)

Most of the mobilized sediment samples (heads, tails, and sluice-box-concentrates) fell into the coarse sand and gravel sizes (>0.25 mm) prior to sieving. Over 99% of the material sampled was sand-size (0.063 to 1.0 mm) or greater, the silt-clay fraction (<0.063 mm) accounted for <1% of the bulk sample (table 5). Concentrations of THg in the dredged material differed greatly between sample types; the greatest concentrations were in the concentrate samples collected from the dredge sluice-box (fig. 19, table 5).

Differences between heads and tails were minor (fig. 19). Concentrations of THg in heads and tails were similar to each other (ranging from 10 to 150 ng/g) and were lower than those measured in the suspended sediment (THg_{SS}) collected from the water samples at the downstream transects (approx. 250 to 450 ng/g). The difference in THg between size fractions of the heads and tails was unexpected with the F1 fraction greater than the F3 fraction. The percentage of THg in the reactive form ($Hg(II)_R$) was also similar for heads and tails, ranging from 0.5 to 7%; however, the size fractions had the opposite trend with the F3 fraction having a higher percentage of $Hg(II)_R$ than the F1 fraction (fig. 19).

The samples of sluice-box concentrate had elevated and highly variable THg concentrations (fig. 19, table 5). The variability was expected because of sample heterogeneity caused by the random inclusion of large grains of Hg-coated sands and Hg amalgam that occur at a lesser frequency in the matrix than can reasonably be subsampled, leading to a highly variable analytical artifact known as the “nugget effect” (Wendt and Thomas, 1990). The sluice-box concentrates exhibited much lower $\%Hg(II)_R$ than the heads and tails, despite possessing the greatest $Hg(II)_R$ concentrations (fig. 20).

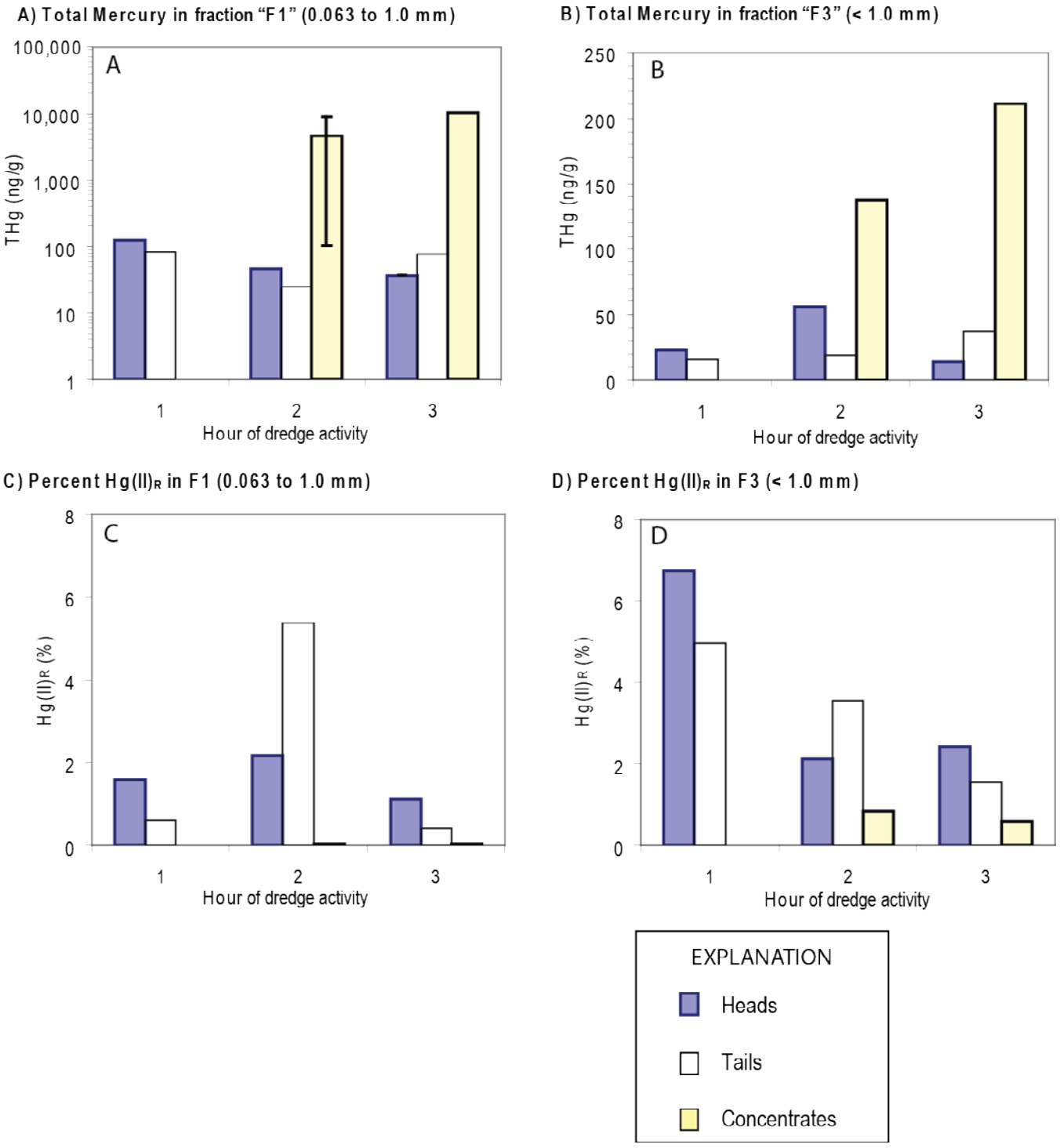


Figure 19. Bar graphs showing the concentrations of total mercury (THg) and the percent of THg as reactive mercury (%$Hg(II)_R$) in two size fractions (sand, 0.063 to 1.0 millimeter; and sand-silt-clay, less than 1.0 millimeter) of material (heads, tails, and sluice-box concentrates) sampled during the October 2007 dredge test, South Yuba River, California.

Table 5. Mercury concentrations in sediment samples collected during the October 2007 dredge test, South Yuba River. All concentrations are on a dry weight basis.

[hr, hour; THg, total mercury; MeHg, methylmercury, $Hg(II)_R$, reactive mercury (II); %, percent; ng/g, nanogram per gram (or part per billion); <, less than; MDL, method detection limit; mm, millimeter]

Sediment type	Size fraction	Percent of total sediment in size fraction (%)	Time (hr)	THg (ng/g)	MeHg (ng/g)	Percent MeHg (%)	$Hg(II)_R$ (ng/g)	Percent $Hg(II)_R$ (%)
Heads	< 1.0 mm	1.14	0-1	22.9	< MDL	< MDL	1.55	6.75
Heads	< 1.0 mm	12.33	1-2	55.8	< MDL	< MDL	1.18	2.12
Heads	< 1.0 mm	2.17	2-3	13.9	< MDL	< MDL	0.34	2.43
Heads	0.063 to 1.0 mm	1.25	0-1	124	< MDL	< MDL	1.95	1.58
Heads	0.063 to 1.0 mm	12.22	1-2	46.5	< MDL	< MDL	1.01	2.18
Heads	0.063 to 1.0 mm	2.12	2-3	36.6	< MDL	< MDL	0.41	1.12
Tails	< 1.0 mm	32.56	0-1	15.9	< MDL	< MDL	0.79	4.96
Tails	< 1.0 mm	10.76	1-2	18.6	< MDL	< MDL	0.66	3.54
Tails	< 1.0 mm	9.12	2-3	37.1	< MDL	< MDL	0.58	1.55
Tails	0.063 to 1.0 mm	32.75	0-1	83.0	< MDL	< MDL	0.51	0.61
Tails	0.063 to 1.0 mm	10.58	1-2	25.1	< MDL	< MDL	1.35	5.37
Tails	0.063 to 1.0 mm	9.06	2-3	78.2	< MDL	< MDL	0.33	0.42
Concentrate	< 1.0 mm[1]	95.42	0-2	137	0.022	0.016	1.16	0.84
Concentrate	< 1.0 mm[1]	95.35	2-3	211	nd	nd	1.24	0.59
Concentrate	0.063 to 1.0 mm[1]	95.65	0-2	4,570	< MDL	< MDL	0.93	0.02
Concentrate	0.063 to 1.0 mm[1]	95.70	2-3	10,300	nd	nd	1.66	0.02
Concentrate	0.0003 to 0.063 mm[1]	0.23	0-2	14,300	1.1	0.008	83.2	0.58
Concentrate	0.0003 to 0.063 mm[1]	0.36	2-3	3,210	0.92	0.029	28.3	0.88

[1] Concentrate samples pre-sieved through 20-mesh screen.

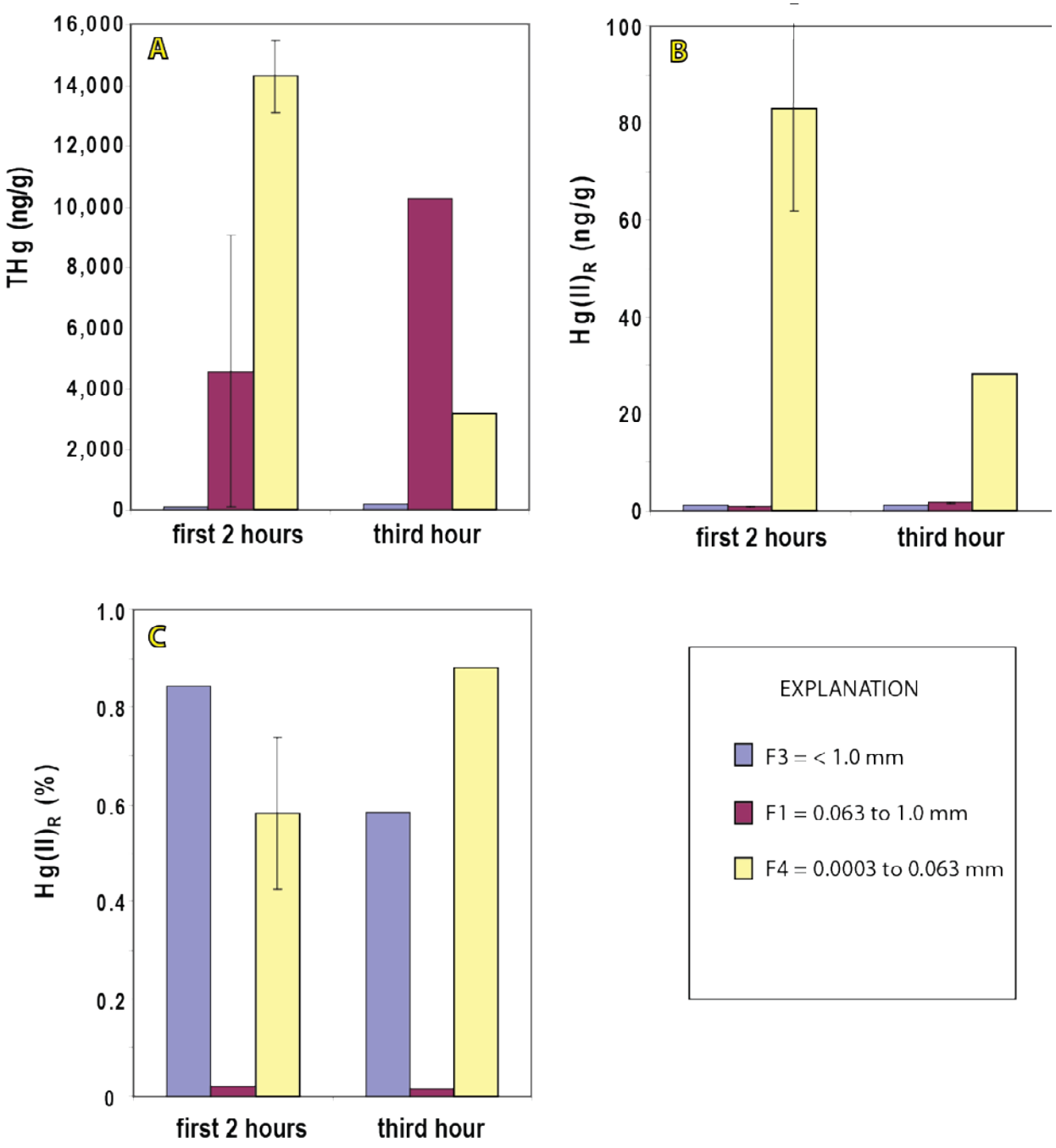


Figure 20. Bar graphs showing concentrations of mercury species in the sluice-box concentrates collected during the October 2007 dredge test, South Yuba River, California. (A) Total mercury (THg), (B) reactive mercury(II) [$Hg(II)_R$], and (C) percentage of THg as $Hg(II)_R$.

Detailed Site Characterization

The detailed site characterization study element encompasses four unique approaches to identifying Hg contamination within the study site: 1) GPR, 2) sediment excavations, 3) a recirculation-tank experiment, and 4) a qualitative "sniping" assessment. The results are presented in separate sections parallel to the organization of the Field Methods section of this report. Although reported independently, each section contributes an important line of evidence in characterizing Hg contamination in the SYR-HC confluence area.

Ground-Penetrating Radar Assessment

The purpose of the GPR assessment of the South Yuba River cobble bar was to see if a subsurface "slickens layer" associated with historical hydraulic mining activity could be identified and thus help select sampling sites associated with the September 2008 detailed site characterization. A subset of the results from the GPR survey is presented in radargrams in fig. 21.

Survey line Y12 (fig. 21A) corresponds to the eastern margin of the cobble bar (see fig. 5). The "first break" arrival time, corresponding to the direct air wave from the transmitted signal, was used to establish the zero time point for the trace. As is the case in all the survey lines, a large amplitude arrival with a two-way traveltime of about 10 nanoseconds is the first reflector (R1). This first reflection corresponds to the surface cobble layer in almost all cases. An exception is the first reflection in line Y12 spanning the distance from 0 to 2 m along the survey line (x-axis). There were no cobbles or other sediment overlying the bedrock in this section, and the movable wooden board track was laid directly onto the bedrock surface.

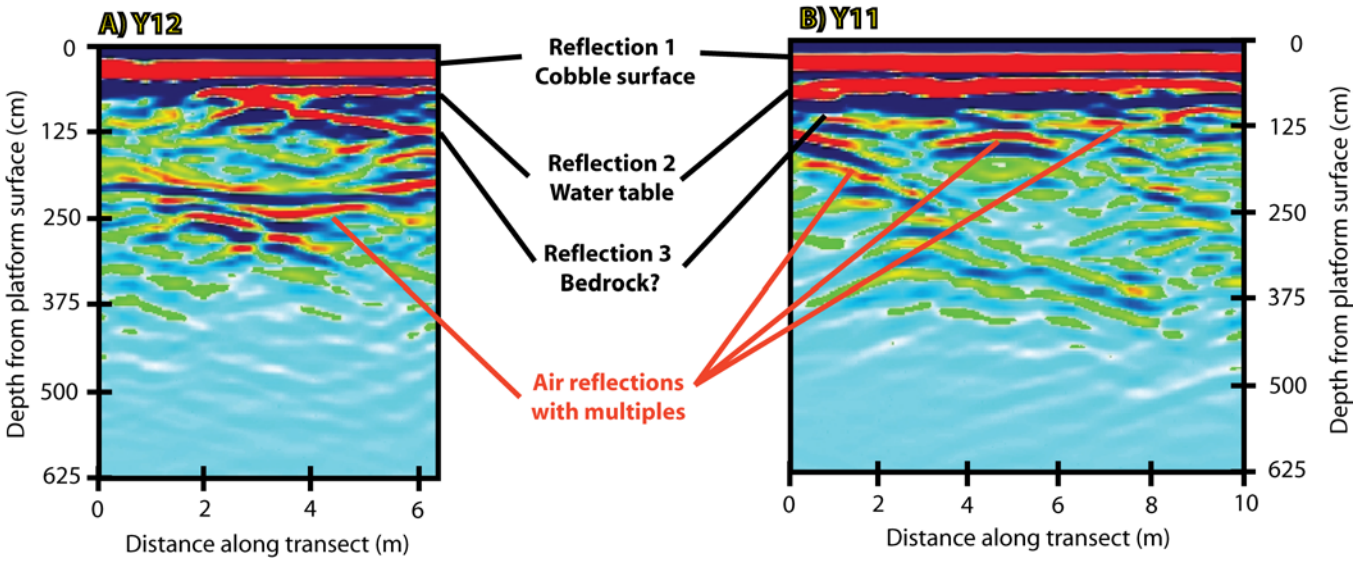


Figure 21. Ground-penetrating radar images with interpretation. (A) Radargram for Line Y12 (east end of cobble bar), and (B) Radargram for line Y11. Signal arrival times are shown in color, with signal density maxima in red and minima in blue.

Line Y12 also indicates that two additional reflectors can be resolved for the portion of the survey spanning the distance from around 2 to 7 m along the line. R2 is a flat-lying layer at a depth of around 1.2 m, and R3 is a layer dipping downward to the north with a depth of 2 m at a distance of about 7 m along the line. R2 is interpreted to represent the water table for which a strong reflection is expected from the large contrast in dielectric permittivity between saturated and unsaturated cobble/sandy sediment. R3 is interpreted as the dipping bedrock contact that rises to the land surface at a distance of approximately 2 m along the survey line.

Survey line Y11 was collected 5 m to the west of line Y12, and interpretation of the results suggests that the same three reflectors can be detected across the survey length (fig. 21B). Beneath the surface cobble layer (R1), the water table (R2) lies at approximately 1.2 m depth followed by what may be the bedrock contact (R3) at a variable depth of around 1.8 to 2 m. The precise detection of the R3 surface is obscured, however, by several concave parabolas arriving at a two-way traveltime of around 40 nanoseconds and later. Parabolas are a clear indication of point-object reflections and diffractions in GPR radargrams, and the numerous arrivals with multiple tails observed in line Y11 obscure the detection of any additional features at depth.

Results from GPR lines Y1 to Y10 showed considerable contamination from air reflections, making the detection of coherent reflectors exceedingly difficult. It was often challenging to resolve the water table (R2 reflector), and no clear detection of a bedrock layer or “slickens” layer was possible over most of the cobble bar. As a result of the noise induced by air reflections, it was not possible to provide a comprehensive imaging of either the bedrock surface or of a target bed such as the “slickens” layer in this study.

Although the results of the GPR assessment were largely ineffective, some useful suggestions can be made from this element of the study. The eastern part of the cobble bar appears to have shallow bedrock that is exposed in some areas, with cobbles and very coarse sediment resting directly on the bedrock contact. Thus, it does not seem likely that a fine-grained “slickens” layer would be preserved in this part of the cobble bar. The effectiveness of applying GPR in such a challenging environment can be maximized by employing a shielded antenna system as a means of reducing the contaminating noise from air reflections. Such contamination is clearly inherent to applications on cobble surfaces as a result of poor ground coupling and the elevated position of antennas riding atop the wooden board platform. It is likely that such a challenging environment would still require additional processing and filtering methods such as those described by Nuzzo (2003) for GPR to be effective at locating “slickens” layers and the depth to bedrock beneath cobble surface layers.

Sediment Excavations

All sediment excavated from Pit 1, Pit 2, and the HMD-CF were dominated by coarse-grained material (table 2). For most samples, more than 60% of the mass was greater than 6.3 mm in diameter (fig. 22A). For the sediment <6.3 mm, only 0.03 to 5% was composed of silt-clay (<0.063 mm size fraction) (fig. 22B). Twenty to 35% of the sediment particles smaller than 1 mm were in the <0.25 mm fraction (fig. 22C). Overall, the HMD material from the actively eroding cliff was similar in particle-size distribution to sediment from the bottom two layers of Pit 2, especially with respect to the material <6.3 mm (fig. 22B) and material <1 mm (fig. 22C).

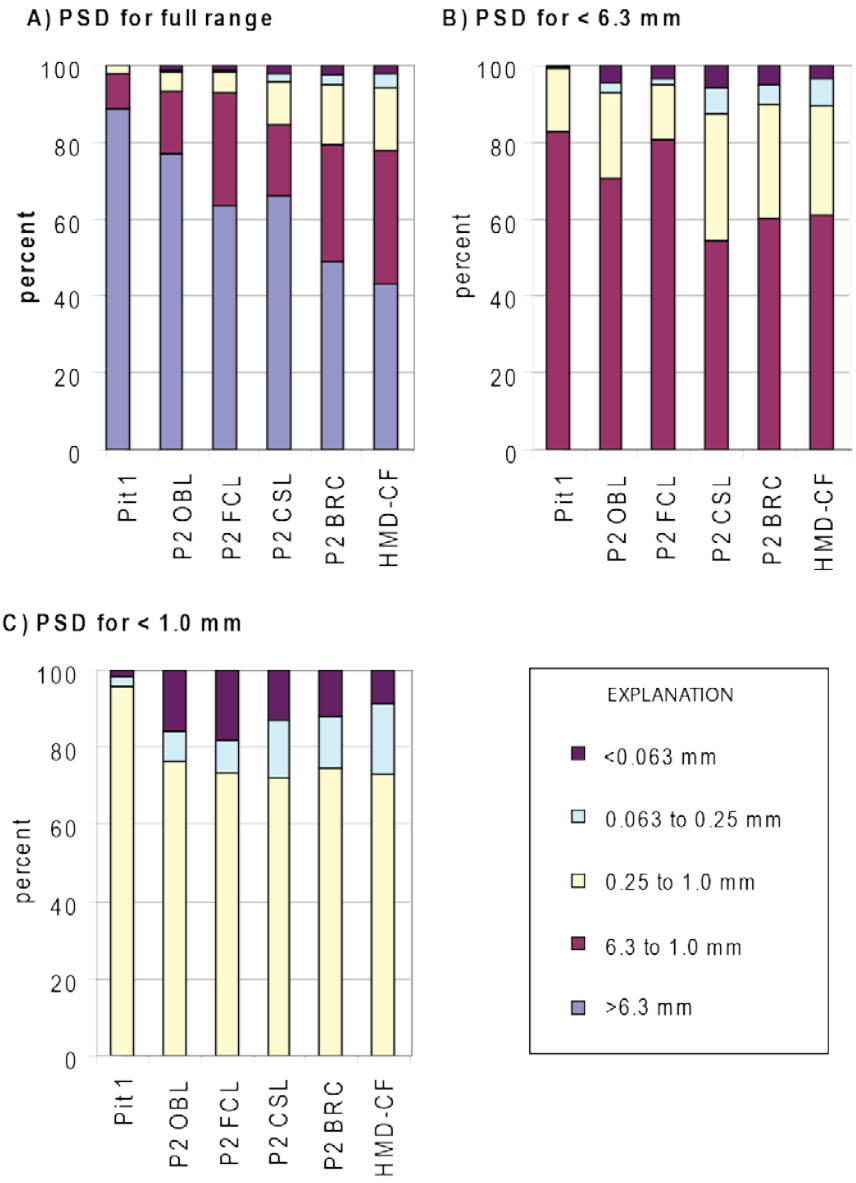


Figure 22. Stacked bar graphs showing the particle-size distribution for excavated sediment collected during September 2008 in the South Yuba River, California, for the following initial size ranges of material: (A) Full size range (non-sieved), (B) material less than 6.3 millimeters (1/4 inch), and (C) material less than 1 millimeter. Sample information is provided in table 2. Site names are abbreviated as follows: P2, pit 2; OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; and HMD-CF, hydraulic mining debris cliff face.

Additional information on particle-size distribution for excavated samples was provided by the laser-scattering analytical approach. Results indicate that Pit 1 sediment was coarser than that from the Pit 2 bedrock contact layer and from the eroding cliff HMD for material < 1.0 mm (fig. 23A). The laser-scattering approach further showed that the three samples analyzed had similar size distributions, although a slightly higher proportion of very fine-grained material was present in the HMD material for material <0.063 mm. For example, about 20% of the HMD sediment <0.063 mm was in the clay-size range (<0.002 mm) compared with about 14 to 18% of the material from Pit 1 and the Pit 2 bedrock contact, respectively (fig. 23B).

