

Metals Transport in the Sacramento River, California, 1996–1997: Volume 2. Interpretation of Metal Loads

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Executive Summary

Transport of metals in the Sacramento River from Shasta Dam to Freeport was evaluated for the period July 1996 through June 1997 using an approach that quantified the dissolved and colloidal concentrations and corresponding loads of metals at six mainstem sites during six sampling periods. Two of the sampling periods (December 1996 and January 1997) took place during relatively high-flow conditions, whereas the other four sampling periods (July, September, and November 1996 and May–June 1997) took place during lower flow conditions. The water year corresponding to the duration of this study was unusual for northern California in that precipitation was concentrated primarily in December and January with an extremely dry period from February to April. The overall precipitation for the year was close to long-term averages; however, severe flooding took place in early January 1997 at several locations in the Sacramento River watershed. Approximately 70 percent of total annual discharge at the two farthest downstream sampling locations (Sacramento River at Freeport and Yolo Bypass at Interstate 80) took place during the 3-month period December 1996 through February 1997. Because of increased transport of suspended sediment and higher total metal concentrations in water during this wet period, the proportion of annual metal loads transported was significantly greater than 70 percent.

The proportions of cadmium, copper, lead, and zinc loads that are exported from the Sacramento River to the San Francisco Bay and

the Sacramento–San Joaquin Delta estuary (hereinafter referred to as the Bay–Delta), and that are associated with the mineralized areas upstream of Keswick Dam, were estimated by comparing metal loads at Keswick Dam with those at the site(s) sampled farthest downstream, generally the Sacramento River at Freeport (and the Yolo Bypass, when flowing). The results are highly dependent on the flow regime. The following proportions of mineralization-related trace-metal loads were observed (percentages represent dissolved plus colloidal loads at Keswick Dam divided by the sum of dissolved and colloidal loads at Freeport and the Yolo Bypass). During moderately high flows in December 1996, percentages were cadmium, 87 percent; copper, 35 percent; lead, 10 percent; and zinc, 51 percent. During flood conditions in early January 1997, percentages were cadmium, 22 percent; copper, 11 percent; lead, 2 percent; and zinc, 15 percent. During irrigation drainage season from rice fields during May–June 1997, percentages were cadmium, 53 percent; copper, 42 percent; lead, 20 percent; and zinc, 75 percent. These estimates must be qualified by the following factors. First, metal loads at Colusa in December 1996 and at Verona during May–June 1997 generally exceeded those determined at Freeport during those sampling periods. Therefore, the above percentages represent maximum estimates of the apparent total proportion of metals from mineralized areas upstream of Keswick Dam. Second, the Sacramento River was sampled at Tower Bridge

instead of at Freeport during January 1997 for logistics reasons.

Available data suggest that trace-metal loads from agricultural drainage may be significant during certain flow conditions. However, additional studies are needed before definitive conclusions can be drawn. Load data for sampling periods during July and September 1996 and during May–June 1997 show increases of dissolved and colloidal copper and colloidal zinc between Colusa and Verona, the reach of the Sacramento River along which the Colusa Basin Drain, the Sacramento Slough, and other agricultural return flows are tributaries. Monthly sampling of these two agricultural drains by the U.S. Geological Survey’s National Water-Quality Assessment Program shows seasonal variations in metal concentrations. For example, “dissolved” (0.45-micrometer filtrate) copper concentrations in National Water-Quality Assessment Program samples from the Colusa Basin Drain reached 6 micrograms per liter in May 1996 and 3 to 4 micrograms per liter in June 1997; “dissolved” copper in the Sacramento Slough reached a maximum of 4 micrograms per liter in December 1996. To put the copper loads associated with agricultural drainage in perspective, the total (dissolved plus colloidal) load of copper from the Colusa Basin Drain in June 1997 was 18 kilograms per day, whereas the copper load in Spring Creek, which drains the inactive mines on Iron Mountain, was 20 kilograms per day during the same sampling period. In contrast, during the January 1997 flood, the copper load in Spring Creek was about 1,100 kilograms per day and the copper load in the Yolo Bypass was about 7,300 kilograms per day. These data clearly indicate that the majority of copper and zinc loads during the January 1997 flood entered the Sacramento River upstream of Colusa and upstream of the influence of most intense agricultural drainage return flows in the Sacramento River Watershed.

This study has demonstrated that some trace metals of environmental significance (cadmium, copper, and zinc) in the Sacramento River are transported largely in dissolved form at upstream sites (below Shasta Dam, below

Keswick Dam, and at Bend Bridge) proximal to the mineralized areas of the West Shasta and East Shasta mining districts. In the acidic water of Spring Creek, cadmium, copper, and zinc are transported almost exclusively in dissolved form. In contrast, these trace metals are transported largely in colloidal form at downstream sites (Colusa, Verona, Freeport, and Yolo Bypass). Aluminum, iron, and lead were observed to be transported predominantly in the colloidal phase at all mainstem Sacramento River sampling sites during all sampling periods in this study. Despite continuous water treatment that has removed 85 to 90 percent of the cadmium, copper, and zinc from the mine drainage at Iron Mountain, Spring Creek remains an important source of these metals to the Sacramento River system.