Concentrations of THg, $Hg(II)_R$, and organic content (loss on ignition) all increased with decreasing particle size (fig. 24, table 6). The concentration of THg in the coarsest size fraction (0.25 to 1.0 mm) ranged from 16 to 515 ng/g for Pit 1 and Pit 2-BRC, respectively. The concentration of THg in the intermediate size fraction (0.063 to 0.25 mm) ranged from 41 to 1,630 ng/g for Pit 1 and Pit 2 CSL, respectively. The THg concentration in samples from the finest size fraction (silt-clay, <0.063 mm) ranged from 147 ng/g in the Pit 2 OBL to 11,100 ng/g in the Pit 2 BRC. The percentage of $Hg(II)_R$ as a function of THg was somewhat variable across the sediment fractions. The highest values of $\%Hg(II)_R$ (17 to 27%) were observed in samples from the 0.063 to 0.25 mm size fraction of the Pit 2 CSL and BRC and in the <0.063 mm size fraction of the Pit 2 BRC (fig. 24D).

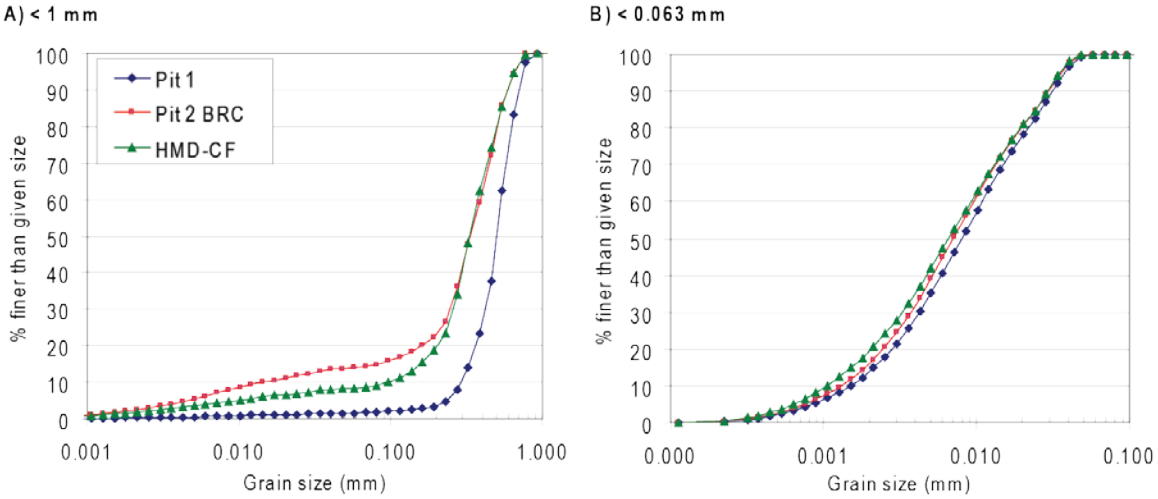


Figure 23. Cumulative particle-size-distribution plots of fine-grained material from three excavated sediment samples (Pit 1, Pit 2 bedrock contact, and cliff face of hydraulic mining debris) collected during September 2008 in the South Yuba River–Humbug Creek, California, confluence area, based on laser scattering. (A) Sand-silt-clay fraction (< 1.0 mm), and (B) silt-clay fraction (< 0.063 mm).

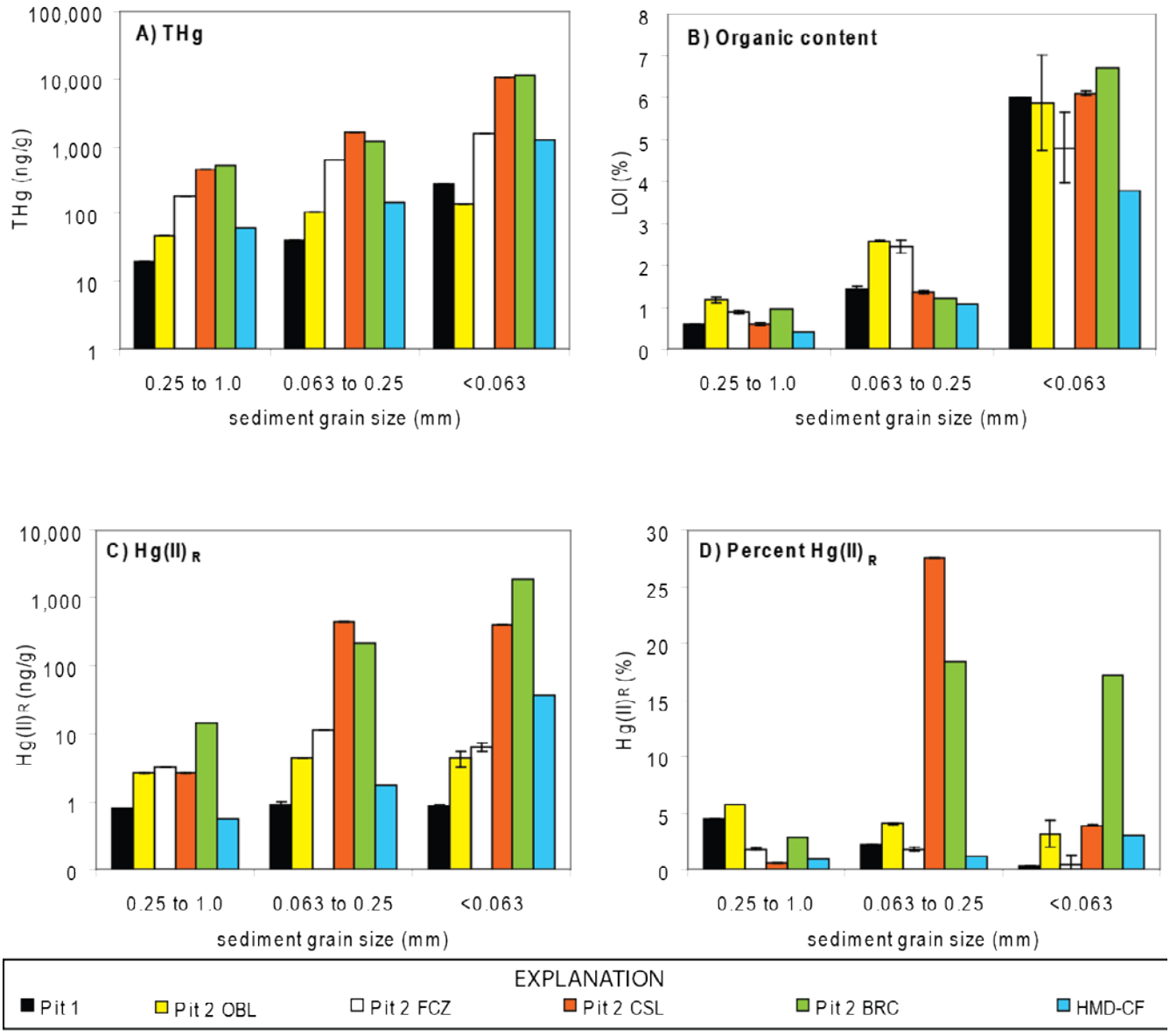


Figure 24. Bar graphs showing sediment concentrations of mercury species and organic content in three size fractions of excavated sediment collected during September 2008 in the South Yuba River–Humbug Creek, California, confluence area: (A) Total mercury (THg), (B) loss on ignition (LOI), (C) reactive mercury ($Hg(II)_R$), and (D) the percentage of THg as $Hg(II)_R$.

Table 6A. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Sediment excavated during September 2008.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Depth interval / sample type	Size fraction (mm)	% dry wt		% LOI		THg (ng/g)		THg	$Hg(II)_R$ (ng/g)		$Hg(II)_R$	$Hg(II)_R$ (%)	
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-200	16-Sep-08	Pit 1 (0 to 2 feet)	excavated	0.25-1.0	77.2	0.3	0.6	0.1	16	5	3	1.1	nd	1	7.0	2.2
SYH-201	16-Sep-08	Pit 1 (2 to 3 feet)	excavated	0.25-1.0	77.6	0.0	0.6	0.0	24	16	6	0.5	nd	1	2.1	1.4
SYH-101	16-Sep-08	Pit 1 (0 to 3 feet)	excavated	0.063-0.25	71.2	0.1	1.4	0.1	41	16	5	0.9	0.1	2	2.2	0.9
SYH-003	16-Sep-08	Pit 1 (0 to 3 feet)	excavated	<0.063	58.9	0.1	6.0	0.1	276	15	2	0.9	nd	1	0.3	0.0
SYH-202	17-Sep-08	Pit 2 OBL	excavated	0.25-1.0	84.8	0.6	1.2	nd	47	13	3	2.7	nd	1	5.8	1.7
SYH-102	17-Sep-08	Pit 2 OBL	excavated	0.063-0.25	65.7	0.6	2.6	0.1	108	22	4	4.4	nd	1	4.1	0.8
SYH-004	17-Sep-08	Pit 2 OBL	excavated	<0.063	59.1	0.4	5.9	0.0	139	34	2	4.4	nd	1	3.2	0.8
SYH-203	17-Sep-08	Pit 2 FCZ	excavated	0.25-1.0	75.7	0.0	0.9	0.1	180	61	3	3.2	0.6	2	1.8	0.7
SYH-103	17-Sep-08	Pit 2 FCZ	excavated	0.063-0.25	64.3	0.4	2.4	0.0	635	132	5	11.4	nd	1	1.8	0.4
SYH-005	17-Sep-08	Pit 2 FCZ	excavated	<0.063	55.3	0.1	4.8	1.1	1,550	12	2	6.5	nd	1	0.4	0.0
SYH-204	17-Sep-08	Pit 2 CSL	excavated	0.25-1.0	71.9	0.2	0.6	0.0	455	103	3	2.7	nd	1	0.6	0.1
SYH-104	17-Sep-08	Pit 2 CSL	excavated	0.063-0.25	66.5	0.5	1.4	0.2	1,630	nd	1	448	47.5	2	27.5	2.9
SYH-006	17-Sep-08	Pit 2 CSL	excavated	<0.063	46.2	0.0	6.1	0.9	10,500	414	3	414	nd	1	3.9	0.2
SYH-205	17-Sep-08	Pit 2 BRC	excavated	0.25-1.0	75.0	0.1	1.0	0.0	515	233	5	14.7	nd	1	2.8	1.3
SYH-106	17-Sep-08	Pit 2 BRC	excavated	0.063-0.25	67.2	0.2	1.2	0.0	1,150	263	4	212	nd	1	18.3	4.2
SYH-007	17-Sep-08	Pit 2 BRC	excavated	<0.063	45.1	0.0	6.7	0.1	11,100	nd	1	1,910	nd	1	17.2	0.0
SYH-206	18-Sep-08	Pit 1 (3 to 3.5 feet)	dredged sediment	0.25-1.0	76.4	0.2	0.8	0.1	42	29	6	0.3	nd	1	0.7	0.5
SYH-108	18-Sep-08	Pit 1 (3 to 3.5 feet)	dredged sediment	0.063-0.25	70.9	0.2	1.1	0.1	29	3	2	0.6	nd	1	2.0	0.2

Table 6A. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Sediment excavated during September 2008.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Depth interval / sample type	Size fraction (mm)	% dry wt	% dry wt	% LOI	% LOI	THg (ng/g)	THg (ng/g)	THg	$Hg(II)_R$ (ng/g)	$Hg(II)_R$ (ng/g)	$Hg(II)_R$	$Hg(II)_R$ (%)	$Hg(II)_R$ (%)
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-008	18-Sep-08	Pit 1 (3 to 3.5 feet)	Dredged sediment	<0.063	58.1	0.3	3.5	0.1	225	11	2	2.2	nd	1	1.0	0.0
na	18-Sep-08	River water near Pit 1	suspended sediment	0.0003 to 0.063	nd	nd	nd	nd	211	nd	2	nd	nd	nd	nd	nd
na	18-Sep-08	Recirculation tank pre-dredge background	suspended sediment	0.0003 to 0.063	nd	nd	nd	nd	635	29	2	nd	nd	nd	nd	nd
na	18-Sep-08	Recirculation tank, dredge 1st flush	suspended sediment	0.0003 to 0.063	nd	nd	nd	nd	407	63	2	8.6	0.2	2	2.1	0.3
na	18-Sep-08	Recirculation tank, 16 hours post-dredge	suspended sediment	0.0003 to 0.063	nd	nd	nd	nd	820	84	2	33.5	0.8	2	4.1	0.4
na	18-Sep-08	Recirculation tank, 40 hours post-dredge	suspended sediment	0.0003 to 0.063	nd	nd	nd	nd	952	15	2	48.2	0.9	2	5.1	0.1
SYH-207	18-Sep-08	HMD-CF	excavated	0.25-1.0	75.0	0.0	0.4	0.0	62	5	3	0.6	nd	1	0.9	0.1
SYH-109	18-Sep-08	HMD-CF	excavated	0.063-0.25	68.4	0.5	1.1	0.0	143	23	5	1.7	nd	1	1.2	0.2
SYH-009	18-Sep-08	HMD-CF	excavated	<0.063	61.5	0.0	3.8	1.3	1,200	102	2	37.5	7.5	2	3.1	0.7

Table 6B. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Surface and bed sediment samples collected during September 2008 and January 2009.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Sample type	Size fraction (mm)	% dry wt	% dry wt	% LOI	% LOI	THg (ng/g)	THg (ng/g)	THg	$Hg(II)_R$ (ng/g)	$Hg(II)_R$ (ng/g)	$Hg(II)_R$	$Hg(II)_R$ (%)	$Hg(II)_R$ (%)
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-302	13-Jan-09	Lake City Tunnel outlet	surface sediment	>1.0	15.7	0.1	66.6	1.8	710	9	2	nd	nd	nd	nd	nd
SYH-210	13-Jan-09	Lake City Tunnel outlet	surface sediment	0.25-1.0	21.5	0.2	32.5	0.2	707	56	2	nd	nd	nd	nd	nd
SYH-113	13-Jan-09	Lake City Tunnel outlet	surface sediment	0.063-0.25	26.4	0.0	18.1	0.5	563	13	2	nd	nd	nd	nd	nd
SYH-012	13-Jan-09	Lake City Tunnel outlet	surface sediment	<0.063	61.9	1.3	12.3	0.4	506	4	2	nd	nd	nd	nd	nd
SYH-301	13-Jan-09	Humbug Creek	bed sediment	>1.0	87.4	0.4	1.7	0.4	19	3	2	nd	nd	nd	nd	nd
SYH-209	13-Jan-09	Humbug Creek	bed sediment	0.25-1.0	74.4	0.3	1.8	0.0	48	3	2	nd	nd	nd	nd	nd
SYH-112	13-Jan-09	Humbug Creek	bed sediment	0.063-0.25	69.8	0.7	2.7	0.0	131	10	2	nd	nd	nd	nd	nd
SYH-011	13-Jan-09	Humbug Creek	bed sediment	<0.063	66.5	0.9	9.1	0.4	487	23	2	nd	nd	nd	nd	nd
SYH-300	18-Sep-08	South Yuba River upstream from Humbug Creek	bed sediment	>1.0	87.4	0.2	1.4	0.6	15	0	2	nd	nd	nd	nd	nd
SYH-208	18-Sep-08	South Yuba River upstream from Humbug Creek	bed sediment	0.25-1.0	75.9	0.2	0.7	0.0	26	1	2	nd	nd	nd	nd	nd
SYH-111	18-Sep-08	South Yuba River upstream from Humbug Creek	bed sediment	0.063-0.25	63.6	0.8	2.1	0.0	127	9	2	nd	nd	nd	nd	nd
SYH-010	18-Sep-08	South Yuba River upstream from Humbug Creek	bed sediment	<0.063	49.3	0.4	10.0	0.1	535	19	2	nd	nd	nd	nd	nd
SYH-212	13-Jan-09	North Bloomfield Tunnel airshaft	surface sediment	0.25-1.0	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd

Table 6B. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Surface and bed sediment samples collected during September 2008 and January 2009.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Sample type	Size fraction (mm)	% dry wt	% dry wt	% LOI	% LOI	THg (ng/g)	THg (ng/g)	THg	$Hg(II)_R$ (ng/g)	$Hg(II)_R$ (ng/g)	$Hg(II)_R$	$Hg(II)_R$ (%)	$Hg(II)_R$ (%)
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-115	13-Jan-09	North Bloomfield Tunnel airshaft	surface sediment	0.063-0.25	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
SYH-016	13-Jan-09	North Bloomfield Tunnel airshaft	surface sediment	<0.063	32.9	0.0	10.1	0.0	2,520	516	2	nd	nd	nd	nd	nd
SYH-211	13-Jan-09	North Bloomfield Tunnel outlet	surface sediment	0.25-1.0	26.6	0.0	16.7	0.2	206	11	2	nd	nd	nd	nd	nd
SYH-114	13-Jan-09	North Bloomfield Tunnel outlet	surface sediment	0.063-0.25	25.1	0.3	15.8	0.0	268	7	2	nd	nd	nd	nd	nd
SYH-013	13-Jan-09	North Bloomfield Tunnel outlet	surface sediment	<0.063	47.7	0.2	10.0	0.8	137	9	2	nd	nd	nd	nd	nd

Table 6C. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Surface and bed sediment samples collected during March and May 2009.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Sample Type	Size fraction (mm)	% dry wt	% dry wt	% LOI	% LOI	THg (ng/g)	THg (ng/g)	THg	$Hg(II)_R$ (ng/g)	$Hg(II)_R$ (ng/g)	$Hg(II)_R$	$Hg(II)_R$ (%)	$Hg(II)_R$ (%)
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-213	27-Mar-09	Humbug Creek	time-integrated	0.25-1.0	63.8	0.0	3.8	0.0	79	nd	1	nd	nd	nd	nd	nd
SYH-116	27-Mar-09	Humbug Creek	time-integrated	0.063-0.25	54.9	0.4	5.1	0.0	472	106	2	nd	nd	nd	nd	nd
SYH-017	27-Mar-09	Humbug Creek	time-integrated	< 0.063	65.9	0.5	7.0	0.1	360	21	2	nd	nd	nd	nd	nd
SYH-214	27-Mar-09	South Yuba River downstream from Humbug Creek	time-integrated	0.25-1.0	68.9	0.6	1.9	0.0	31	nd	1	nd	nd	nd	nd	nd
SYH-117	27-Mar-09	South Yuba River downstream from Humbug Creek	time-integrated	0.063-0.25	47.9	nd	3.9	nd	243	nd	1	nd	nd	nd	nd	nd
SYH-018	27-Mar-09	South Yuba River downstream from Humbug Creek	time-integrated	< 0.063	56.0	0.7	9.7	0.0	230	1	2	nd	nd	nd	nd	nd
SYH-215	27-Mar-09	South Yuba River upstream from Humbug Creek	time-integrated	0.25-1.0	76.3	0.5	1.1	0.0	29	nd	1	nd	nd	nd	nd	nd
SYH-118	27-Mar-09	South Yuba River upstream from Humbug Creek	time-integrated	0.063-0.25	27.9	2.9	12.1	2.0	167	nd	1	nd	nd	nd	nd	nd

Table 6C. Concentration data for mercury, reactive mercury(II), and other constituents in bed sediment and suspended sediment, South Yuba River and Humbug Creek, Nevada County, California: Surface and bed sediment samples collected during March and May 2009.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2; n=2 for all dry wt and LOI measurements. OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; ng/g, nanogram per gram; wt, weight; LOI, loss on ignition; THg, total mercury; $Hg(II)_R$, reactive mercury(II); sed, sediment; AVG, average; N, number of replicate analyses; DEV, deviation; mm, millimeter; <, less than; >, greater than; %, percent; nd, not determined]

Lab code	Date collected	Location	Sample Type	Size fraction (mm)	% dry wt	% dry wt	% LOI	% LOI	THg (ng/g)	THg (ng/g)	THg	$Hg(II)_R$ (ng/g)	$Hg(II)_R$ (ng/g)	$Hg(II)_R$	$Hg(II)_R$ (%)	$Hg(II)_R$ (%)
					AVG	DEV	AVG	DEV	AVG	DEV	N	AVG	DEV	N	AVG	DEV
SYH-019	27-Mar-09	South Yuba River upstream from Humbug Creek	time-integrated	< 0.063	35.9	nd	nd	nd	263	nd	1	nd	nd	nd	nd	nd
SYH-021	5-May-09	Humbug Creek	storm, grab	0.0003 to 0.063	nd	nd	nd	nd	417	237	3	15.0	0.5	3	5.1	0.7
SYH-022	5-May-09	South Yuba River downstream from Humbug Creek	storm, grab	0.0003 to 0.063	nd	nd	nd	nd	223	48	3	7.9	1.9	3	3.4	0.4
SYH-023	5-May-09	South Yuba River at Edwards Crossing	storm, grab	0.0003 to 0.063	nd	nd	nd	nd	279	43	3	10.3	1.5	3	3.9	0.8
SYH-020	5-May-09	South Yuba River upstream from Humbug Creek	storm, grab	< 0.063	nd	nd	nd	nd	136	2	2	nd	nd	nd	nd	nd
SYH-021	5-May-09	Humbug Creek	storm, grab	< 0.063	nd	nd	nd	nd	139	3	2	nd	nd	nd	nd	nd
SYH-022	5-May-09	South Yuba River downstream from Humbug Creek	storm, grab	< 0.063	nd	nd	nd	nd	139	7	2	nd	nd	nd	nd	nd
SYH-023	5-May-09	South Yuba River at Edwards Crossing	storm, grab	< 0.063	nd	nd	nd	nd	145	nd	1	nd	nd	nd	nd	nd

Recirculation-Tank Experiment

Background concentrations of THg and TSS in the South Yuba River were low at the start of the recirculation-tank experiment (table 7), similar to previous measurements of the South Yuba River during low-flow conditions in October 2007 (table 4). Contamination from the tank was determined to be minimal because the addition of river water to the tank did not substantially increase any of the measured concentrations (THg or TSS) above the background river-water concentrations (table 7).

Concentrations of pTHg and TSS were highest during the initial operation of the venturi dredge, with "first flush" concentrations of 42 ng/L and 95 mg/L, respectively, and decreased with time over the next 40 hours (table 7, fig. 25). The corresponding THg concentration associated with suspended-sediment particles (THg_{SS}) was 407 ng/g at first flush and subsequently increased over time to 820 ng/g at 16 hours and 952 ng/g at 40 hours (table 6A). Similarly, the $Hg(II)_R$ concentration associated with suspended particles ($Hg(II)_{R\text{-}SS}$) increased from 9 ng/g at first flush to 33 ng/g at 16 hours and 48 ng/g at 40 hours (table 6A). In contrast, the concentration of $pHg(II)_R$ stayed relatively constant over time (0.75 ng/L at first flush, 1.1 ng/L after 16 hours, and 0.79 ng/L after 40 hours). However, the $\%Hg(II)_R$, calculated from either pTHg and $pHg(II)_R$ (as nanograms per liter) or THg_{SS} (as nanograms per gram), increased over time (tables 6A, 7, fig. 26). These trends reflect the fact that relatively coarse-grained particles with relatively low THg_{SS} and $Hg(II)_{R\text{-}SS}$ concentrations (on a nanogram per gram basis) tend to settle out of the water column more quickly than finer-grained (silt-clay sized) particles with comparatively higher concentrations of THg_{SS} and $Hg(II)_{R\text{-}SS}$ (on a nanogram per gram basis). Thus, concentrations of both pTHg and $pHg(II)_R$ in the water column (as nanograms per liter) decreased with time; THg_{SS} and $Hg(II)_{R\text{-}SS}$ concentrations of the suspended sediment (as nanograms per gram) increased over time.

Table 7. Concentration data for mercury species and suspended sediment in water during 2008 and 2009.

[Note: DEV is calculated as |X1-X2|/2 where n = 2 and the standard deviation where n >2. TSS, total suspended sediment; THg, total mercury; $Hg(II)_R$, reactive mercury(II); AVG, average; DEV, devation; mg/L, milligrams per liter; ng/L, nanograms per liter; nd, not determined]

Sample	TSS (mg/L) AVG	TSS (mg/L) DEV	Particulate THg (ng/L) AVG	Particulate THg (ng/L) DEV	Particulate $Hg(II)_R$ (ng/L) AVG	Particulate $Hg(II)_R$ (ng/L) DEV	Percent $Hg(II)_R$ (%) AVG
A. Recirculation Tank Experiment, September 2008							
South Yuba River water	0.8	nd	1.3	nd	nd	nd	nd
Pre-dredge background	2.2	0.05	1.0	0.3	nd	nd	nd
Dredge first flush	95	11	42	6.9	0.75	0.09	1.8
20 hours post-dredge	33	2.7	28	1.1	1.1	0.05	3.9
40 hours post-dredge	18	2.7	19	1.8	0.79	0.01	4.2
B. Storm event, May 5, 2009							
Humbug Creek	135	38	43	1.1	2.2	0.32	5.1
South Yuba River downstream from Humbug Creek	75	12	17	1.5	0.56	0.05	3.4
South Yuba River at Edwards Crossing	42	2.5	11	2.1	0.44	0.03	3.9

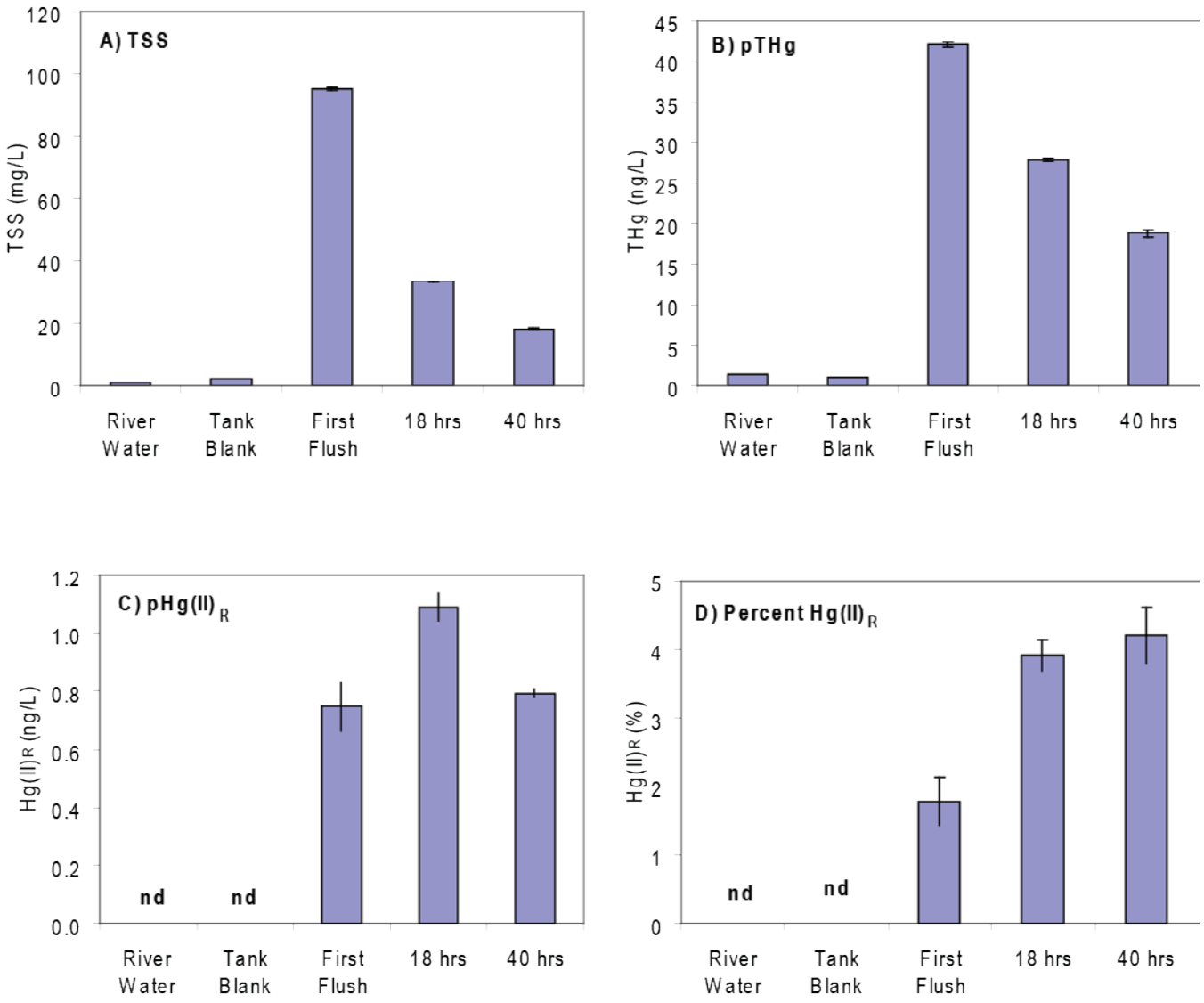


Figure 25. Bar graphs showing volumetric concentrations of (A) total suspended sediment, (B) particulate total mercury concentration, (C) reactive mercury concentration, and (D) percent reactive mercury for samples associated with the September 2008 recirculation-tank experiment, South Yuba River, California. nd, not determined.

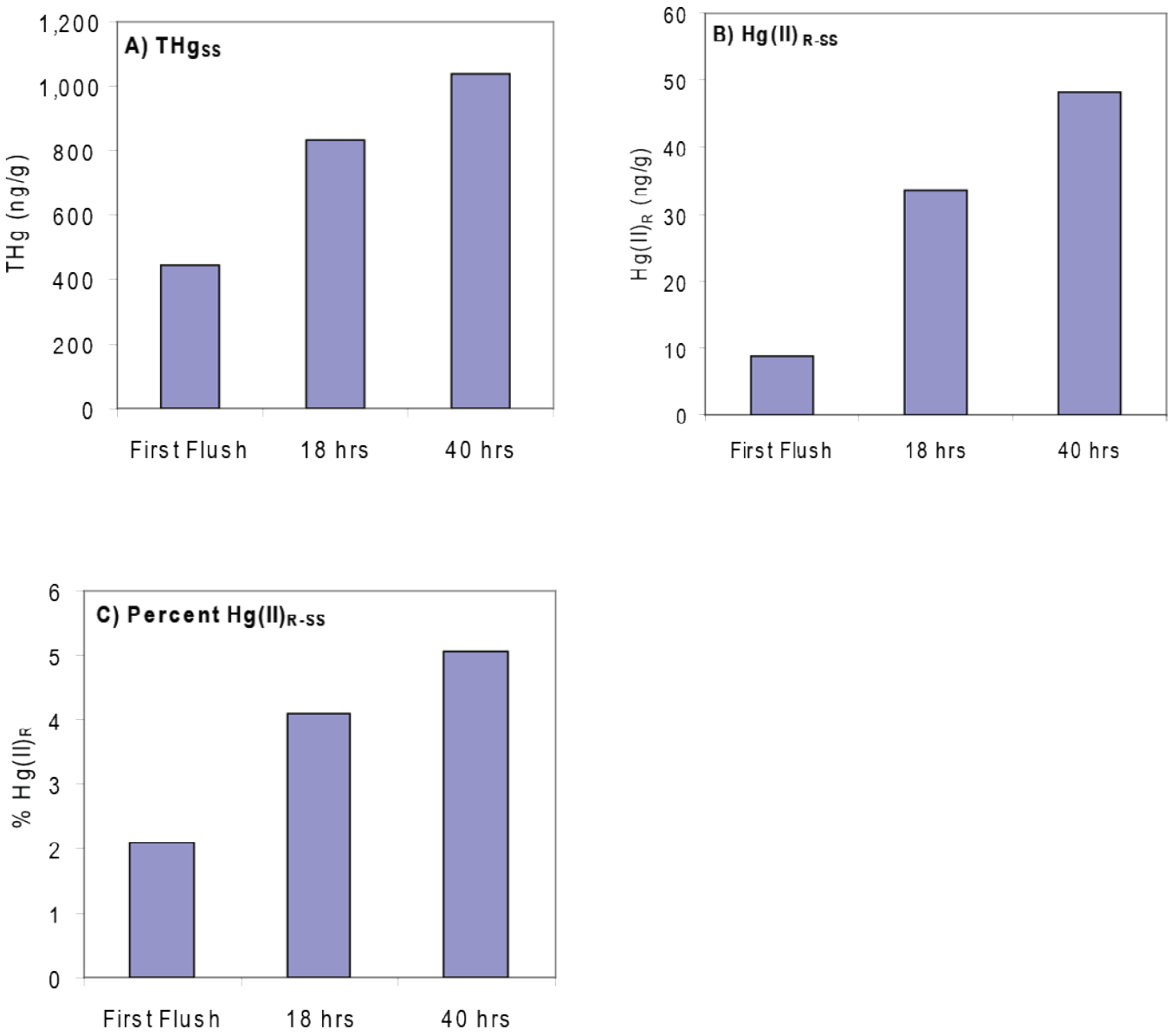


Figure 26. Bar graphs showing (A) total mercury concentration, (B) reactive mercury concentration, and (C) percent reactive mercury for samples associated with the September 2008 recirculation-tank experiment, South Yuba River, California.

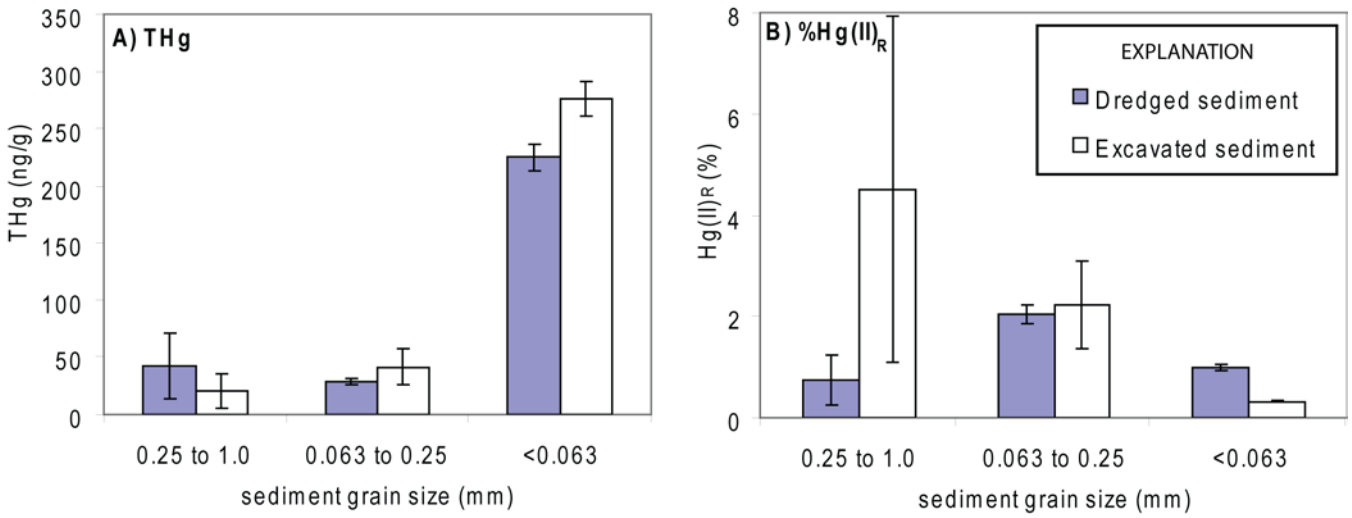


Figure 27. Bar graph showing (A) concentration of total mercury, and (B) percentage of total mercury as reactive mercury, for three particle-size fractions of sediment from Pit 1, 0-3 foot depth (hand excavated) and 3 to 3.5 foot depth (mobilized with venturi dredge into recirculation tank), South Yuba River.

Concentrations of THg were similar between hand-excavated material from Pit 1 (0 to 3 ft depth) and material removed by the venturi dredge from the bottom of Pit 1 (3 to 3.5 ft depth) in each of the three size fractions analyzed (fig. 27). The concentration of THg in the finest fraction (silt-clay, <0.063 mm) was somewhat lower in the pumped material that settled in the tank (225 ng/g) compared with the hand-excavated material (276 ng/g). A likely factor contributing to this difference is the tendency for the finest particles, which contained relatively elevated concentrations of THg (table 6), to remain suspended in overlying water of the recirculation tank. A higher degree of variability was observed in the largest particle-size fraction analyzed (coarse sand, 0.25 to 1.0 mm) with regard to concentrations of THg and $Hg(II)_R$, which is expected because of environmental sample heterogeneity, the "nugget effect" discussed earlier.

Sniping Assessment

Sniping revealed an elevated presence of Hg(0) and Hg-Au amalgam in the SYR-HC confluence area compared to locations both upstream and downstream from the SYR-HC confluence (table 8). Three of the four sniping locations in the SYR-HC delta area were rated "medium" or "high" with regard to Hg contamination on the basis of the relative abundance of liquid Hg(0), Hg-Au amalgam, and Hg-stained Au relative to "clean" Au (without visible Hg staining). One of the two upstream sniping locations had no visible Hg-bearing heavy minerals, and the other had a minor amount of visible Hg-Au amalgam; whereas, both locations had minor to moderate amounts of clean Au. Three of the four downstream sniping locations did not yield any heavy minerals, and the fourth was considered "low" with regard to Hg contamination on the basis of the recovery of approximately equal amounts of clean Au and Hg-stained Au and no visible Hg-Au amalgam or liquid Hg. The presence of clean Au and Hg-stained Au at all the sites where heavy minerals were recovered suggests that overall, Au was present in greater quantity than Hg.

Table 8. Results of sniping assessment and panning of heavy minerals, South Yuba River, California, September 2008.

[Note: Snipe locations are described in detail in Table 3. tsp, teaspoon; Au, gold; Hg, mercury; nr, no recovery of heavy minerals; 0, not observed; 1, minor; 2, moderate; 3, abundant]

Site #	Snipe location	Black sand (tsp)	Clean Au	Hg-stained Au	Hg-Au amalgam	Liquid Hg	Qualitative Hg contamination level
1	Near river bar at South Yuba River – Humbug Creek confluence	3	1	2	1	1	High
2	Near river bar at South Yuba River – Humbug Creek confluence	6	1	2	2	1	High
3	Near river bar at South Yuba River – Humbug Creek confluence	2	1	2	1	0	Medium
4	Near river bar at South Yuba River – Humbug Creek confluence	12	3	1	0	0	Low
5	South Yuba River downstream from Humbug Creek	0	1	1	0	0	Low
6	South Yuba River downstream from Humbug Creek	nr	nr	nr	nr	nr	nr
7	South Yuba River upstream from Humbug Creek	1	1-2	0	1	0	Low
8	South Yuba River upstream from Humbug Creek	3	1-2	0	0	0	Very Low
9	South Yuba River downstream from Humbug Creek	nr	nr	nr	nr	nr	nr
10	South Yuba River downstream from Humbug Creek	nr	nr	nr	nr	nr	nr

Sediment Source Assessment

The sediment source assessment focused on 1) the distribution of Hg in the suspended and bed sediment, and 2) the mineralogical and geochemical signature of the sediment fractions within the SYR-HC confluence area. Together, these measurements indicate the likely historical and modern sources of sediment containing elevated levels of Hg in the area.

Mercury Distribution

The time-integrated suspended-sediment samples, storm-event samples of suspended sediment, and samples collected from the bed surface and banks of Humbug Creek and the South Yuba River provide an indication of the speciation and concentration of Hg in sediment currently being supplied to the SYR-HC confluence area, as well as to downstream environments in the South Yuba River. Concentrations of THg on sediment—on the basis of various sampling methods for three sites, one within Humbug Creek and one each immediately upstream and downstream from the SYR-HC confluence—are presented for three particle-size ranges: 1) silt-clay fraction (< 0.063 mm, fig. 28A), 2) fine-sand fraction (0.063 to 0.25 mm, fig. 28B), and 3) coarse-sand fraction (0.25 to 1.0 mm, fig. 28C). Overall, THg concentrations were highest in the silt-

clay fraction, and lowest in the coarse-sand fraction. The time-integrated sediment collectors show lower THg concentrations in the silt-clay fraction compared with sediment collected from the streambed or streambanks. This is consistent with the expectation that the finest grained material (fine silt and clay) generally is not retained in the time-integrated collectors. The fine-grained, silt-clay fraction may have been transported downstream; however, there is the potential that some portion of this size fraction may also be deposited along the streambanks and in bed sediment during lower flow conditions.

Concentrations of THg in surficial (0 to 5-cm depth) bed sediment collected in the South Yuba River upstream from Humbug Creek were 535 ng/g in the silt-clay fraction and 127 ng/g in the fine-sand fraction. For comparison, concentrations of THg in a similar sample from Humbug Creek (collected at the footbridge just upstream from the SYR-HC confluence) were of similar magnitude: 487 and 131 ng/g in the same two respective size fractions (table 6B).

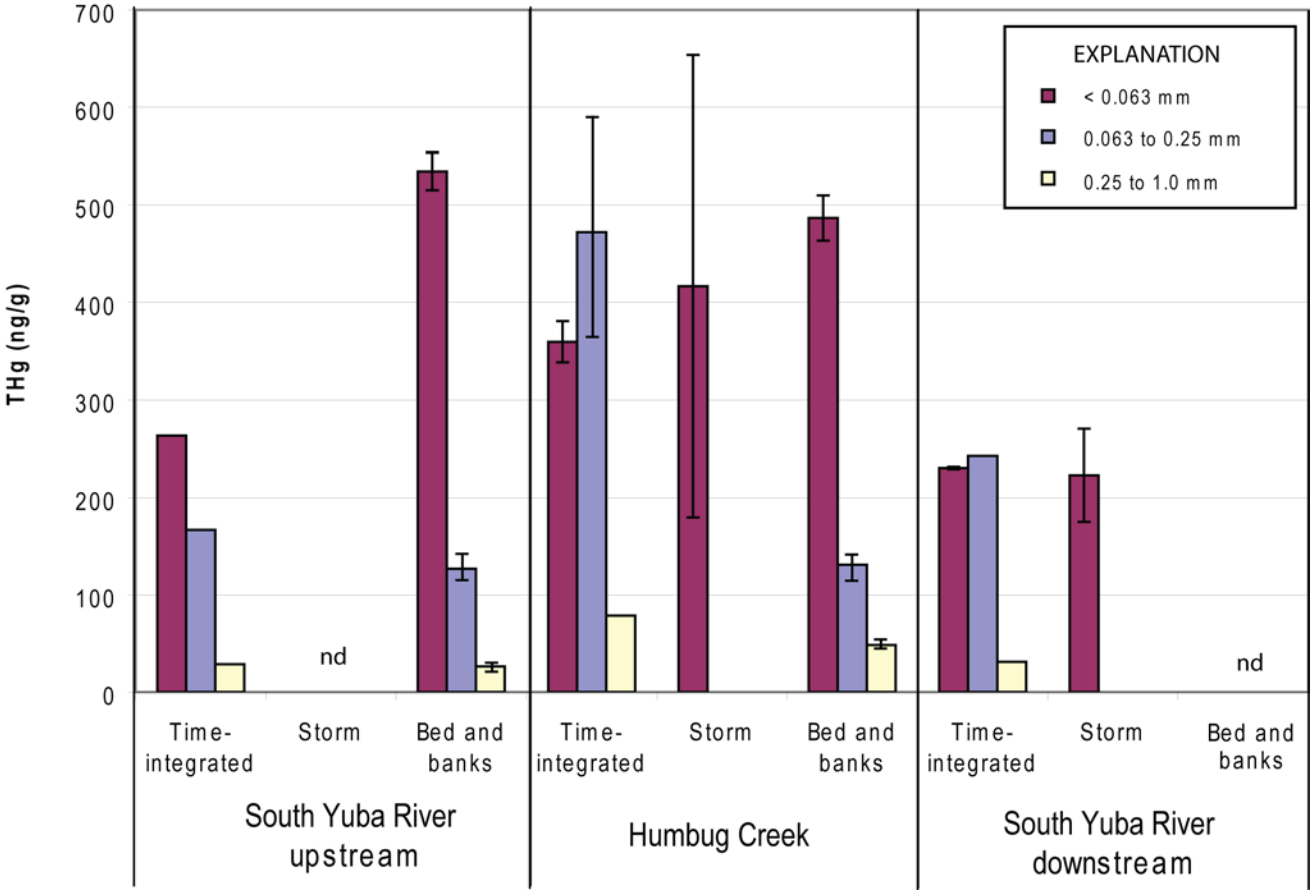


Figure 28. Bar graphs showing total mercury concentration in various samples of suspended sediment and excavated bed sediment grain-sizes collected from three areas: South Yuba River, California, upstream from the South Yuba River–Humbug Creek confluence, within Humbug Creek, and South Yuba River downstream from the confluence. nd, not determined.

Concentrations of THg in samples from the time-integrated sediment collectors in Humbug Creek were higher than samples from identical collectors at sites within the South Yuba River main channel, both upstream and downstream from the SYR-HC confluence. Concentrations of THg were 263 ng/g (silt-clay) and 167 ng/g (fine sand) in samples from South Yuba River upstream from the SYR-HC confluence, 360 ng/g (silt-clay) and 472 ng/g (fine sand) in samples from Humbug Creek, and 230 ng/g (silt-clay) and 243 ng/g (fine sand) in samples from the South Yuba River main channel downstream from the SYR-HC confluence (table 6C).

The concentration of THg in the suspended-sediment sample (0.0003 to 0.063 mm fraction) collected from Humbug Creek during the peak-flow storm event of May 5, 2009, was 417 ng/g compared to 223 ng/g from the South Yuba River just downstream from the confluence and 279 ng/g over 6 km downstream in the South Yuba River at Edwards Crossing (table 6C, fig. 29). The concentration trend mirrors the trend in particle-size distributions of material <0.063 mm with substantially more fines (clay-sized particles) in suspension in Humbug Creek than the South Yuba River (fig. 30). It is important to note that the samples collected on this date were instantaneous samples that may not represent the full range of concentrations at the sites throughout the duration of the peak-flow event.

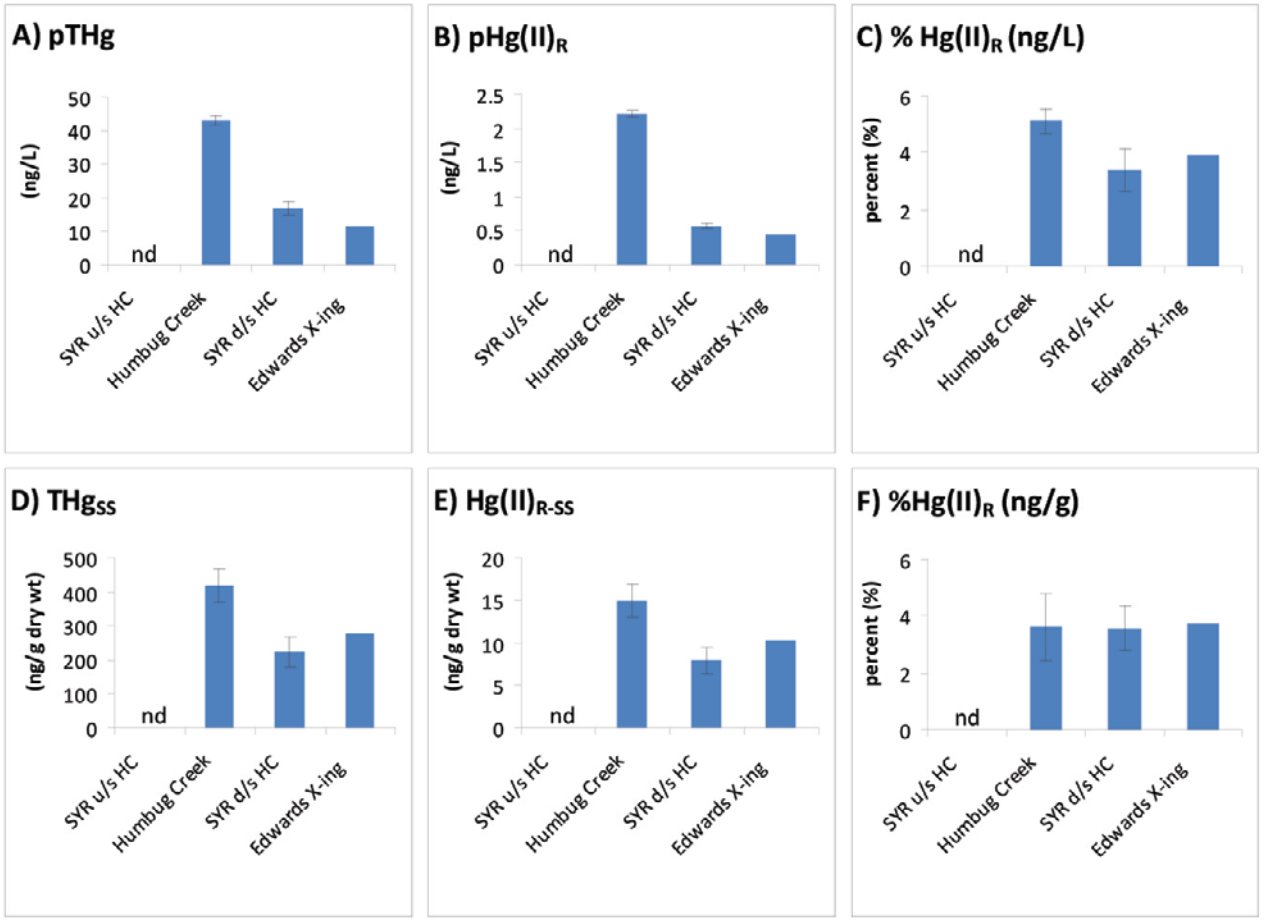


Figure 29. Bar graphs showing concentrations of mercury species in water and in suspended sediment collected from the South Yuba River and Humbug Creek, California, during a storm event on May 5, 2009: (A) Particulate total mercury (THg), volumetric basis, (B) Particulate reactive mercury(II) [$Hg(II)_R$], volumetric basis, (C) percentage of THg as $Hg(II)_R$, volumetric basis, (D) particulate THg, dry weight basis, (E) particulate $Hg(II)_R$, dry weight basis, and (F) percentage of THg as $Hg(II)_R$, dry weight basis. nd, not determined; u/s, upstream; d/s, downstream; HC, Humbug Creek; SYR, South Yuba River; X-ing, Crossing.

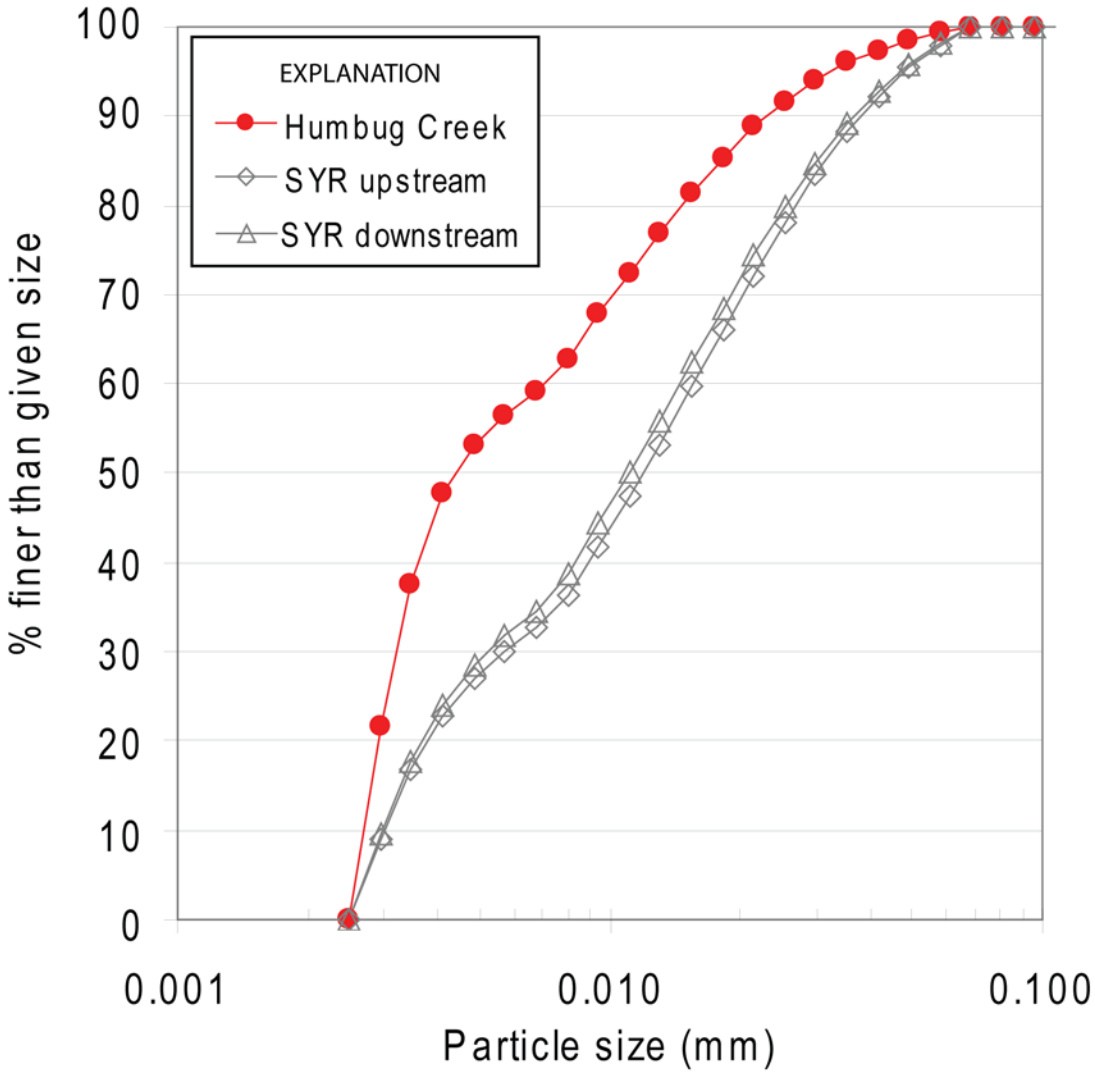


Figure 30. Log-linear plot of cumulative particle-size distribution, based on LISST-100X laboratory measurements, of the silt-clay-size (finer than 0.063 mm) suspended-sediment samples collected during a storm event on May 5, 2009, South Yuba River and Humbug Creek, California.

Sediment Provenance Based on Mineralogy

Quantitative mineralogical data for the sediment samples collected in this study were evaluated for their possible utility in distinguishing sediment sources within the study area. Detailed mineralogical data for three particle-size fractions (silt-clay, fine sand, and coarse sand) are provided for each sample in appendix 2 (table 2A-1). Mineral formulas are also shown in appendix 2 (table 2A-2). The data, as summarized in fig. 31, show that there are systematic variations in mineralogy as a function of particle size and location and that the presence or absence of certain minerals can be diagnostic for certain groups or types of sample.

Using the mineralogical data, provenance was assigned for a subset of bed, excavated, and suspended-sediment samples independently for each particle-size fraction using MinUnMix (Eberl, 2004). To calculate the provenance, three samples were assumed to be end-members: the two bed-sediment samples from South Yuba River upstream from Humbug Creek and from Humbug Creek and the excavated sample of HMD from the cliff face (fig. 31). Results of the calculation indicate that Pit 1 sediment (0 to 3 ft and 3 to 3.5 ft, from the recirculation-tank experiment) has mineralogical similarities to upstream South Yuba River sediment in both the silt-clay and coarse-sand fractions (fig. 32). It is not known why this relation did not appear to hold for the fine-sand fraction. The top two layers of Pit 2 had a strong affinity for Humbug Creek bed sediment in the silt-clay and fine-sand fractions, but this relation was not apparent in the coarse-sand fraction. The lower two layers of Pit 2 had a strong affinity for the HMD cliff face material in the fine-sand fraction (probably driven largely by quartz content, fig. 31), but this relation was not apparent in the other two size fractions.

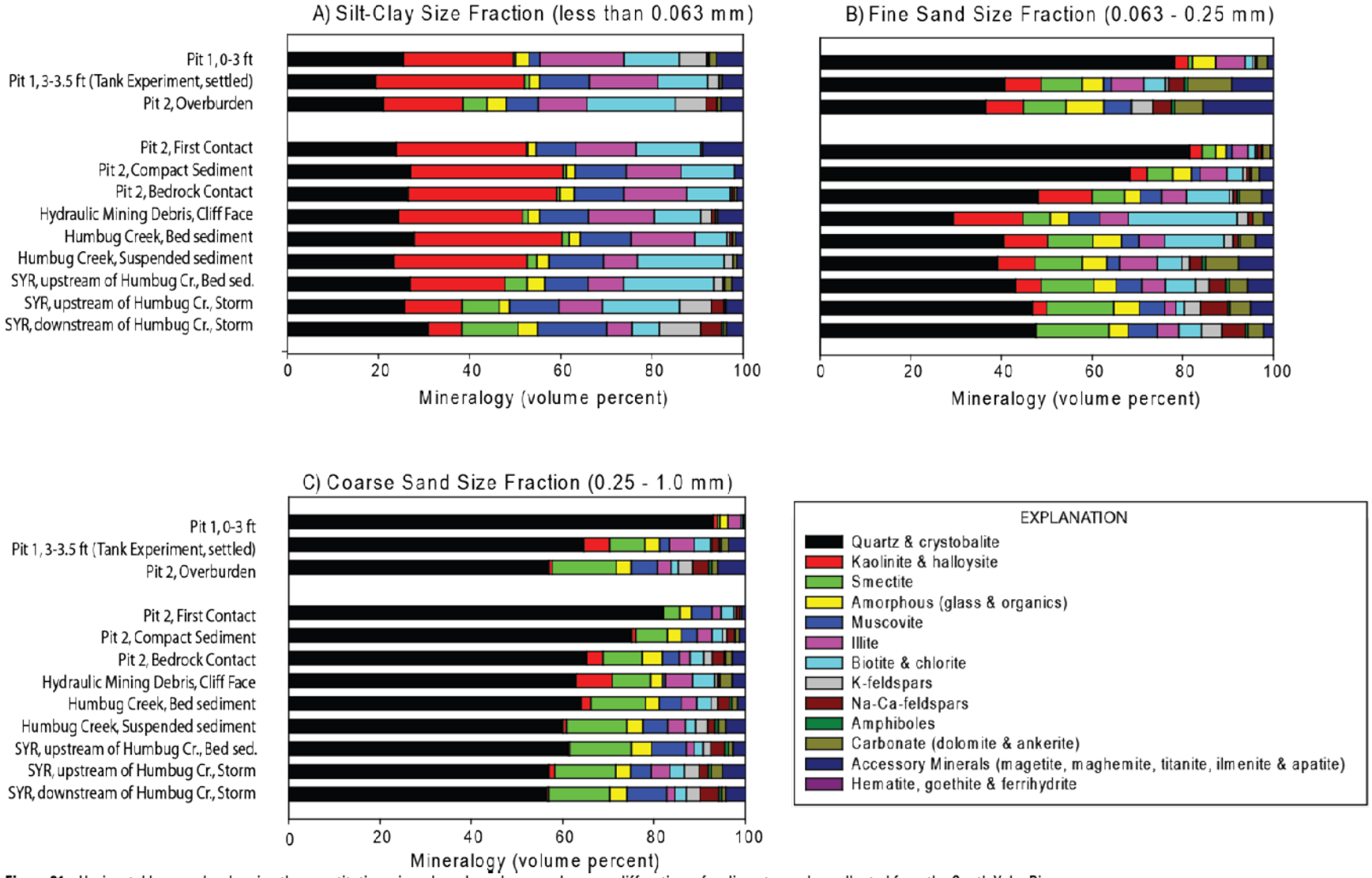


Figure 31. Horizontal bar graphs showing the quantitative mineralogy, based on powder x-ray diffraction, of sediment samples collected from the South Yuba River and Humbug Creek. (A) Silt-clay fraction (less than 0.063 mm), (B) fine-sand fraction (0.063 to 0.25 mm), and (C) coarse-sand fraction (0.25 to 1.0 mm)

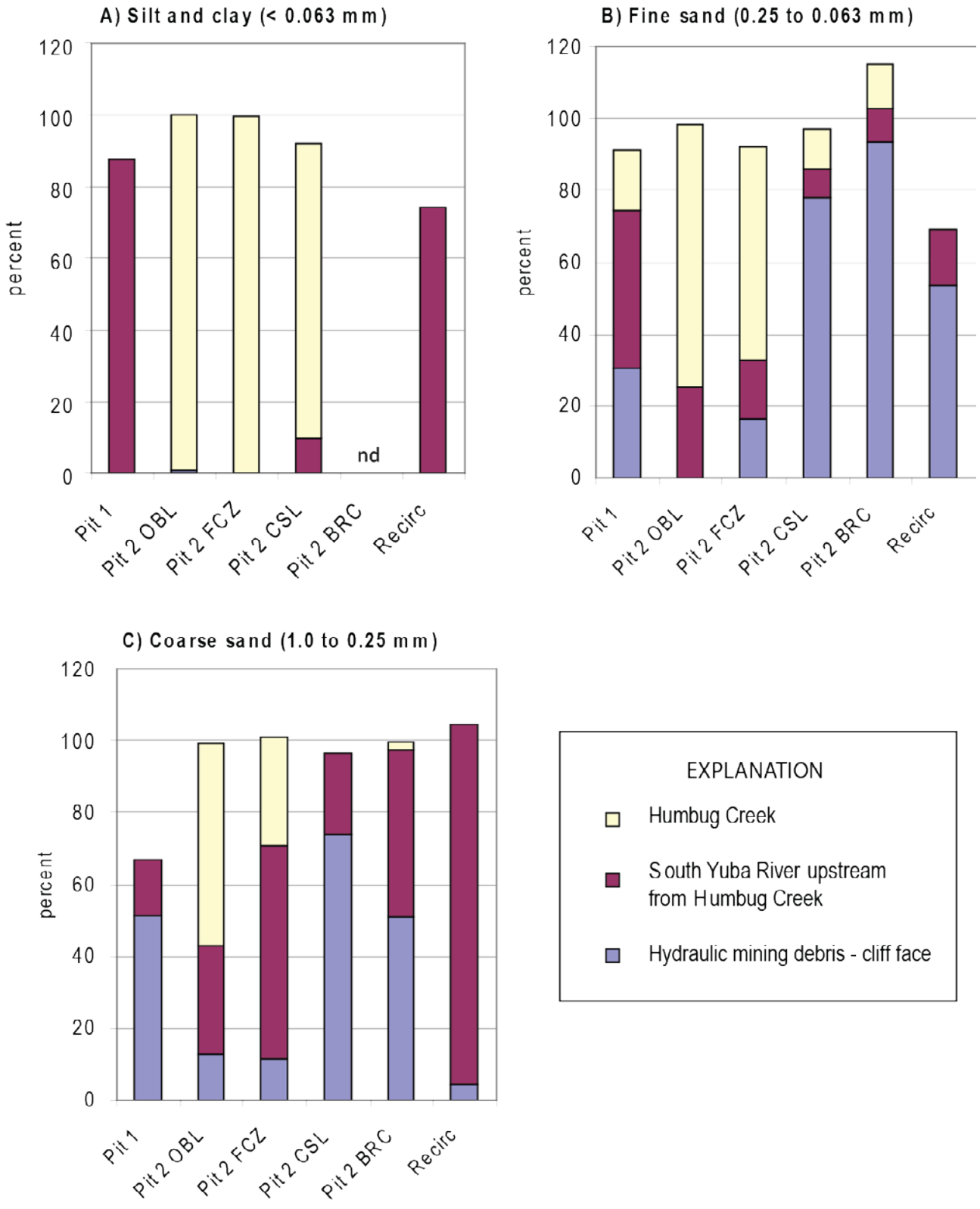


Figure 32. Bar graphs depicting the sediment provenance results as the relative proportions of assumed source materials in excavated sediment, calculated using MinUnMix (Eberl, 2004). (A) Silt-clay fraction (less than 0.063 mm), (B) fine-sand fraction (0.063 to 0.25 mm), and (C) coarse-sand fraction (0.25 to 1.0 mm). Vertical axis is proportion of three hypothesized end-members (see fig. 31 and text). nd, not determined.

The provenance results appear to be based largely on the relative abundance of quartz (SiO_2) and plagioclase (Na-Ca feldspar, $(Na,Ca)Al_{1-2},Si_{3-2}O_8$), which varied greatly across study sites and the sediment layers of Pit 2. Quartz was particularly abundant in the sand-size fractions associated with the HMD cliff face material and the lowest two layers of Pit 2 (fig. 31). Plagioclase is present at levels of at least 4.8% (by volume) in the silt-clay fraction (<0.063 mm) from the South Yuba River upstream from Humbug Creek and from Pit 1, but is present at concentrations <1.6% in all samples from Humbug Creek, all four layers of Pit 2, and HMD-CF (appendix 2: table 2A-1). Plagioclase abundance in the fine-sand and coarse-sand size fractions is relatively low in the three sediment samples that had both a large proportion of quartz and elevated Hg in the silt-clay fraction—the two lowest layers of Pit 2 and HMD-CF (fig. 31).

The provenance results provide a strong line of evidence indicating the relative abundance of HMD among the current local source mixtures in the sediment. Although there were no previous studies that quantitatively characterized mineralogical data on the basis of particle-size fractions <1 mm, quartz is known to be anomalously abundant in Tertiary auriferous gravel deposit (Goldman, 1961, 1964; Dupras and Chevreaux, 1984; James, 1993). The auriferous gravels that were the target of hydraulic mining in areas such as Malakoff Diggins, North Bloomfield, and Lake City in the Humbug Creek drainage were intensely weathered during the Eocene (about 50 million years before present), resulting in a low abundance of plagioclase, a mineral much more susceptible to chemical weathering than quartz. The ratio of quartz to plagioclase can be considered to be a weathering index whose value will increase with increased weathering. Another weathering index that is used in the geochemical literature is the ratio of aluminum (Al) to calcium (Ca). Ca tends to be removed from rock and soil during weathering (congruent behavior), whereas Al tends to form secondary clay minerals such as kaolinite ($Al_2Si_2O_5(OH)_4$). Both of these weathering indices show a distinct mineralogical and chemical signature to HMD, with elevated ratios of quartz to plagioclase and Al (as Al_2O_3) to Ca (as CaO) (appendix 2: table 2A−3). The relation of Hg to each of these weathering indices for sediment samples in this study is shown in figure 33. In both cases, the correlations are significant ($p<0.001$ and $p<0.0335$, respectively), based on Spearman Rank Order nonparametric statistics. This provides confirmation that the primary source of Hg in sediment from the Humbug Creek area is HMD. These ratios were recently used as indicators of HMD in sediment from San Francisco Bay (Bouse and others, 2010).

The use of the weathering ratios also removes the effects of particle size on the observed concentration trends, allowing comparison of the HMD signature across the different grain sizes. The cliff-face HMD and the lower two layers of Pit 2 (CSL and BRC, shown in red in figure 33), have the highest values of quartz/plagioclase for each particle-size fraction, and among the highest values of Al_2O_3/CaO. Samples from the upper two layers of Pit 2 (OBL and FCZ), from Humbug Creek, and from the South Yuba River downstream from Humbug Creek had intermediate values of both ratios, in most cases larger than values for samples from Pit 1 and from the South Yuba River upstream from Humbug Creek. Samples from the North Bloomfield Tunnel and from the airshaft on the Humbug Creek trail were anomalous with regard to these two ratios because of the high degree of chemical precipitate (hydrous iron and manganese oxides) that make up the modern sediment deposits associated with these underground mine workings.

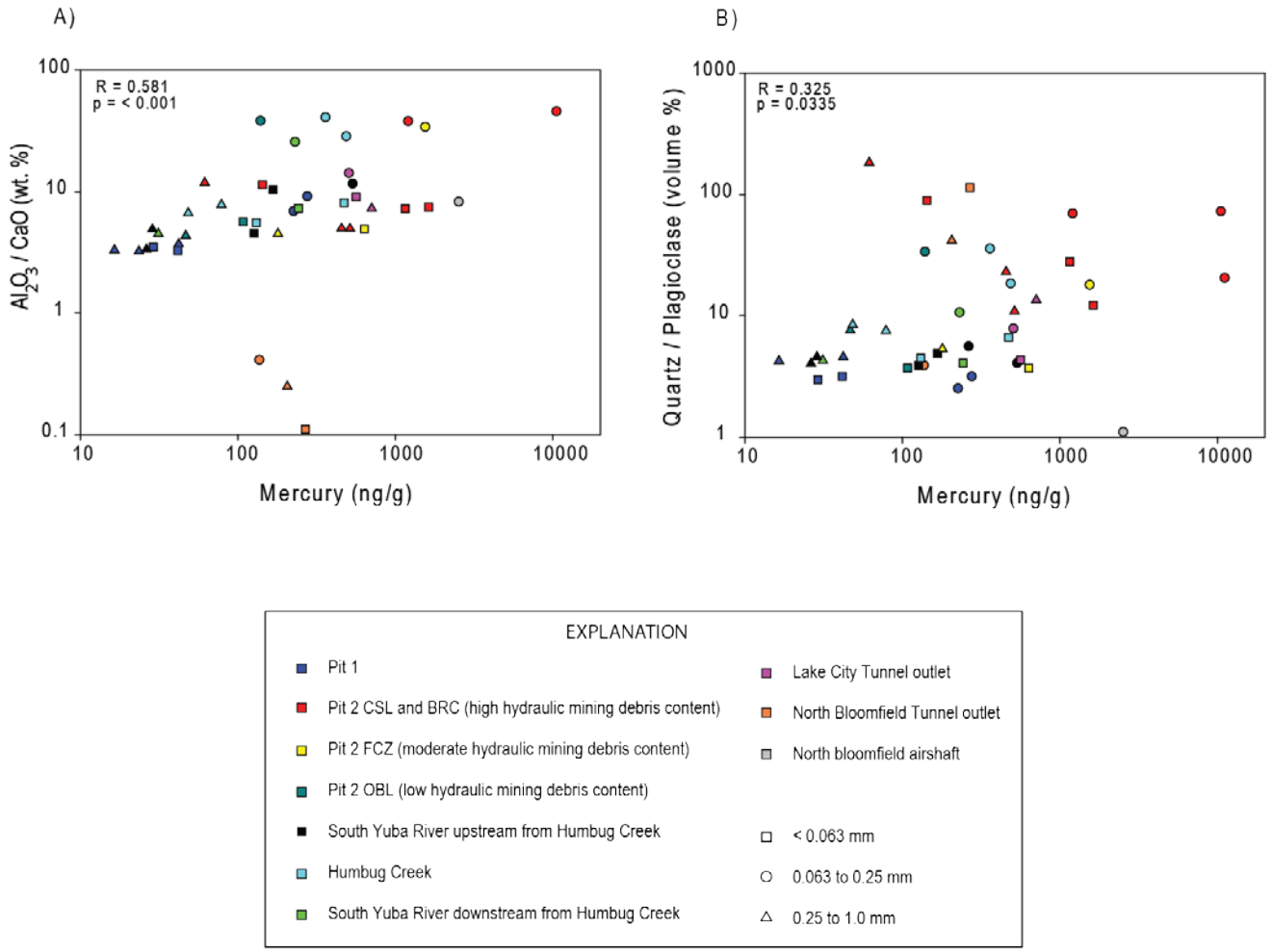


Figure 33. Correlation plots of total mercury concentration to ratios of (A) aluminum to calcium, and (B) quartz to plagioclase, in sediment from the South Yuba River–Humbug Creek, California, confluence area.

Microscopic Assessment of Heavy Minerals

Concentrates of heavy minerals from the 2007 dredge test and the 2008 excavations in the SYR-HC confluence area were examined with an optical microscope and SEM to characterize grains of Au and Hg-Au amalgam. In the concentrates from the 2007 dredge test, grains of Hg-Au amalgam of about 0.20 to 1.00 mm in diameter (medium to coarse-sand size) were made up of composites of smaller grains, commonly 0.020 to 0.050 mm in size (fig. 34A). The smaller individual grains of amalgam making up the composite grains may represent, in some cases, pseudomorphs—minerals that have taken the crystalline form of the original Au grains, some of which have visible crystal faces. Inspection of approximately 20 composite grains of Hg-Au amalgam recovered from the 2007 dredge test showed generally smooth surfaces with no visible beads of liquid Hg(0) (fig. 34B–D). Heavy mineral concentrates from the bedrock contact layer of Pit 2, excavated in 2008, also yielded composite grains of amalgam in the medium to coarse-sand size range (fig. 34E). Small spherules of Hg(0), ranging in size from 1 to 10 µm, were found on the surface of several of the amalgam grains (figs. 34F–H).

Biota Assessment

The invertebrate samples collected during 2007 had THg concentrations ranging from 0.020 to 0.190 µg/g (all concentrations are on a wet-weight basis) and MeHg concentrations ranging between 0.016 and 0.226 µg/g (Table 9). In samples collected in 2008, concentrations of THg ranged from 0.012 to 0.180 µg/g, with MeHg concentrations ranging from 0.010 to 0.133 µg/g. Both years, the taxon with the lowest mean MeHg and THg concentrations was the filter-feeding caddisfly (figs. 35 and 36, table 9), a taxon not collected from the reference site (BR-20) or from Humbug Creek (HUM-1). The water strider was the taxon with the highest MeHg and THg concentrations during both 2007 and 2008. There were significant variations among taxa for both Hg and MeHg concentrations (Hg: $F_{3,32.6} = 32.48$, $p<0.0001$; MeHg: $F_{3,33} = 41.15$, $p<0.0001$), with water striders having significantly higher concentrations than all other taxa (adjusted p-value < 0.0001). The next highest concentrations were found in stoneflies and dragonflies, which were not significantly different from one another for either THg or MeHg. Caddisflies had significantly lower MeHg concentrations than the other three taxa. However, THg concentrations in caddisflies were significantly lower than stoneflies but were not different from dragonflies.

Compared to the reference site upstream of mining impacts in the Bear River, samples of water striders from 2007 had two to seven times more MeHg (fig. 35). Concentrations of MeHg in water striders collected in 2008 were lower than those from 2007, but concentrations from all sites had higher concentrations than the reference (fig. 36). Stoneflies had higher MeHg concentrations at SYR-4 than at the reference site during both years, but the other sites were similar or somewhat lower than the reference, especially during 2008. At the two sites where dragonfly larvae were collected during 2007, Gomphidae from HUM-1 and SYR-7 were 2 and 5 times higher in MeHg, respectively, than the Aeshnidae from the reference site (fig. 35). In 2008 however, Gomphidae collected from all six sites were at the most twice (SYR-7) that of the reference site (fig. 36).

Although there was some evidence of variation among sites (Figs. 35 and 36), it was not as strong as year or taxa effects (Hg: $\chi^2 = 4.75$, df = 1, p=0.029; MeHg: $\chi^2 = 3.43$, df = 1, p = 0.064). The highest concentrations of MeHg in caddisflies both years were found at the site furthest downstream from Humbug Creek, South Yuba River at Edwards Crossing (SYR-7). The highest site-specific concentrations in water striders each year were found at SYR-1 (SYR-1a in 2008), upstream of the preliminary dredge test site (0.226 µg/g in 2007 and 0.133 µg/g in 2008).

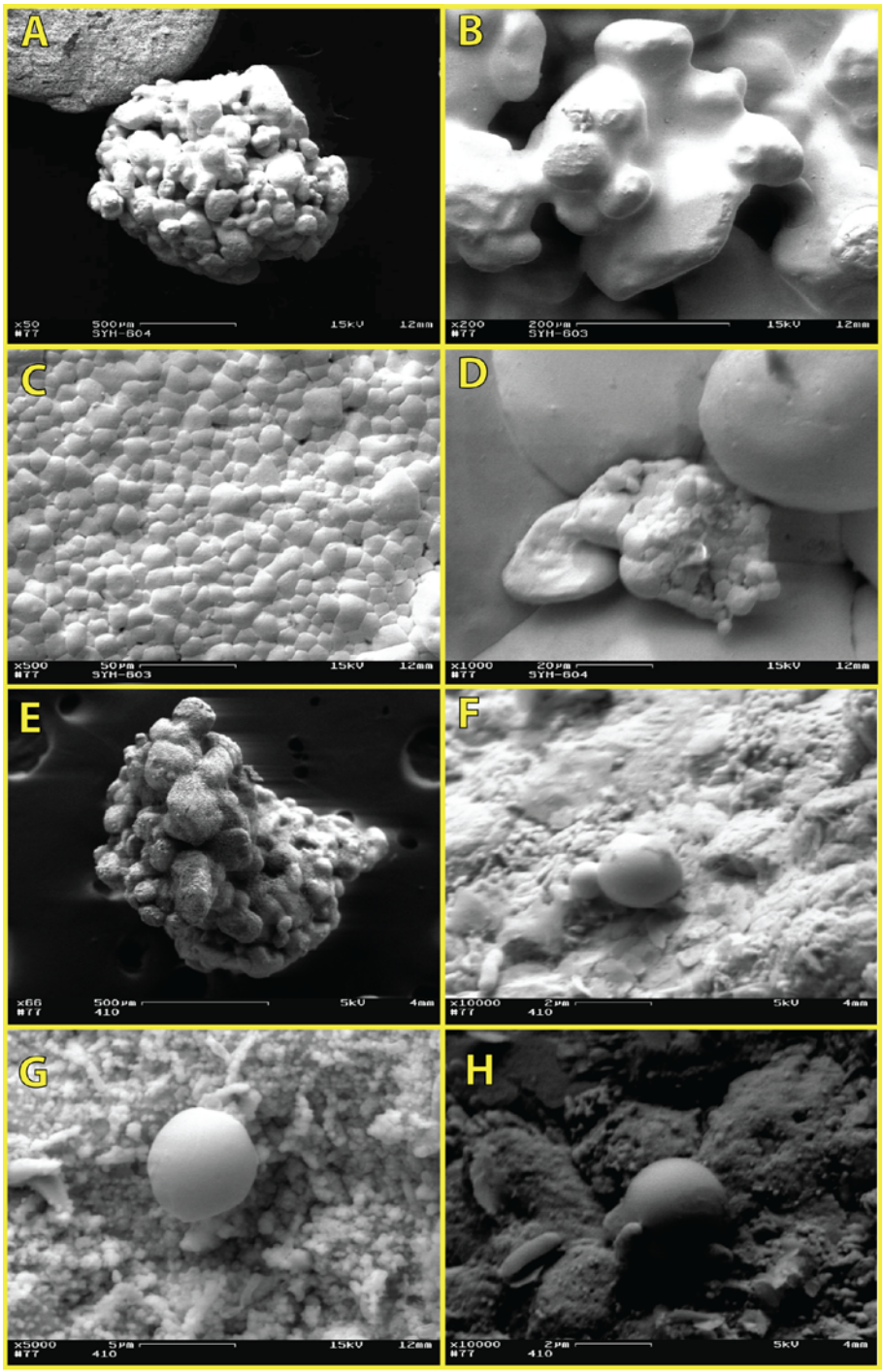


Figure 34. Photomicrographs from scanning electron microscope (secondary electron mode) showing grains of gold-mercury amalgam. (A–D) Samples from 2007 dredge test in South Yuba River. Scale bars in micrometers (µm). (A) Composite of amalgam grains, about 700 by 1,000 µm, from the third hour of the dredge test, (B) close-up of smooth amalgam surface, texture may represent pseudomorph of gold crystals approximately 100 µm in diameter, from the first 2 hours of the dredge test, (C) botryoidal texture on amalgam surface, from the first 2 hours of the dredge test, and (D) close-up view of smooth amalgam surface and finer-grained amalgam material. (E–H) Sample from Pit 2, bedrock contact with spherical beads of liquid elemental mercury (Hg(0)). (E) Composite of amalgam grains, approximately 700 by 1,000 µm, (F) beads of Hg(0) approximately 0.5 and 2 µm in diameter, (G) bead of Hg(0) approximately 5 µm in diameter, and (H) bead of Hg(0) approximately 2 µm in diameter.

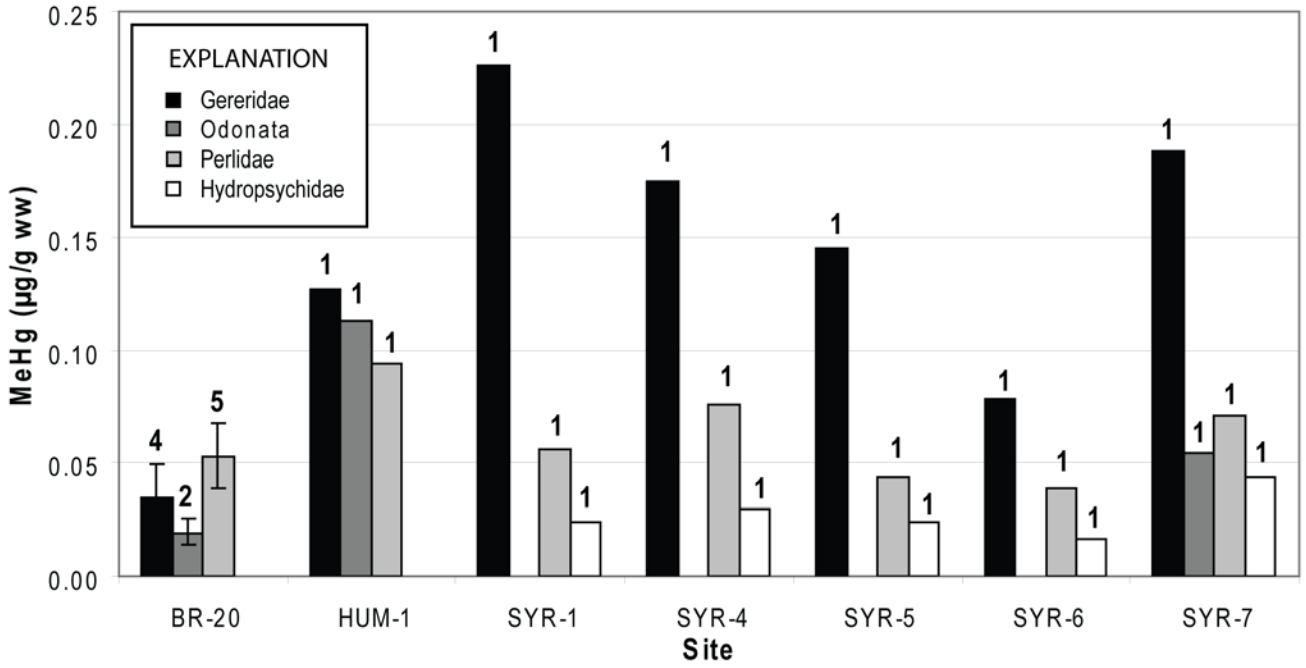


Figure 35. Bar graphs showing methylmercury (MeHg) concentrations for individual composite samples of adult water striders (Order Hemiptera, Family Gerridae), dragonfly larvae (Order Odonata, Family Gomphidae), stonefly larvae (Order Plecoptera, Family Perlidae), and caddisfly larvae (Order Tricoptera, Family Hydropsychidae) collected from the South Yuba River–Humbug Creek, California, confluence area during September 2007, and geometric mean MeHg concentrations in adult water striders, dragonfly larvae (Order Odonata, Family Aeshnidae), and stonefly larvae collected from the Bear River at Highway 20 (BR-20, Reference site) during 1999–2002. The numbers above the bars indicate the number of observations (n).

Table 9. Concentrations of total mercury and methylmercury in individual composites of biological samples collected at Humbug Creek and the South Yuba River, California, in September 2007 and September 2008.

[g, gram; No., number of individual oranisms in composite; ng/g, nanogram per gram; ww, wet weight; THg, total mercury; MeHg, methylmercury; %, percent; nd, not determined]

Unique Sample Code	Site identifier	Year	Order	Family	Age	No.	Total mass (g)	Ave. Mass (g)	% moisture	THg (ng/g ww)	MeHg (ng/g ww)
SYR6-091307-003	SYR-6	2007	Hemiptera	Gerridae	Adult	25	1.44	0.057	nd	96	78
SYR2-091307-003	SYR-2	2007	Hemiptera	Gerridae	Adult	25	1.13	0.045	nd	94	85
HUM1-091307-005	HUM-1	2007	Hemiptera	Gerridae	Adult	25	1.35	0.054	nd	116	127
SYR5-091307-003	SYR-5	2007	Hemiptera	Gerridae	Adult	23	1.32	0.057	nd	148	145
SYR3-091307-002	SYR-3	2007	Hemiptera	Gerridae	Adult	23	1.11	0.048	nd	137	165
SYR4-091307-003	SYR-4	2007	Hemiptera	Gerridae	Adult	30	1.60	0.053	nd	174	175
SYR7-091407-005	SYR-7	2007	Hemiptera	Gerridae	Adult	25	1.29	0.052	nd	190	188
SYR1-091307-003	SYR-1	2007	Hemiptera	Gerridae	Adult	17	0.97	0.057	nd	188	226
SYR3-091307-001	SYR-3	2007	Odonata	Libellulidae	Larva	3	1.24	0.413	nd	20	23
SYR2-091307-002	SYR-2	2007	Odonata	Libellulidae	Larva	3	1.19	0.397	nd	51	55
SYR7-091407-001	SYR-7	2007	Odonata	Gomphidae	Larva	3	1.15	0.383	nd	56	55
HUM1-091307-004	HUM-1	2007	Odonata	Gomphidae	Larva	5	0.88	0.176	nd	82	113
SYR6-091307-002	SYR-6	2007	Plecoptera	Perlidae	Larva	12	1.66	0.138	nd	37	39
SYR5-091307-002	SYR-5	2007	Plecoptera	Perlidae	Larva	8	1.22	0.153	nd	53	44
SYR1-091307-002	SYR-1	2007	Plecoptera	Perlidae	Larva	8	1.12	0.14	nd	53	56
SYR7-091407-003	SYR-7	2007	Plecoptera	Perlidae	Larva	8	1.47	0.184	nd	90	71
SYR4-091307-002	SYR-4	2007	Plecoptera	Perlidae	Larva	9	1.84	0.204	nd	77	76
HUM1-091307-002	HUM-1	2007	Plecoptera	Perlidae	Larva	15	1.67	0.111	nd	86	94
SYR6-091307-001	SYR-6	2007	Trichoptera	Hydropsychidae	Larva	80	0.58	0.007	nd	24	16
SYR1-091307-001	SYR-1	2007	Trichoptera	Hydropsychidae	Larva	100	0.59	0.006	nd	46	24
SYR5-091307-001	SYR-5	2007	Trichoptera	Hydropsychidae	Larva	75	0.34	0.005	nd	26	24
SYR4-091307-001	SYR-4	2007	Trichoptera	Hydropsychidae	Larva	100	0.53	0.005	nd	35	30
SYR7-091407-006	SYR-7	2007	Trichoptera	Hydropsychidae	Larva	90	0.42	0.005	nd	61	44
HUM1-091108-006	HUM-1	2008	Hemiptera	Gerridae	Adult	25	1.62	0.065	64.27	63	59
HUM1-091108-005	HUM-1	2008	Hemiptera	Gerridae	Adult	25	1.54	0.062	64.86	73	61

Table 9. Concentrations of total mercury and methylmercury in individual composites of biological samples collected at Humbug Creek and the South Yuba River, California, in September 2007 and September 2008.

[g, gram; No., number of individual oranisms in composite; ng/g, nanogram per gram; ww, wet weight; THg, total mercury; MeHg, methylmercury; %, percent; nd, not determined]

Unique Sample Code	Site identifier	Year	Order	Family	Age	No.	Total mass (g)	Ave. Mass (g)	% moisture	THg (ng/g ww)	MeHg (ng/g ww)
SYR1-091108-005	SYR-1	2008	Hemiptera	Gerridae	Adult	22	1.11	0.050	75.57	80	78
SYR6-091208-004	SYR-6	2008	Hemiptera	Gerridae	Adult	23	1.21	0.053	61.81	115	80
SYR4-091108-006	SYR-4	2008	Hemiptera	Gerridae	Adult	24	1.31	0.055	78.19	81	87
SYR7-091208-005	SYR-7	2008	Hemiptera	Gerridae	Adult	27	1.37	0.051	71.92	116	102
SYR1a-091108-004	SYR-1a	2008	Hemiptera	Gerridae	Adult	25	1.31	0.052	68.96	180	133
SYR4-091108-005	SYR-4	2008	Odonata	Gomphidae	Larva	8	0.99	0.124	nd	12	10
SYR1a-091108-003	SYR-1a	2008	Odonata	Gomphidae	Larva	10	1.12	0.112	82.9	26	17
SYR4-091108-003	SYR-4	2008	Odonata	Gomphidae	Larva	4	1.49	0.373	85.77	26	22
SYR1-091108-004	SYR-1	2008	Odonata	Gomphidae	Larva	10	1.65	0.165	85.27	30	26
SYR4-091108-004	SYR-4	2008	Odonata	Gomphidae	Larva	4	1.54	0.385	82.61	29	26
HUM1-091108-004	HUM-1	2008	Odonata	Gomphidae	Larva	4	1.07	0.268	86.65	32	30
SYR6-091208-002	SYR-6	2008	Odonata	Gomphidae	Larva	4	1.39	0.348	76.16	42	30
SYR7-091208-003	SYR-7	2008	Odonata	Gomphidae	Larva	4	1.54	0.385	84.91	47	35
SYR1-091108-003	SYR-1	2008	Odonata	Gomphidae	Larva	4	1.63	0.408	78.19	48	38
SYR1-091108-002	SYR-1	2008	Odonata	Gomphidae	Larva	4	1.69	0.423	78.38	44	39
HUM1-091108-003	HUM-1	2008	Odonata	Gomphidae	Larva	4	1.05	0.263	81.58	46	40
SYR7-091208-004	SYR-7	2008	Odonata	Gomphidae	Larva	6	1.53	0.255	83.31	57	50
SYR6-091208-001	SYR-6	2008	Plecoptera	Perlidae	Larva	12	1.30	0.108	83.08	28	23
SYR1-091108-001	SYR-1	2008	Plecoptera	Perlidae	Larva	9	1.31	0.146	86.52	33	24
HUM1-091108-002	HUM-1	2008	Plecoptera	Perlidae	Larva	9	1.17	0.130	83.18	34	37
SYR7-091208-002	SYR-7	2008	Plecoptera	Perlidae	Larva	12	1.39	0.116	84.13	58	42
SYR1a-091108-002	SYR-1a	2008	Plecoptera	Perlidae	Larva	9	1.31	0.146	86.28	59	51
HUM1-091108-001	HUM-1	2008	Plecoptera	Perlidae	Larva	6	1.60	0.267	83.50	57	52
SYR4-091108-002	SYR-4	2008	Plecoptera	Perlidae	Larva	9	1.06	0.118	83.51	67	62
SYR1a-091108-001	SYR-1a	2008	Plecoptera	Perlidae	Larva	6	1.55	0.258	83.51	86	63
SYR4-091108-001	SYR-4	2008	Plecoptera	Perlidae	Larva	6	1.58	0.263	78.39	102	86
SYR6-091208-003	SYR-6	2008	Trichoptera	Hydropsychidae	Larva	150	0.77	0.005	89.69	18	11

Table 9. Concentrations of total mercury and methylmercury in individual composites of biological samples collected at Humbug Creek and the South Yuba River, California, in September 2007 and September 2008.

[g, gram; No., number of individual oranisms in composite; ng/g, nanogram per gram; ww, wet weight; THg, total mercury; MeHg, methylmercury; %, percent; nd, not determined]

Unique Sample Code	Site identifier	Year	Order	Family	Age	No.	Total mass (g)	Ave. Mass (g)	% moisture	THg (ng/g ww)	MeHg (ng/g ww)
SYR1-091108-006	SYR-1	2008	Trichoptera	Hydropsychidae	Larva	130	0.89	0.007	89.62	19	12
SYR4-091108-007	SYR-4	2008	Trichoptera	Hydropsychidae	Larva	70	0.60	0.009	88.91	26	20
SYR1a-091108-005	SYR-1a	2008	Trichoptera	Hydropsychidae	Larva	100	0.70	0.007	82.94	41	27
SYR7-091208-001	SYR-7	2008	Trichoptera	Hydropsychidae	Larva	130	0.64	0.005	85.69	80	30

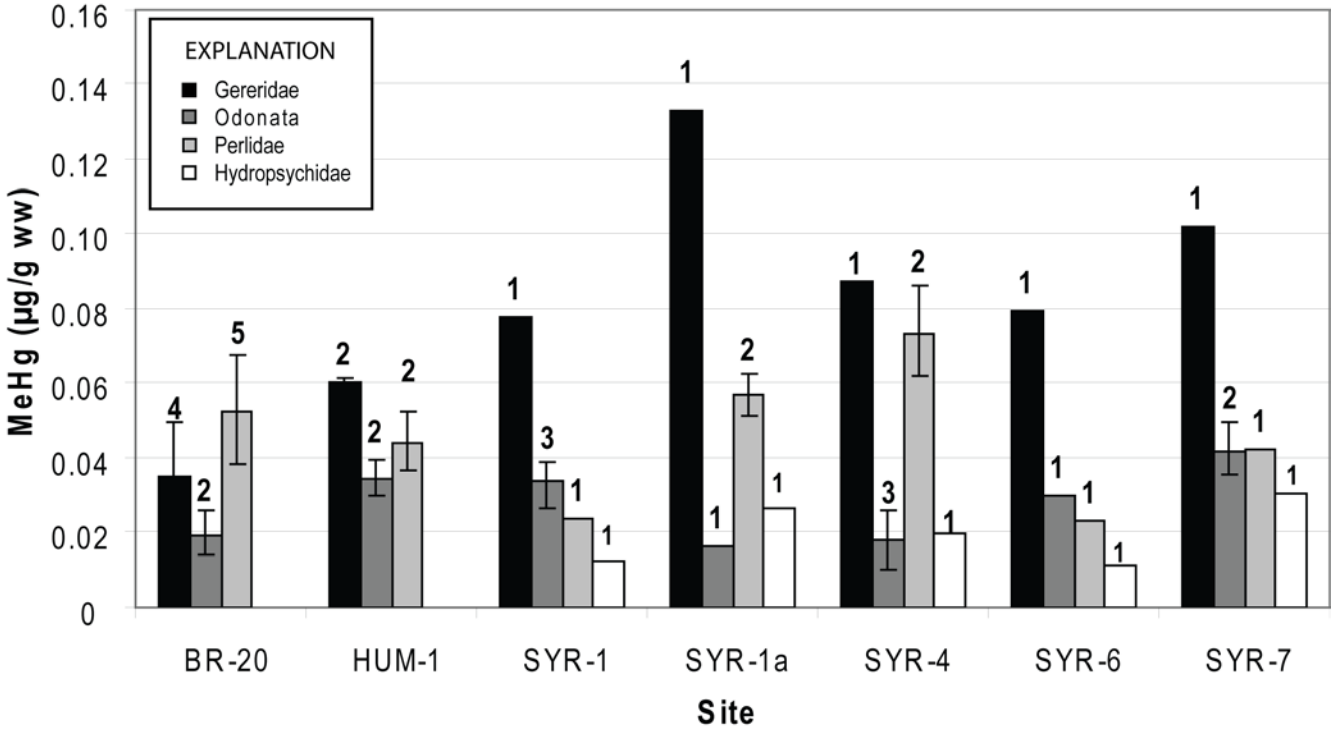


Figure 36. Bar graph showing the geometric mean methylmercury (MeHg) concentrations and ranges for composite samples of adult water striders (Order Hemiptera, Family Gerridae), dragonfly larvae (Order Odonata, Family Gomphidae), stonefly larvae (Order Plecoptera, Family Perlidae), and caddisfly larvae (Order Tricoptera, Family Hydropsychidae) collected from the South Yuba River–Humbug Creek, California, study area during September 2008, and geometric mean MeHg concentrations in adult water striders, dragonfly larvae (Order Odonata, Family Aeshnidae), and stonefly larvae collected from the Bear River at Highway 20 (BR-20, Reference site) during 1999–2002. The numbers above the bars indicate the number of observations (n).

There was a significant change in both Hg and MeHg concentrations between years, with 2007 having higher concentrations than 2008 (Hg: $F_{1,36.8} = 5.35$, $p<0.0265$; MeHg: $F_{1,37.1} = 19.06$, $p<0.0001$). All taxa collected in 2007 contained higher concentrations of MeHg than the same taxa from the same sites in 2008 (fig. 37), with the exception of water striders from SYR-6 and stoneflies from SYR-4 which appeared not to differ between years (fig. 37B). The average annual decline in THg concentration (no figure) ranged from 7% in caddisflies to 32% in water striders. The average annual decline in MeHg (fig. 37) ranged from 31% for caddisflies to 49% for dragonflies.

There was no significant interaction effect between year and taxa (Hg: $F_{3,32.3} = 0.39$, $p=0.76$; MeHg: $F_{3,32.6} = 0.30$, $p=0.83$). We tested the effect of year for each taxon by comparing the appropriate rows (or "slices") of least squares means for the combination factorial effect, year*taxa. Although THg significantly declined between years ($F=5.35$, $df=1,36.8$, $p=0.0265$), none of the taxa specifically exhibited significant change between years ($p>0.05$), although the water striders were nearly significant ($F=3.81$, $df=1,33.8$, $p=0.0594$). There was a significant decrease in MeHg between years ($F=19.06$, $df=1,37.1$, $p<0.0001$), with specific decreases exhibited in dragonflies ($F=7.48$, $df=1,36.4$, $p=0.0096$), water striders ($F=7.15$, $df=1,34.1$, $p=0.0114$), and stoneflies ($F=4.25$, $df=1,32.5$, $p=0.0472$).

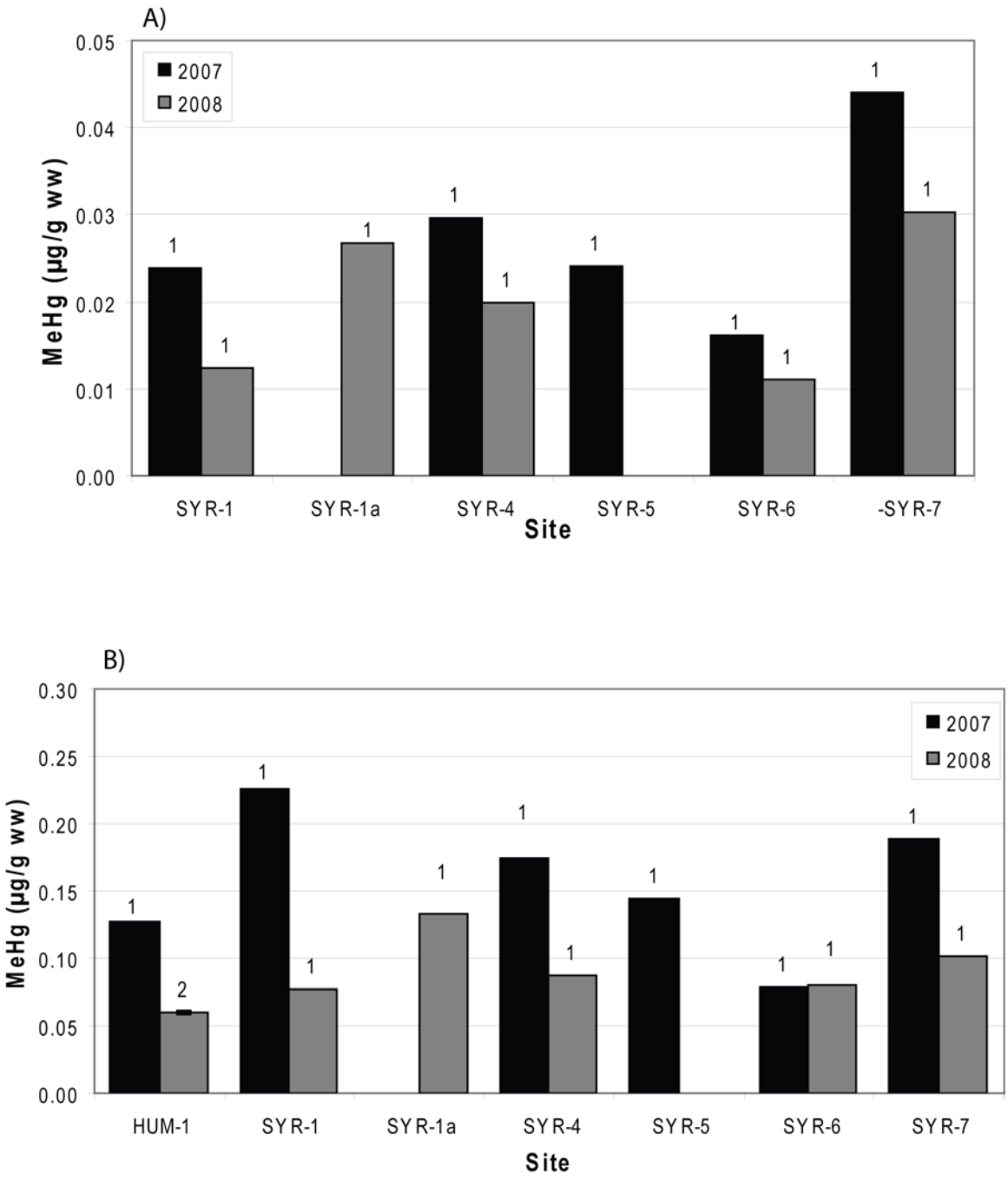
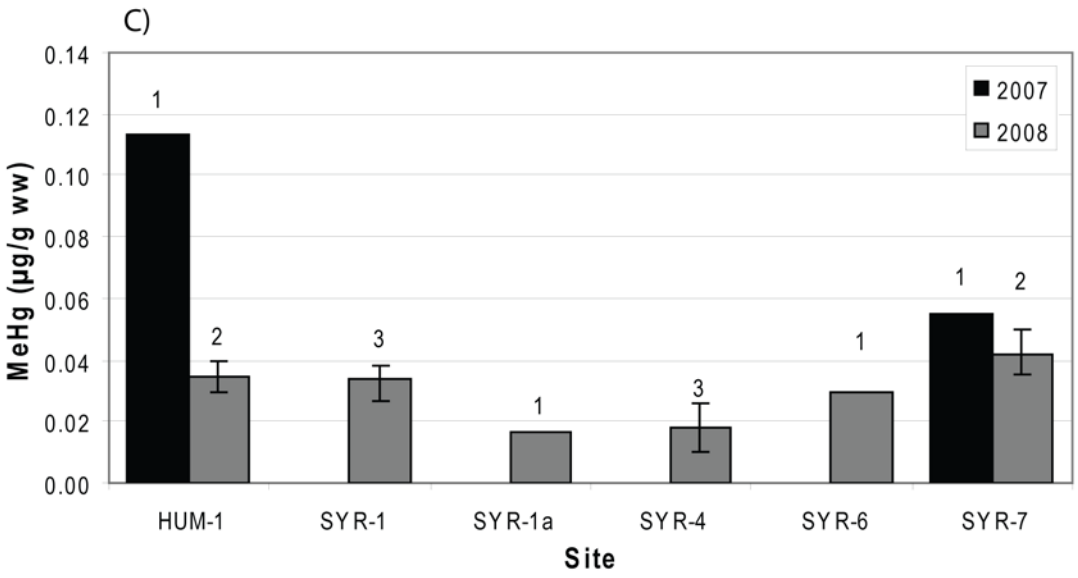


Figure 37. Comparison of methylmercury (MeHg) concentrations in individual composite samples of (A) larval caddisflies (Order Trichoptera, Family Hydropsychidae), (B) water striders (Order Hemiptera, Family Gerridae), (C) larval dragonflies (Order Odonata, Family Gomphidae), and (D) larval stoneflies (Order Plecoptera, Family Perlidae) collected from the South Yuba River–Humbug Creek, California, study area in September 2007 and September 2008. The numbers above the bars indicate the number of observations (n).



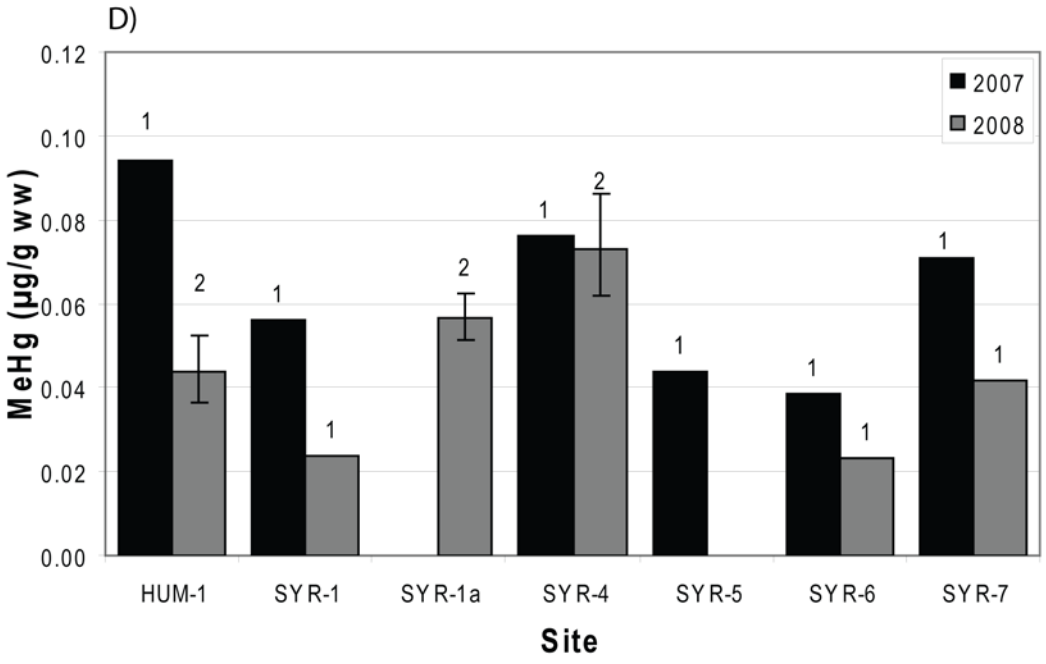


Figure 37.—Continued

Discussion

Sediment Characterization

Prior to the development of this study, the SYR-HC confluence area was considered a Hg 'hot spot' by the BLM on the basis of anecdotal reports of Hg recovered by recreational suction dredgers. The extensive and detailed characterization of the confluence presented here has identified variable degrees of Hg contamination and distribution associated with the various sub-habitats of the area and with a variety of sediment depositional and transport environments. But the study did not confirm the anecdotal reports that several hundred pounds of Hg(0) might be located on bedrock or associated with slickens layers within the South Yuba River channel below the Humbug Creek confluence. The river-bar materials at the confluence and at the 2007 dredge test site several hundred meters downstream were relatively low in THg compared to other HMD-influenced watersheds, and similar in concentration to downstream environments including the San Francisco Bay-Delta Estuary (Choe and Gill, 2003; Conaway and others, 2003; Bouse and others, 2010), Englebright Lake (Alpers and others, 2006), and the lower Yuba River upstream from Daguerre Point Dam (Hunerlach and others, 2004) with THg of approximately 200 to 300 ng/g in the silt-clay size fraction (<0.063 mm). However, the buried layers associated with Pit 2 were markedly more elevated in THg concentration (up to 11,100 ng/g in the silt-clay size fraction), and targeted sniping of the SYR-HC confluence indicated elevated Hg, reflecting the area's mining legacy of Hg contamination (Alpers and others, 2005a). The strong relations between THg, sediment mineralogy, and major-element chemistry confirm that sediment with elevated THg concentrations was derived largely from Tertiary auriferous gravel deposits historically targeted by hydraulic mining operations and thus contains a major component of HMD.

The speciation of the Hg currently being transported and that potentially could be mobilized by future suction dredging is of particular importance because it is likely to affect methylation and bioaccumulation of Hg in downstream environments. Although THg is typically recognized as the constituent of concern in mining-affected areas with regard to regulatory decisions, $Hg(II)_R$ poses a greater concern because it is more readily available for methylation than the bulk THg measurement (Marvin-DiPasquale and others, 2009b). Because the buried layers of sediment in the study area were relatively more elevated in $Hg(II)_R$ (approximately 500-fold) than THg (approximately 100-fold) compared to the surface sediment layers, the potential influence caused by mobilization of $Hg(II)_R$ is even greater than that suggested by THg. These factors reveal the inherent difficulty in quantifying potential effects of sediment mobilization because small differences in sediment mobilization can result in large differences in THg and $Hg(II)_R$ mobilization from these spatially variable relic sediment layers.

Transport Calculations

Ultimately, the importance of the results of this study relate to whether the Hg in the sediment has a negative effect. Potential for a negative effect is closely related to the transport of sediment into the water column where it may become a threat to local users or be transported downstream. The following transport calculations provide a basis for comparing the relative contribution of sediment and THg from the South Yuba River and Humbug Creek to the confluence area, the estimated THg loads from the entire South Yuba River that are based on previous research, and the estimates of THg mobilized by suction dredging.

Watershed Loads

Although the current study was not designed to compute sediment and Hg loads, the data collected do allow for a relative comparison of Hg sources to the SYR-HC confluence area. The measured THg_{SS} concentrations in fine-grained suspended sediment from Humbug Creek were about twice as high as those measured in the South Yuba River but much lower than the fine-grained excavated samples from Pit 2 (table 6, figs. 28 and 29). In addition, the Humbug Creek watershed has a higher erodability index than the South Yuba River (Curtis and others, 2005). It is thus likely that the Humbug Creek produces higher loads of sediment and pTHg per unit watershed area compared to the South Yuba River. This supposition is consistent with the TSS concentration data associated with the May 5, 2009, storm samples in which TSS concentrations in Humbug Creek were about twice as high as those measured in the South Yuba River. These higher TSS concentrations are more than balanced by the difference in watershed area. The area of the Humbug Creek drainage (2,764 hectares) represents only 4.3% of the area of the South Yuba River watershed upstream from the SYR-HC confluence (64,377 hectares). Although flows are not exactly proportional to drainage area and there are several large diversions in the upper South Yuba River watershed (Webster and others, 2005), it is expected that the streamflow of the South Yuba River greatly exceeds that of Humbug Creek at the confluence during most flow conditions. Thus, the loads of suspended sediment and total Hg from Humbug Creek are likely to be substantially less than those from the South Yuba River upstream from the SYR-HC confluence despite the lower THg_{SS} concentrations in the South Yuba River.

For comparison, concentrations of THg_{SS} in the South Yuba River during 2001–2004 were within a relatively consistent range (around 100 to 1,000 ng/g) with most of the THg_{SS} near 300 ng/g (Alpers and others, 2004), similar to the THg concentration in the surface sediment layers measured in this study (Pit 1, Pit 2 OBL, SYR bed sediment). The importance of this consistent relation suggests that the streamflow conditions encountered during the previous studies (2001–2004) and this study (2009) did not mobilize large amounts of sediment from the more deeply buried, contaminated sediment layers (for example, Pit 2 CSL and BRC). However, low average THg_{SS} concentrations could also be caused by the mixing of multiple sources of sediment with differing concentrations and grain sizes encountered in stormflows.

Although not measured in this study, previous data for the South Yuba River watershed provide enough information to estimate annual sediment and Hg loads for the South Yuba River. Curtis and others (2006) reported annual suspended-sediment flux on the South Yuba River at Jones Bar (USGS streamgage 11417500) during 2001–2003 of approximately 1,000, 3,700, and 6,900 metric tons per year, respectively, on the basis of the average of several load estimation methods. The related THg loads in the fine-grained fraction would be around 510, 1,900, and 3,500 g of Hg per year (g/yr), on the basis of the particle-size distribution of the suspended sediment reported by Curtis and others (2006) and the consistent THg_{SS} concentration noted by Alpers and others (2004) and observed in this study. The period 2001–2003 was relatively dry; average annual flows were exceeded in 89, 63, and 46% of years between 1941 and 2009, respectively, on the basis of the entire flow record. A long-term average of THg loads was also calculated for the greater Yuba River watershed by using data from a coring study in Englebright Lake (Alpers and others, 2006; Snyder and others, 2004, 2006).

Mercury Potentially Mobilized by Suction Dredging

The calculations of the amount and type of sediment potentially mobilized by a standard commercial suction dredge in the SYR-HC confluence area suggest that suction dredging can contribute a substantial amount of THg to downstream

environments, particularly if material similar to the compact sediment (slickens) layer and bedrock contact zones are dredged. If the dredging activity is located in river-bar materials, the enhanced loads are based solely on the increase in fine-grained sediment mobilized. Under the latter scenario, approximately 100,000 to 1,000,000 hours of dredging with an 8-in.-diameter (20-cm) nozzle would be required to equal the THg load associated with natural particulate transport processes during an average dry year in the South Yuba River (figs. 38A and 38B, table 10). However, if material similar to the compact sediment and bedrock contact materials are dredged, sediment with much higher THg content would be mobilized, and only approximately 100 to 1,000 hours of dredging would be required to exceed an average dry year's natural watershed THg load (figs. 38C and 38D, table 10). These buried layers also correspond to the zones specifically targeted by the suction-dredging community because they are the zones most likely to contain recoverable grains of Au and Hg-Au amalgam.

Suction-dredging activity would have to increase to 10,000 to 100,000 hours to equal the long-term Hg accumulation rate in Englebright Lake (North, Middle, and South Yuba River watersheds combined with multiple large storm events). Although this represents a large amount of time, records from the California Department of Fish and Game indicate approximately 3,650 suction-dredge permits (3,200 resident and 447 non-resident) were issued statewide per year on average over the past 15 years (Horizon Water and Environment, 2009), implying only about 270 hours of dredging per permit per year are required to reach the 1,000,000 hour mark. This estimate of dredge time is reasonable for a statewide assessment but would be unlikely for only the South Yuba River. Furthermore, this estimate accounts for the dredging of the Hg-rich layers exclusively, a situation that is unlikely given the variable spatial distribution of these Hg-rich layers.

After the extensive characterization of the sediment and Hg contamination associated with the SYR-HC confluence area, the largest source of uncertainty in the calculated Hg mobilization rates are the actual dredging rates. Initial estimates (figs. 38A and 38B) were performed with published dredge rates (Keene Engineering, Inc., 2008). Revised calculations (figs. 38C and 38D) were based on dredge performance rates updated by Keene (P. Keene, Keene Engineering, Inc., written commun., 2010). Unfortunately, the rate at which sediment was moved during the dredge test was not quantified during this study, therefore this evaluation is based on qualitative observation only. However, actual dredge mobilization rates likely fall between the wide range of calculated rates. Future efforts to quantify sediment mobilization caused by recreational suction dredging should include the quantification of the dredge rate so that a more accurate assessment of Hg mobilization through dredging can be determined.

Another approach to comparing suction dredging to natural loading rates on a greater watershed scale can be derived from previous estimates of the contribution of suction dredging to natural suspended-sediment loads. The USFS estimated the contribution of suction dredging in the Siskiyou National Forest at 0.7% of the overall sediment load (Cooley, 1995). On the basis of the elevated concentrations of THg and $Hg(II)_R$ in the contaminated layers of the SYR-HC confluence area, the contribution of THg and $Hg(II)_R$ from dredging in hydraulic-mining affected sites increases approximately 100- to 500-fold, respectively. This amounts to a 70% contribution of THg and 350% of $Hg(II)_R$ from dredging relative to natural loads. However, this assumes that all the sediments mobilized in the watershed are contaminated to the same degree as the relic sediment layers at the SYR-HC confluence (Pit 2, CSL and BRC). A more conservative estimate of the proportion of relic sediment layers at a hydraulic-mining affected site (10%) still yields a 7% contribution of THg and 35% contribution of $Hg(II)_R$ relative to natural loads in watersheds where relic layers persist. These estimates are, like the previous analysis, dependent on numerous assumptions and estimates and thus possess a high degree of uncertainty.

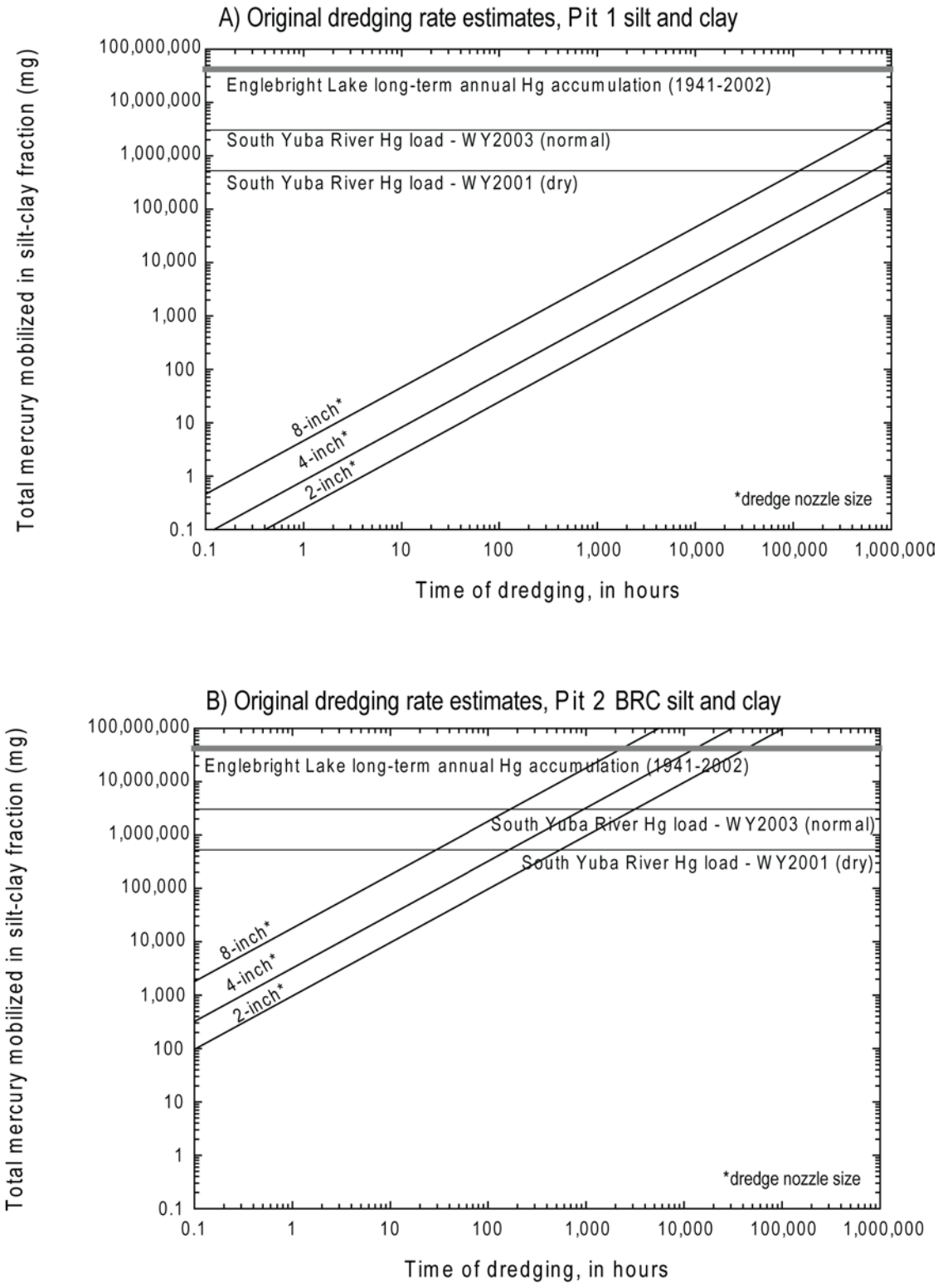
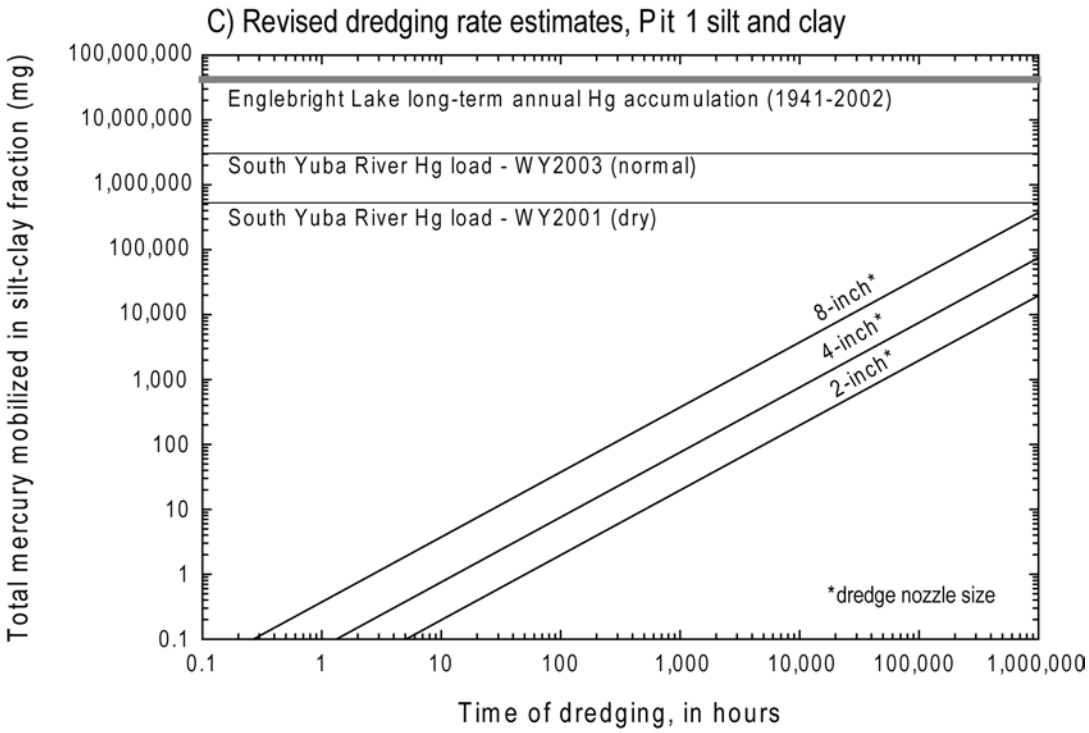


Figure 38. Log-log plots of estimated total mercury mass moved by various sizes of commercially available suction dredge versus hours dredged (using two sets of dredge performance rates from Keene Engineering, Inc.) (A) Pit 1, original dredge rates (Keene Engineering, Inc., 2008), (B) Pit 2 Bedrock Contact Layer, original dredge rates (Keene Engineering, Inc., 2008), (C) Pit 1, revised dredge rates (P. Keene, Keene Engineering, Inc., written commun., 2010), and (D) Pit 2 Bedrock Contact layer, revised dredge rates (P. Keene, Keene Engineering, Inc., written commun., 2010).



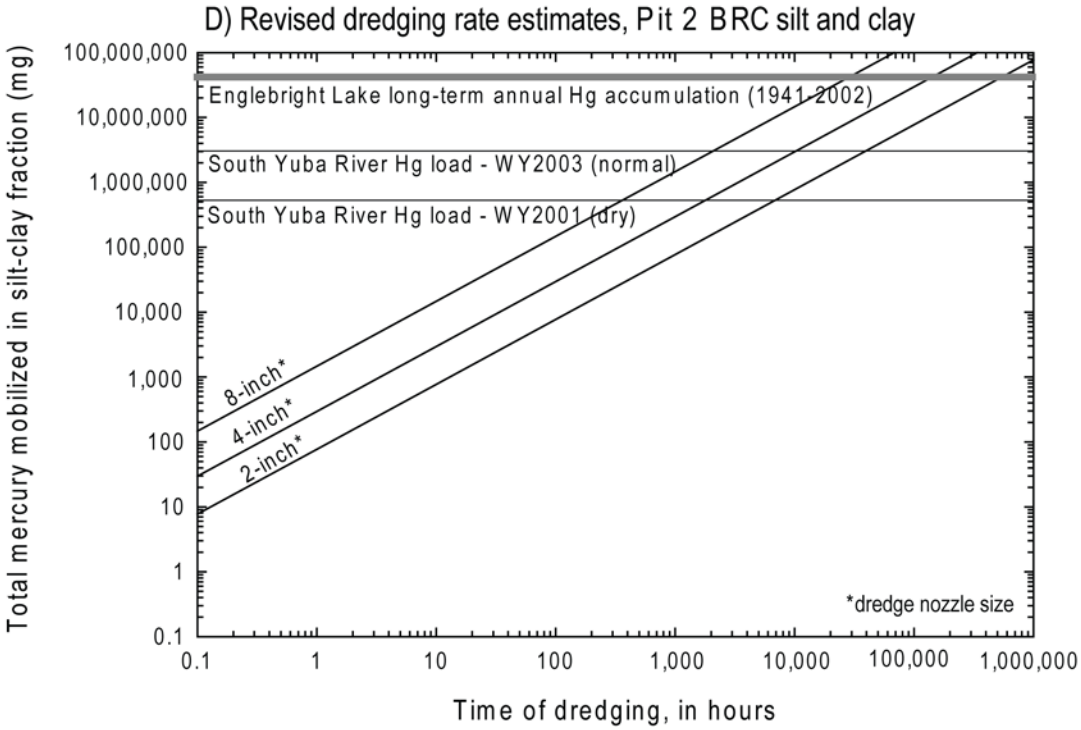


Figure 38.—Continued

Table 10A. Calculated rates of potential mercury mobilization by suction dredging for various materials sampled at the South Yuba River – Humbug Creek, California, confluence area Sediment properties used in calculation.

[**Abbreviations**: OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; THg, total mercury; $Hg(II)_R$, reactive mercury; kg/m^3, kilogram per cubic meter; µg/kg; microgram per kilogram; kg/hr, kilogram per hour; m^3/hr, cubic meter per hour; mg/hr, milligram per hour; in., inch; HP, horsepower; hr, hour; ", inch; <, less than; >, greater than; mg, milligram; g/m^3, gram per cubic centimeter; %, percent]

Dredge material	PIT 1	HMD-CF	Pit 2 OBL	Pit 2 FCZ	Pit 2 CSL	Pit 2 BRC
particle density (kg/m^3)	2,650	2,650	2,650	2,650	2,650	2,650
THg (µg/kg)	276	1,205	139	1,546	10,525	11,106
$Hg(II)_R$ (µg/kg)	0.88	37.5	4.4	6.5	414	1,913
% of mass <63µm (see Table 2)	0.03%	3.4%	1.1%	1.3%	2.6%	2.9%

Table 10B. Calculated rates of potential mercury mobilization by suction dredging for various materials sampled at the South Yuba River Humbug Creek, California, confluence area: Sediment properties used in calculation: Rates of sediment and mercury dredged using dredge performance rates from Keene Engineering, Inc. (2008): Calculated rates of potential mercury mobilization by suction dredging for various materials sampled at the South Yuba River

[**Abbreviations**: OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; THg, total mercury; $Hg(II)_R$, reactive mercury; kg/m^3, kilogram per cubic meter; µg/kg; microgram per kilogram; kg/hr, kilogram per hour; m^3/hr, cubic meter per hour; mg/hr, milligram per hour; in., inch; HP, horsepower; hr, hour; ", inch; <, less than; >, greater than; mg, milligram; g/m^3, gram per cubic centimeter; %, percent]

Dredge Nozzle diameter (in.)	Engine HP	Dredge-Engine	PIT 1				HMD-CF				PIT 2 OBL			
			sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr
2	2.5	2" / 2.5HP	0.00034	0.9	0.25	0.001	0.038	102	123	4	0.01	34	5	0.1
2.5	4	2.5" / 4HP	0.00054	1.4	0.39	0.001	0.062	163	196	6	0.02	54	7	0.2
3	5	5" / 5HP	0.00067	1.8	0.49	0.002	0.077	204	246	8	0.03	67	9	0.3
4 (4 models)	6.5	4" / 6.5HP	0.00112	3.0	0.82	0.003	0.128	340	409	13	0.04	112	16	0.5
5	9	5" / 9HP	0.00202	5.4	1.5	0.005	0.231	611	737	23	0.08	201	28	1
5	11	5" / 11HP	0.00224	5.9	1.6	0.005	0.256	679	819	25	0.08	224	31	1
5	13(2 x 6.5)	5" / 13HP	0.00224	5.9	1.6	0.005	0.256	679	819	25	0.08	224	31	1
6	13 (2 x 6.5)	6" / 13HP	0.00314	8.3	2.3	0.007	0.359	951	1,146	36	0.12	313	44	1
6	18 (2 x 9)	6" / 18HP	0.00337	8.9	2.5	0.008	0.385	1,019	1,228	38	0.13	335	47	1
6	20 (2 x 10)	6" / 20HP	0.00337	8.9	2.5	0.008	0.385	1,019	1,228	38	0.13	335	47	1
6	22 (2 x 11)	6" / 22HP	0.00337	8.9	2.5	0.008	0.385	1,019	1,228	38	0.13	335	47	1
6	32 (2 x 16)	6" / 32HP	0.00381	10.1	2.8	0.009	0.436	1,155	1,392	43	0.14	380	53	2
8	36 (2 x 18)	8" / 36HP	0.00628	16.6	4.6	0.015	0.718	1,902	2,292	71	0.24	626	87	3
Dredge Nozzle diameter (in.)	Engine HP	Dredge-Engine	PIT 2				PIT 2 CSL				PIT 2 BRC			
			sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	$Hg(II)_R$ mg/hr
2	2.5	2" / 2.5HP	0.01	38	60	0	0.03	80	841	33	0.03	87	965	166
2.5	4	2.5" / 4HP	0.02	62	95	0	0.05	128	1,346	53	0.05	139	1,544	266
3	5	5" / 5HP	0.03	77	119	1	0.06	160	1,682	66	0.07	174	1,930	332
4 (4 models)	6.5	4" / 6.5HP	0.05	128	198	1	0.10	266	2,804	110	0.11	290	3,216	554
5	9	5" / 9HP	0.09	231	357	2	0.18	480	5,047	199	0.20	521	5,789	997
5	11	5" / 11HP	0.10	257	397	2	0.20	533	5,608	221	0.22	579	6,433	1108
5	13(2 x 6.5)	5" / 13HP	0.10	257	397	2	0.20	533	5,608	221	0.22	579	6,433	1108
6	13 (2 x 6.5)	6" / 13HP	0.14	359	555	2	0.28	746	7,851	309	0.31	811	9,006	1551
6	18 (2 x 9)	6" / 18HP	0.15	385	595	3	0.30	799	8,411	331	0.33	869	9,649	1662
6	20 (2 x 10)	6" / 20HP	0.15	385	595	3	0.30	799	8,411	331	0.33	869	9,649	1662
6	22 (2 x 11)	6" / 22HP	0.15	385	595	3	0.30	799	8,411	331	0.33	869	9,649	1662
6	32 (2 x 16)	6" / 32HP	0.16	436	674	3	0.34	906	9,533	375	0.37	985	10,936	1884
8	36 (2 x 18)	8" / 36HP	0.27	719	1,111	5	0.56	1,492	15,701	618	0.61	1,622	18,012	3,103

Table 10C. Calculated rates of potential mercury mobilization by suction dredging for various materials sampled at the South Yuba River - Humbug Creek confluence area: Sediment properties used in calculation: Rates of sediment and mercury dredged using revised dredge performance rates from Keene Engineering, Inc. (2010).

[**Abbreviations:** OBL, overburden layer; FCZ, first contact zone; CSL, compact sediment layer; BRC, bedrock contact; HMD-CF, hydraulic mining debris cliff face; THg, total mercury; Hg(II)R, reactive mercury; kg/m^3, kilogram per cubic meter; µg/kg; microgram per kilogram; kg/hr, kilogram per hour; m^3/hr, cubic meter per hour; mg/hr, milligram per hour; in., inch; HP, horsepower; hr, hour; ", inch; <, less than; >, greater than; mg, milligram; g/m^3, gram per cubic centimeter; %, percent

Dredge nozzle diameter (in.)	Engine HP	Dredge-engine	PIT 1				HMD-CF				PIT 2 OBL			
			sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr
2	2.5	2" / 2.5HP	0.000027	0.07	0.02	0.00006	0.0031	8	10	0.3	0.001	3	0.4	0.01
2.5	3.5	2.5" / 4HP	0.000034	0.09	0.02	0.00008	0.0038	10	12	0.4	0.001	3	0.5	0.01
3	4	5" / 5HP	0.000067	0.18	0.05	0.00016	0.0077	20	25	0.8	0.003	7	0.9	0.03
4	6	4" / 6.5HP	0.000103	0.27	0.08	0.00024	0.0118	31	38	1	0.004	10	1.4	0.05
5	9	5" / 9HP	0.000204	0.54	0.15	0.00048	0.0233	62	74	2	0.01	20	2.8	0.09
6	14	6" / 14HP	0.000240	0.64	0.18	0.00056	0.0274	73	88	3	0.01	24	3.3	0.11
8	46	8" / 46HP	0.000511	1.36	0.37	0.00119	0.0584	155	187	6	0.02	51	7.1	0.22
10	95	10" / 95HP	0.001093	2.90	0.80	0.00255	0.1248	331	399	12	0.04	109	15.1	0.48
Dredge Nozzle diameter (in.)	Engine HP	Dredge-Engine	PIT 2 FCZ				PIT 2 CSL				PIT 2 BRC			
			sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr	sediment m^3/hr	sediment kg/hr	THg mg/hr	Hg(II)$_R$ mg/hr
2	2.5	2" / 2.5HP	0.001	3.1	4.8	0.02	0.002	6	67	3	0.003	7	77	13
2.5	3.5	2.5" / 4HP	0.001	3.8	6.0	0.03	0.003	8	84	3	0.003	9	96	17
3	4	5" / 5HP	0.003	7.7	12	0.05	0.006	16	168	7	0.007	17	193	33
4	6	4" / 6.5HP	0.004	12	18	0.08	0.009	25	258	10	0.010	27	296	51
5	9	5" / 9HP	0.01	23	36	0.15	0.018	48	510	20	0.020	53	585	101
6	14	6" / 14HP	0.01	27	42	0.18	0.022	57	600	24	0.023	62	688	119
8	46	8" / 46HP	0.02	59	90	0.38	0.046	121	1,279	50	0.050	132	1,467	253
10	95	10" / 95HP	0.05	125	193	0.81	0.098	259	2,731	107	0.106	282	3,133	540

Biota

The observed decrease in MeHg burden in all but two of the 16 taxa-site combinations between 2007 and 2008 is an intriguing result. Interannual variation of MeHg in invertebrates has been documented in other watersheds (for example, Suchanek and others, 2000; Slotton and others, 2004; Wiener and others, 2007) but is typically less consistent among taxa and of a lesser magnitude than the average differences observed in this study (31 to 49%). Reasons for these decreases are not clear, but they may be related to a decline in suction-dredging activity in the South Yuba River between 2007 and 2008 resulting from the moratorium placed on this reach of river prior to the current study. Suction dredging during 2007 and prior years likely enhanced THg transport during summer months, which would have contributed to enhanced Hg methylation resulting in increased MeHg bioaccumulation by invertebrates. Conversely, the lack of dredging activity in 2008 would have led to less THg transport and production of less MeHg, with associated lower bioaccumulation of MeHg by invertebrates. The biota sampled in this study typically have short life spans, making them sensitive to changes in MeHg availability over relatively short time scales. Thus, they are suitable as indicators of changes in MeHg contamination from year to year. Flow conditions at the site are unlikely to have been a major factor, because 2007 and 2008 were very similar to each other hydrologically and were similar to the average conditions over the entire hydrologic record. These results for interannual variation of the MeHg in biota strongly support the need for continued monitoring during the suction-dredge moratorium to capitalize on conditions that would otherwise be impossible to replicate and would provide the greatest evidence regarding the effect of such human activities. Should the moratorium be lifted, additional monitoring would be encouraged in order to document any change in the biota following the reinstitution of recreational suction dredging.

Implications

The transport calculations suggest that the use of suction dredging to actively remove buried Hg-contaminated layers in the Humbug Creek delta would also mobilize fine-grained sediment, leading to the transport of substantial amounts of Hg associated with fine (silt-clay sized) particles far downstream. The elevated concentrations of THg and $Hg(II)_R$ measured in the recirculation-tank water corroborates results from the preliminary dredge test where LISST measurements showed an increase in the clay-sized particles (<0.002 mm diameter). Although not directly measured in the tank experiment, the particles remained suspended in the water column for longer than 40 hours after the venturi dredge test, indicating they were clay-sized or smaller. The high $Hg(II)_R$ concentration associated with the fine-sediment fraction and the increased likelihood of further oxidation of these fine particles while in the water column present a potential concern for downstream environments receiving these particles (Marvin-DiPasquale and Cox, 2007), as is discussed in detail by Marvin-DiPasquale and others (2011). The potential negative influence of suction dredging would be greatest where and when buried relic HMD layers are mobilized by human activity.

The sediment associated with the eroding cliff face below the BLM picnic area is of potential environmental concern in the SYR-HC confluence area. This sediment, which likely represents HMD, was elevated in concentrations of Hg relative to Pit 1 and the overburden of Pit 2, but to a lesser degree than the buried compact sediment of Pit 2. In addition, the fine-grained fraction of HMD sediment was elevated in concentrations of $Hg(II)_R$ relative to the fine material from Pit 1. Although the HMD may have been depleted of the finest sediment fraction by decades of percolation of surface water, it still may be of environmental concern because of high rates of ongoing natural erosion. HMD deposits such as this one may be sources for a large portion of storm-driven loads of Hg and especially $Hg(II)_R$ in rivers draining the western slope of the Sierra Nevada.

Conclusions

Concentrations of Hg in surficial riverbed sediment, suspended sediment during storm events and a dredge test were in the range of concentrations observed in sediment elsewhere in the Yuba River watershed and in other Sierra Nevada watersheds affected by historical Au mining. However, buried sediment deposits had more elevated concentrations of Hg, especially in fine-grained fraction (<0.063 mm). The highest concentrations of Hg in sediment were in the bottom of a pit excavated near the mouth of Humbug Creek (Pit 2 compact sediment and bedrock contact zones), an area that appeared to have remained undisturbed for many decades, perhaps since the days of active hydraulic mining that ended in the late 1800s. These sediment layers were apparently protected from erosion during stormflows by boulders and the geometry of their location.

A closed-circuit tank experiment with a venturi pump at the base of a hand-excavated pit (Pit 1) in a gravel bar within the South Yuba River resulted in fine-grained suspended sediment remaining in suspension more than 40 hours following the disturbance simulation. Although the concentration of Hg in the water column declined over time as particles settled out, the concentration of THg and $Hg(II)_R$ on the suspended particles increased over time as coarser particles lower in Hg settled.

Concentrations of MeHg in invertebrates collected from Humbug Creek and the reach of the South Yuba River studied in this project were elevated compared with a control site (on the nearby Bear River) that was relatively unaffected by historical mining. Invertebrate MeHg concentrations were lower in 2008 than in 2007 in at least two of three sampled taxa at each of the five sites with comparable data in the South Yuba River and in Humbug Creek. One factor in the reduction in MeHg bioaccumulation in this area may have been a local moratorium on suction dredging that started in 2008. However, the data contained in this report are insufficient to determine the cause for this inter-annual variation. Further monitoring of MeHg in biota where previous data exist during the statewide suction-dredging moratorium that began in 2009 would be helpful in evaluating this possibility.

The removal of the protected, Hg-rich sediment layers by activities such as suction dredging or high-banking would likely result in increased loads of THg and $Hg(II)_R$ mobilized downstream in the fine-sediment fraction, which would likely not be caught with standard recovery equipment (such as the sluice box on a standard suction dredge). Mobilizing this Hg-rich sediment would increase downstream loads for long distances; fine particles would not settle until they reach quiescent environments such as Englebright Lake or downstream wetlands of the Sacramento River and San Francisco Estuary where the Hg-rich particles of silt and clay size may be deposited. Development and testing of enhanced recovery technologies for fine-grained sediment and Hg may be of interest for developing more effective Hg-removal techniques in remote locations such as the SYR-HC confluence area. In addition to the disturbance of buried sediment, an eroding cliff face composed of hydraulic mining debris may also be contributing a substantial load of THg and $Hg(II)_R$ to the South Yuba River though stream bank erosion.

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Appendix 1: Quality Assurance and Quality Control

Laboratories analyzing samples for mercury species followed similar quality-assurance procedures as those outlined by Olund and others (2004) and the U.S. Environmental Protection Agency (2002). Calibration standards and certified (CRM) and standard (SRM) reference materials were obtained from NIST, International Atomic Energy Association (IAEA), and National Research Council Canada to ensure accuracy of results for the most similar available matrix for a selected sample analysis.

Data released from the laboratories were screened according to the following data-quality objectives: Relative percent difference (RPD) of duplicate samples must be less than 30 percent, matrix blanks must be less than twice the MDL. Spiked samples must have an RPD between 70 and 130 percent recovery with a duplicate spike RPD less than 35 percent, and Standard Reference Materials must have of 75 to 125 percent recovery for THg and 65 to 135 percent recovery for MeHg. Results showing laboratory performance are summarized in table 1A-1.

Appendix 1. Table 1A-1. Laboratory Quality Control Results Summary: Mercury species.[CRM, certified reference material; %, percentage; MS, matrix spike; RPD, relative percent difference; Dup, duplicate; MDL, method detection limit; na, not applicable; NIST, National Institute for Standards and Testing; IAEA, International Atomic Energy Association; DORM, Dogfish muscle certified reference material; ng, nanogram; ng/L, nanogram per liter; ng/g, nanogram per gram; Avg, average; SE, standard error; n, number of measurements; <, less than; THg, total mercury; $Hg(II)_R$ reactive mercury; MeHg, methylmercury; fTHg, filtered total mercury; fMeHg, filtered methylmercury; pTHg, particulate total mercury; $pHg(II)_R$, particulate reactive mercury; pMeHg, particulate methylmercury; THg_{SS}, total mercury in suspended sediment; %, percent; na, not applicable]

Mercury species	Collection date range	Project analytes	Method detection limit			Matrix blank			CRM % recovery				Analytical duplicate RPD (%)			MS % recovery		
			ng	ng/L	ng/g	Avg	SE	n	Name	Avg	SE	n	Avg	SE	n	Avg	SE	n
Sediment (bed, excavated and suspended)																		
THg	2007–2009	THg, pTHg, THg_{SS}	na	0.1	[1] 2.2	na	na	na	IAEA 405	104	9	10	13.5	6.6	7	93	1	9
$Hg(II)_R$	2007–2009	$Hg(II)_R$, $pHg(II)_R$	0.03	na	[1] 0.02	na	na	na	na	na	na	na	19.7	5.8	7	na	na	na
MeHg	2007–2009	MeHg, pMeHg	0.001	na	[2] 0.003 to 1.0	na	na	na	IAEA 405	101	5	4	[7] 9.7	[7] 3.4	[7] 2	[7] 74	[7] 4	[7] 2
Filtered water (filtrate)																		
THg	2007	fTHg	na	0.1	na	<MDL	na	1	NIST 1641d	91	3	7	23	7	8	100	8	2
MeHg	2007	fMeHg	0.001	[3] 0.03	na	<MDL	na	1	na	na	na	na	19	na	1	101	5	2
Biota (tissue)																		
THg	2007	THg	na	na	0.04 to 0.4	<MDL	na	8	DORM-2	105.4	4.1	8	8.2	2.2	13	110.1	1.6	9
THg	2008	THg	na	na	0.04	<MDL	na	3	DORM-3	101	0.5	2	[4] 26.8	17.8	4	100.0	2.0	4
MeHg	2007	MeHg	na	na	1.0	<MDL	na	9	DORM-2	107.9	3.6	9	[5] 11.4	2.9	14	[6] 110	2.8	10
MeHg	2008	MeHg	na	na	1.0	<MDL	na	4	DORM-3	87.5	1.5	2	7.0	2.7	4	98.0	2.0	4

[1] Estimate based 2.5 grams of wet sediment digested with a % dry weight value of 70%. These values can vary considerably.

[2] Estimate based a range of 1.0 g of sediment extracted with KOH/methanol to 0.001 g of dry suspended particulates captured on a filter and extracted via distillation.

[3] Estimate based on the distillation of 30 mL of filtered surface water.

[4] The duplicate for SYR4-091108-005 had an RPD of 80% (greater than the acceptance limit of 35%). Reanalysis met the objective and it was determined that the failure was caused by an error in the duplicate preparation and not a matrix issue.

[5] The duplicate for sample HUM-091307-002 had an RPD of 39% which exceeded the acceptance limit of 35%. Therefore, results for this sample should be considered an estimate.

[6] One sample from 2007 had a recovery of 141%, which exceeded the acceptable criterion for MeHg (135%) and was reanalyzed. On reanalysis, the recovery was acceptable (103%), indicating that the original result was an isolated analytical error.

[7] Initial value below detection limit — data for other projects in same analytical runs.

Appendix 2. Mineralogy and Major Element Data for Sediment Samples

The following tables summarize the full mineralogical and geochemical results and chemical formulas used to determine provenance for selected sediment samples using RockJock (Eberl, 2003), MinUnMix (Eberl, 2004), and nonparametric correlation analysis.

Table 2A-1. Mineralogy of sediment samples determined by x-ray diffraction.

[Mineralogy determined by whole-pattern matching using powder x-ray diffraction. values in volume percent, normalized to 100%; mm, millimeter; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	Quartz + cristo-balite	Kaolin-ite + Hallloy-site	Plagio-clase (Na-Ca) feld-spars	Potas-sium feld-spars	Musco-vite	Illite	Smec-tite	Amor-phous (glass) + fulvic acid]	Biotite + chlorite	Amph-ibole (actino-lite)	Dolo-mite + anke-rite	Magne-tite + Mag-hemite	Fluor-apatite + titanite	Ilme-nite	Hema-tite	Goe-thite	Ferri-hydrite	Total
SYH-003	Pit 1	Excavated sediment, 0 to 3 feet	< 0.063	25.9	12.5	8.2	2.3	10.9	0.8	8.7	16.9	7.0	2.7	0.3	0.2	0.0	0.0	0.0	0.9	2.9	100.0
SYH-004	Pit 2 OBL	Excavated sediment	< 0.063	26.6	32.5	0.8	3.1	11.0	2.4	11.4	9.6	0.4	0.4	0.0	0.2	0.0	0.4	0.1	1.3	0.0	100.0
SYH-005	Pit 2 FCZ	Excavated sediment	< 0.063	27.9	32.4	1.6	2.4	11.2	0.0	14.0	7.0	0.5	0.7	0.1	0.3	0.0	0.4	0.0	1.7	0.0	100.0
SYH-006	Pit 2 CSL	Excavated sediment	< 0.063	24.0	28.5	0.3	1.9	8.6	0.0	13.3	14.1	0.3	0.0	0.0	0.0	0.0	0.0	0.1	2.7	6.1	100.0
SYH-007	Pit 2 BRC	Excavated sediment	< 0.063	24.5	27.1	1.2	2.4	10.8	0.0	14.4	10.2	2.4	0.8	0.1	0.1	0.0	0.4	0.0	3.2	2.4	100.0
SYH-008	Pit 1	Dredged sediment, Recirculation Tank	< 0.063	31.1	7.2	12.3	4.3	15.3	0.0	5.4	6.1	9.0	4.5	0.5	0.5	0.0	0.1	0.1	0.8	2.8	100.0
SYH-009	HMD-CF	Excavated sediment	< 0.063	25.5	24.2	0.4	3.0	2.3	0.0	18.6	12.0	6.0	0.3	0.2	0.5	0.1	0.9	0.0	2.9	3.0	100.0
SYH-010	SYR-0	Bed, bank sediment	< 0.063	21.2	17.4	5.2	4.4	7.0	0.0	10.7	19.4	6.7	2.3	0.3	0.3	0.0	0.4	0.0	1.1	3.8	100.0
SYH-011	HUM-1	Bed, bank sediment	< 0.063	19.5	32.6	1.1	2.1	11.0	0.0	15.0	10.9	2.5	0.0	0.0	0.4	0.0	0.1	0.2	1.5	2.9	100.0
SYH-012	LC-MTO	Surface sediment	< 0.063	23.6	26.2	3.0	2.3	6.3	0.0	14.8	18.7	1.3	0.4	0.3	0.3	0.0	0.0	0.2	0.9	1.7	100.0
SYH-013	NB-MTO	Surface sediment	< 0.063	2.5	1.5	0.6	0.2	0.0	0.0	0.0	28.6	16.5	2.9	0.9	0.0	0.5	1.0	0.0	1.6	43.1	100.0
SYH-016	NB-RHA	Surface sediment	< 0.063	1.0	0.0	0.9	0.1	0.0	0.0	0.0	18.1	9.3	1.1	0.4	0.1	0.2	1.3	0.0	0.9	66.6	100.0
SYH-017	HUM-1	Time-integrated suspended sediment	< 0.063	27.2	33.3	0.8	1.8	11.3	12.1	0.0	11.6	0.1	0.0	0.0	0.0	0.1	0.0	0.2	1.7	0.0	100.0
SYH-018	SYR-1a	Time-integrated suspended sediment	< 0.063	23.5	29.1	2.2	2.6	11.9	7.5	0.0	19.1	1.8	0.0	0.0	0.8	0.1	0.0	0.1	1.3	0.0	100.0

Table 2A-1. Mineralogy of sediment samples determined by x-ray diffraction.

[Mineralogy determined by whole-pattern matching using powder x-ray diffraction. values in volume percent, normalized to 100%; mm, millimeter; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	Quartz + cristo-balite	Kaolin-ite + Hallloy-site	Plagio-clase (Na-Ca) feld-spars	Potas-sium feld-spars	Musco-vite	Illite	Smec-tite	Amor-phous (glass) + fulvic acid]	Biotite + chlorite	Amph-ibole (actino-lite)	Dolo-mite + anke-rite	Magne-tite + Mag-hemite	Fluor-apatite + titanite	Ilme-nite	Hema-tite	Goe-thite	Ferri-hydrite	Total
SYH-019	SYR-0	Time-integrated suspended sediment	< 0.063	26.9	20.9	4.8	3.9	9.6	7.8	0.0	19.7	1.9	0.3	0.2	1.1	0.4	0.0	0.3	1.0	1.2	100.0
SYH-100	Pit 1	Excavated sediment, 0 to 3 feet	0.063 to 0.25	46.9	3.1	14.8	5.7	5.5	0.2	2.3	1.8	3.6	5.9	0.6	3.9	0.0	0.6	0.6	0.3	4.1	100.0
SYH-102	Pit 2 OBL	Excavated sediment	0.063 to 0.25	39.2	8.2	10.5	5.4	2.8	0.0	8.3	5.5	1.7	2.7	0.9	5.7	0.2	1.3	1.8	1.0	4.9	100.0
SYH-103	Pit 2 FCZ	Excavated sediment	0.063 to 0.25	43.1	5.6	11.7	4.9	5.7	0.0	5.2	6.6	2.9	3.7	0.8	3.6	0.0	0.5	0.9	0.2	4.6	100.0
SYH-104	Pit 2 CSL	Excavated sediment	0.063 to 0.25	68.4	3.8	5.6	4.1	1.9	1.5	4.5	3.6	0.8	0.7	0.3	1.6	0.0	0.3	0.5	0.6	1.9	100.0
SYH-106	Pit 2 BRC	Excavated sediment	0.063 to 0.25	81.6	2.7	2.9	2.4	1.3	0.0	3.6	1.6	0.4	1.0	0.2	1.3	0.0	0.4	0.3	0.4	0.0	100.0
SYH-108	Pit 1	Dredged sediment, Recirculation Tank	0.063 to 0.25	47.7	0.1	16.0	4.3	6.3	1.6	3.2	5.0	4.5	5.2	0.7	2.5	0.1	0.8	0.3	0.0	1.9	100.0
SYH-109	HMD-CF	Excavated sediment	0.063 to 0.25	78.3	2.9	0.9	5.0	0.1	0.8	5.6	1.7	0.5	0.3	0.0	0.7	`	1.6	0.1	0.5	0.6	100.0
SYH-111	SYR-0	Bed, bank sediment	0.063 to 0.25	36.5	8.4	9.4	8.3	6.1	0.0	0.0	0.0	4.8	4.1	0.7	5.0	0.0	1.2	1.1	0.0	14.4	100.0
SYH-112	HUM-1	Bed, bank sediment	0.063 to 0.25	40.9	7.9	9.1	4.7	1.7	0.0	7.1	4.9	0.6	3.5	0.8	7.1	0.0	2.5	2.8	0.6	5.8	100.0
SYH-113	LC-MTO	Surface sediment	0.063 to 0.25	25.2	16.1	5.8	1.4	3.1	0.0	14.8	27.1	1.3	0.6	0.2	0.6	0.0	0.0	0.2	1.0	2.6	100.0
SYH-114	NB-MTO	Surface sediment	0.063 to 0.25	11.3	0.7	0.1	0.1	0.0	0.0	0.0	31.5	20.6	0.2	6.0	0.0	0.4	0.3	0.0	1.5	27.3	100.0
SYH-115	NB-RHA	Surface sediment	0.063 to 0.25	1.4	0.0	0.1	0.9	0.0	0.0	0.0	25.3	2.1	1.5	0.7	0.0	0.4	0.7	0.0	1.2	65.7	100.0
SYH-116	HUM-1	Time-integrated suspended sediment	0.063 to 0.25	48.1	11.9	7.2	3.4	4.7	5.5	0.0	9.5	0.8	1.0	0.5	4.2	0.7	0.0	0.9	0.5	1.2	100.0

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[Mineralogy determined by whole-pattern matching using powder x-ray diffraction. values in volume percent, normalized to 100%; mm, millimeter; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	Quartz + cristo-balite	Kaolin-ite + Hallloy-site	Plagio-clase (Na-Ca) feld-spars	Potas-sium feld-spars	Musco-vite	Illite	Smec-tite	Amor-phous (glass) + fulvic acid]	Biotite + chlorite	Amph-ibole (actino-lite)	Dolo-mite + anke-rite	Magne-tite + Mag-hemite	Fluor-apatite + titanite	Ilme-nite	Hema-tite	Goe-thite	Ferri-hydrite	Total
SYH-117	SYR-1a	Time-integrated suspended sediment	0.063 to 0.25	40.5	9.8	9.9	6.3	3.8	5.7	0.0	13.2	1.9	1.2	0.5	2.6	0.7	0.0	0.3	0.4	3.2	100.0
SYH-118	SYR-0	Time-integrated suspended sediment	0.063 to 0.25	29.5	15.3	6.0	4.1	6.8	6.3	0.0	24.0	2.4	0.9	0.2	1.7	0.6	0.0	0.3	0.8	1.0	100.0
SYH-200	Pit 1	Excavated sediment, 0 to 3 feet	0.25 to 1.0	56.6	0.4	13.3	3.8	8.7	0.0	1.7	2.5	3.0	4.2	0.5	0.5	0.1	0.3	0.0	0.2	4.0	100.0
SYH-202	Pit 2 OBL	Excavated sediment	0.25 to 1.0	65.4	3.5	8.6	4.4	3.7	0.0	2.4	2.9	2.0	2.6	0.3	1.1	0.1	0.3	0.5	0.1	2.2	100.0
SYH-203	Pit 2 FCZ	Excavated sediment	0.25 to 1.0	64.0	2.2	12.0	3.1	4.8	1.0	2.4	3.1	1.5	2.5	0.5	0.9	0.1	0.3	0.1	0.4	1.1	100.0
SYH-204	Pit 2 CSL	Excavated sediment	0.25 to 1.0	81.8	0.3	3.6	2.5	4.6	0.4	1.5	2.7	0.7	0.8	0.1	0.4	0.0	0.0	0.0	0.5	0.2	100.0
SYH-205	Pit 2 BRC	Excavated sediment	0.25 to 1.0	75.2	0.9	6.9	3.1	3.4	0.7	2.7	2.2	0.9	1.6	0.4	0.6	0.0	0.3	0.1	0.5	0.7	100.0
SYH-206	Pit 1	Dredged sediment, Recirculation Tank	0.25 to 1.0	61.3	0.4	13.4	4.4	7.6	0.0	1.8	2.0	1.7	3.1	0.8	0.6	0.0	0.3	0.0	0.3	2.4	100.0
SYH-207	HMD-CF	Excavated sediment	0.25 to 1.0	93.1	0.9	0.5	1.7	0.0	0.0	2.8	0.5	0.3	0.0	0.0	0.2	0.0	0.0	0.0	0.0	0.0	100.0
SYH-208	SYR-0	Bed, bank sediment	0.25 to 1.0	57.0	0.7	14.1	3.3	5.7	1.9	1.2	1.5	3.1	3.5	0.8	0.8	0.2	0.3	0.3	0.3	5.3	100.0
SYH-209	HUM-1	Bed, bank sediment	0.25 to 1.0	64.7	5.6	7.7	3.4	2.0	1.1	4.4	3.5	0.4	1.6	0.4	1.4	0.0	0.1	0.6	0.1	3.0	100.0
SYH-210	LC-MTO	Surface sediment	0.25 to 1.0	23.8	11.3	1.8	0.6	1.3	0.0	16.5	38.2	2.2	0.3	0.3	0.2	0.0	0.0	0.2	1.1	2.3	100.0
SYH-211	NB-MTO	Surface sediment	0.25 to 1.0	42.6	4.8	1.0	3.3	0.6	0.0	0.0	15.7	3.8	0.5	4.8	0.0	0.3	0.1	0.0	1.7	20.8	100.0
SYH-212	NB-RHA	Surface sediment	0.25 to 1.0	1.9	0.0	0.3	0.4	0.0	0.0	0.6	25.6	9.1	2.4	0.7	0.1	0.3	1.1	0.0	1.2	56.5	100.0

Table 2A-1. Mineralogy of sediment samples determined by x-ray diffraction.

[Mineralogy determined by whole-pattern matching using powder x-ray diffraction. values in volume percent, normalized to 100%; mm, millimeter; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	Quartz + cristo-balite	Kaolin-ite + Hallloy-site	Plagio-clase (Na-Ca) feld-spars	Potas-sium feld-spars	Musco-vite	Illite	Smec-tite	Amor-phous (glass) + fulvic acid]	Biotite + chlorite	Amph-ibole (actino-lite)	Dolo-mite + anke-rite	Magne-tite + Mag-hemite	Fluor-apatite + titanite	Ilme-nite	Hema-tite	Goe-thite	Ferri-hydrite	Total
SYH-213	HUM-1	Time-integrated suspended sediment	0.25 to 1.0	63.1	7.8	8.4	2.6	0.7	5.8	0.0	4.9	0.5	0.4	0.3	2.5	0.2	0.0	0.4	0.1	2.3	100.0
SYH-214	SYR-1a	Time-integrated suspended sediment	0.25 to 1.0	57.0	1.3	13.3	3.4	4.4	4.1	0.0	3.1	3.3	2.0	0.7	1.6	0.8	0.0	0.2	0.0	4.8	100.0
SYH-215	SYR-0	Time-integrated suspended sediment	0.25 to 1.0	60.0	0.9	13.1	3.6	5.4	3.8	0.0	2.3	2.6	1.5	0.9	1.0	0.5	0.0	0.1	0.0	4.2	100.0

Table 2A-2. Mineral formulas and standards used for x-ray diffraction analysis

[See front matter of report for explanation of chemical symbols; XRD, x-ray diffraction; na, not applicable]

Mineral	Formula	Standards used for matching powder XRD patterns
Quartz	SiO_2	
Cristobalite	SiO_2	
Kaolinite	$Al_2Si_2O_5(OH)_4$	Disordered
Halloysite	$Al_2Si_2O_5(OH)_4$	
Plagioclase feldspars	$NaAlSi_3O_8$ to $CaAl_2Si_2O_8$	Oligoclase, andesine, albite (var. clevelandite)
Potassium feldspars	$KAlSi_3O_8$	Intermediate microcline, sanidine, orthoclase
Muscovite	$KAl_2(AlSi_3O_{10})(OH,F)_2$	2M1
Illite	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2,(H_2O)]$	1Md
Smectite (montmorillonite)	$(Na,Ca)_{0.33}(Al,Mg)_2(Si_4O_{10})(OH)_2 \cdot nH_2O$	
Biotite	$K(Mg,Fe)_3AlSi_3O_{10}(F,OH)_2$	1M
Chlorite	$(Mg,Fe)_3(Si,Al)_4O_{10}(OH)_2 \cdot (Mg,Fe)_3(OH)_6$	CCa-2, CMM
Amphibole (tremolite-actinolite)	$Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2$	
Dolomite	$CaMg(CO_3)_2$	
Ankerite	$CaFe(CO_3)_2$	
Magnetite	Fe_3O_4	
Maghemite	Fe_2O_3	
Fluorapatite	$Ca_5(PO_4)_3(F,OH)$	
Titanite (sphene)	$CaTiSiO_5$	
Ilmenite	$FeTiO_3$	
Hematite	Fe_2O_3	Fine grind
Goethite	$FeO(OH)$	
Ferrihydrite	$FeO(OH) \cdot 0.4H_2O$	
Amorphous (glass)	na	White River tephra
Organics	na	Humic acid

Table 2A-3. Major element chemistry of sediment samples determined by x-ray fluorescence and loss on ignition

[mm, millimeter; nd, not determined; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	All values in weight percent											
				SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Totals	Loss on ignition
SYH-003	Pit 1	Excavated sediment, 0 to 3 feet	< 0.063	63.2	19.2	7.76	2.77	2.09	2.15	1.25	0.87	0.16	0.20	99.7	21.2
SYH-004	Pit 2 OBL	Excavated sediment	< 0.063	65.7	23.8	6.06	0.9	0.62	1.98	0.72	1.06	0.08	0.09	100.9	11.7
SYH-005	Pit 2 FCZ	Excavated sediment	< 0.063	64.8	23.3	6.00	0.92	0.68	2.00	0.72	1.04	0.08	0.11	99.6	10.1
SYH-006	Pit 2 CSL	Excavated sediment	< 0.063	59.7	23.4	9.43	0.81	0.51	1.69	0.35	0.97	0.21	0.13	97.3	23.3
SYH-007	Pit 2 BRC	Excavated sediment	< 0.063	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
SYH-008	Pit 1	Dredged sediment, Recirculation Tank	< 0.063	65.1	16.2	7.68	3.21	2.33	2.19	1.46	0.80	0.15	0.18	99.3	6.1
SYH-009	HMD-CF	Excavated sediment	< 0.063	61.7	20.2	11.84	0.88	0.53	1.55	0.49	1.45	0.04	0.25	98.9	18.5
SYH-010	SYR-0	Bed, bank sediment	< 0.063	63.9	19.0	7.71	2.17	1.63	1.95	0.99	0.88	0.23	0.25	98.7	12.5
SYH-011	HUM-1	Bed, bank sediment	< 0.063	61.5	23.8	7.06	1.16	0.83	1.86	0.64	1.13	0.24	0.16	98.3	11.1
SYH-012	LC-MTO	Surface sediment	< 0.063	68.0	21.7	5.82	1.07	1.52	1.47	0.92	1.06	0.05	0.18	101.7	17.1
SYH-013	NB-MTO	Surface sediment	< 0.063	<11.0	4.63	48.8	0.28	11.2	0.29	0.19	< 0.25	7.82	0.16	73.4	18.9
SYH-016	NB-RHA	Surface sediment	< 0.063	13.5	1.82	68.8	0.18	0.22	0.06	0	0.03	0.05	0.43	85.2	16.4
SYH-017	HUM-1	Time-integrated suspended sediment	< 0.063	65.7	22.2	5.83	1.15	0.54	2.00	0.38	1.08	0.15	0.10	99.1	nd
SYH-018	SYR-1a	Time-integrated suspended sediment	< 0.063	66.3	22.2	5.95	1.59	0.86	2.09	0.78	0.92	0.13	0.14	100.9	nd
SYH-019	SYR-0	Time-integrated suspended sediment	< 0.063	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
SYH-100	Pit 1	Excavated sediment, 0 to 3 feet	0.063 to 0.25	69.0	11.7	9.61	2.55	3.58	1.55	1.51	1.12	0.15	0.11	100.9	2.6
SYH-102	Pit 2 OBL	Excavated sediment	0.063 to 0.25	64.6	12.5	12.5	2.17	2.21	1.29	1.08	1.83	0.20	0.11	98.5	4.2
SYH-103	Pit 2 FCZ	Excavated sediment	0.063 to 0.25	68.1	12.3	8.68	2.21	2.49	1.39	1.04	1.20	0.16	0.11	97.7	4.0
SYH-104	Pit 2 CSL	Excavated sediment	0.063 to 0.25	78.1	8.31	6.38	1.24	1.11	1.00	0.66	0.87	0.24	0.10	98.0	2.8
SYH-106	Pit 2 BRC	Excavated sediment	0.063 to 0.25	88.5	5.23	4.06	0.68	0.72	0.52	0.36	0.80	0.10	0.07	101.0	1.8
SYH-108	Pit 1	Dredged sediment, Recirculation Tank	0.063 to 0.25	71.2	11.6	7.69	2.63	3.32	1.58	1.62	0.83	0.12	0.12	100.7	2.4
SYH-109	HMD-CF	Excavated sediment	0.063 to 0.25	87.3	5.71	3.99	0.49	0.50	0.88	0.32	1.47	0.07	0.06	100.7	1.8
SYH-111	SYR-0	Bed, bank sediment	0.063 to 0.25	68.1	12.3	11.5	2.06	2.71	1.76	1.12	1.28	0.15	0.13	101.2	4.4
SYH-112	HUM-1	Bed, bank sediment	0.063 to 0.25	65.4	10.8	14.5	2.30	1.93	1.08	0.82	2.35	0.22	0.10	99.5	3.9
SYH-113	LC-MTO	Surface sediment	0.063 to 0.25	69.0	19.6	5.91	1.35	2.16	1.29	0.86	1.01	0.06	0.17	101.5	25.5
SYH-114	NB-MTO	Surface sediment	0.063 to 0.25	74.8	4.64	24.6	0.32	42.0	0.38	0.74	<1.1	16.87	0.12	164.5	20.8

Table 2A-3. Major element chemistry of sediment samples determined by x-ray fluorescence and loss on ignition

[mm, millimeter; nd, not determined; <, less than]

Lab ID	Field ID, sample name	Sample type	Grain-size fraction (mm)	All values in weight percent											
				SiO_2	Al_2O_3	Fe_2O_3	MgO	CaO	K_2O	Na_2O	TiO_2	MnO	P_2O_5	Totals	Loss on ignition
SYH-115	NB-RHA	Surface sediment	0.063 to 0.25	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
SYH-116	HUM-1	Time-integrated suspended sediment	0.063 to 0.25	74.0	12.4	7.64	1.92	1.52	1.32	0.82	1.23	0.20	0.10	101.2	nd
SYH-117	SYR-1a	Time-integrated suspended sediment	0.063 to 0.25	72.7	14.6	6.41	2.27	2.00	2.03	1.22	0.77	0.12	0.11	102.2	nd
SYH-118	SYR-0	Time-integrated suspended sediment	0.063 to 0.25	67.7	17.2	6.55	2.14	1.65	2.01	0.97	0.85	0.18	0.15	99.4	nd
SYH-200	Pit 1	Excavated sediment, 0 to 2 feet	0.25 to 1.0	75.4	10.6	5.12	2.06	3.22	1.43	1.45	0.43	0.18	0.10	100.0	2.0
SYH-201	Pit 1	Excavated sediment, 0 to 3 feet	0.25 to 1.0	76.6	10.5	4.96	2.15	3.26	1.41	1.61	0.46	0.09	0.10	101.1	1.8
SYH-202	Pit 2 OBL	Excavated sediment	0.25 to 1.0	79.8	8.38	5.25	1.55	1.94	0.92	0.94	0.67	0.10	0.07	99.6	2.0
SYH-203	Pit 2 FCZ	Excavated sediment	0.25 to 1.0	81.7	9.02	4.01	1.63	2.01	1.18	1.26	0.38	0.08	0.10	101.4	2.0
SYH-204	Pit 2 CSL	Excavated sediment	0.25 to 1.0	90.8	5.38	2.61	0.8	1.08	0.62	0.56	0.25	0.06	0.06	102.2	1.2
SYH-205	Pit 2 BRC	Excavated sediment	0.25 to 1.0	89.7	7.54	3.81	1.32	1.52	0.98	0.88	0.36	0.10	0.09	106.3	1.8
SYH-206	Pit 1	Dredged sediment, recirculation Tank	0.25 to 1.0	79.1	10.3	4.21	1.94	2.78	1.52	1.36	0.39	0.08	0.09	101.7	1.9
SYH-207	HMD-CF	Excavated sediment	0.25 to 1.0	99.8	2.73	1.14	0.25	0.23	0.33	0.41	0.14	0.01	0.04	105.1	0.8
SYH-208	SYR-0	Bed, bank sediment	0.25 to 1.0	80.3	10.2	4.92	1.91	3.05	1.42	1.33	0.39	0.10	0.10	103.7	1.8
SYH-209	HUM-1	Bed, bank sediment	0.25 to 1.0	84.5	8.22	4.63	1.12	1.23	0.71	0.89	0.49	0.10	0.10	102.0	2.8
SYH-210	LC-MTO	Surface sediment	0.25 to 1.0	68.1	19.2	6.19	1.13	2.62	1.25	0.70	0.92	0.09	0.20	100.3	42.4
SYH-211	NB-MTO	Surface sediment	0.25 to 1.0	63.3	5.19	20.1	0.48	20.9	0.63	0.89	<0.45	10.3	0.12	121.8	23.0
SYH-212	NB-RHA	Surface sediment	0.25 to 1.0	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
SYH-213	HUM-1	Time-integrated suspended sediment	0.25 to 1.0	82.7	9.78	4.66	1.35	1.25	0.79	0.96	0.43	0.10	0.10	102.2	nd
SYH-214	SYR-1a	Time-integrated suspended sediment	0.25 to 1.0	78.8	10.9	4.42	2.15	2.42	1.46	1.24	0.41	0.09	0.08	102.0	nd
SYH-215	SYR-0	Time-integrated suspended sediment	0.25 to 1.0	79.7	10.9	4.09	2.05	2.22	1.48	1.33	0.38	0.07	0.07	102.3	nd

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For more information concerning the research in this report, contact the

Director, California Water Science Center
U.S. Geological Survey
6000 J Street, Placer Hall
Sacramento, California 95819
http://ca.water.usgs.gov