Abstract

Metals transport in the Sacramento River, northern California, from July 1996 to June 1997 was evaluated in terms of metal loads from samples of water and suspended colloids that were collected on up to six occasions at 13 sites in the Sacramento River Basin. Four of the sampling periods (July, September, and November 1996; and May–June 1997) took place during relatively low-flow conditions and two sampling periods (December 1996 and January 1997) took place during high-flow and flooding conditions, respectively. This study focused primarily on loads of cadmium, copper, lead, and zinc, with secondary emphasis on loads of aluminum, iron, and mercury.

Trace metals in acid mine drainage from abandoned and inactive base-metal mines, in the East and West Shasta mining districts, enter the Sacramento River system in predominantly dissolved form into both Shasta Lake and Keswick Reservoir. The proportion of trace metals that was dissolved (as opposed to colloidal) in samples collected at Shasta and Keswick dams decreased in the order zinc \approx cadmium > copper > lead. At four sampling sites on the Sacramento River—71, 256, 360, and 412 kilometers downstream of

Keswick Dam—trace-metal loads were predominantly colloidal during both high- and low-flow conditions. The proportion of total cadmium, copper, lead, and zinc loads transported to San Francisco Bay and the Sacramento–San Joaquin Delta estuary (referred to as the Bay–Delta) that is associated with mineralized areas was estimated by dividing loads at Keswick Dam by loads 412 kilometers downstream at Freeport and the Yolo Bypass. During moderately high flows in December 1996, mineralization-related total (dissolved + colloidal) trace-metal loads to the Bay–Delta (as a percentage of total loads measured downstream) were cadmium, 87 percent; copper, 35 percent; lead, 10 percent; and zinc, 51 percent. During flood conditions in January 1997 loads were cadmium, 22 percent; copper, 11 percent; lead, 2 percent; and zinc, 15 percent. During irrigation drainage season from rice fields (May–June 1997) loads were cadmium, 53 percent; copper, 42 percent; lead, 20 percent; and zinc, 75 percent. These estimates must be qualified by the following factors: (1) metal loads at Colusa in December 1996 and at Verona in May–June 1997 generally exceeded those determined at Freeport during those sampling periods. Therefore, the above percentages represent maximum estimates of the apparent total proportion of metals from mineralized areas upstream of Keswick Dam; and (2) for logistics reasons, the Sacramento River was sampled at Tower Bridge instead of at Freeport during January 1997.

Available data suggest that trace metal loads from agricultural drainage may be significant during certain flow conditions in areas where metals such as copper and zinc are added as agricultural amendments. Copper loads for sampling periods in July and September 1996 and in May–June 1997 show increases of dissolved and colloidal copper and in colloidal zinc between Colusa and Verona, the reach of the Sacramento River along which the Colusa Basin Drain, the Sacramento Slough, and other agricultural return flows are tributaries. Monthly sampling of these two agricultural drains by the USGS National Water-Quality Assessment Program shows

seasonal variations in metal concentrations, reaching maximum concentrations of 4 to 6 micrograms per liter in “dissolved” (0.45-micrometer filtrate) copper concentrations in May 1996, December 1996, and June 1997. The total (dissolved plus colloidal) load of copper from the Colusa Basin Drain in June 1997 was 18 kilograms per day, whereas the copper load in Spring Creek, which drains the inactive mines on Iron Mountain, was 20 kilograms per day during the same sampling period. For comparison, during the January 1997 flood, the copper load in Spring Creek was about 1,100 kilograms per day and the copper load in the Yolo Bypass was about 7,300 kilograms per day. The data clearly indicate that most copper and zinc loads during the January 1997 flood entered the Sacramento River upstream of Colusa, and upstream of the influence of the most intense agricultural drainage return flows in the Sacramento River watershed.

This study has demonstrated that some trace metals of environmental significance (cadmium, copper, and zinc) in the Sacramento River are transported largely in dissolved form at upstream sites (below Shasta Dam, below Keswick Dam, and at Bend Bridge) proximal to the mineralized areas of the West Shasta and East Shasta mining districts. In contrast, these trace metals are transported largely in colloidal form at downstream sites (Colusa, Verona, Freeport, and Yolo Bypass). Aluminum, iron, and lead were observed to be transported predominantly in the colloidal phase at all mainstem Sacramento River sampling sites during all sampling periods in this study. Despite continuous water treatment, which has removed 85 to 90 percent of the cadmium, copper, and zinc from the mine drainage at Iron Mountain, Spring Creek remains a significant source of these metals to the Sacramento River system.

Introduction

The Sacramento River is the largest river in California in length (327 mi or 526 km) and discharge (mean annual runoff of 16,960,000 acre-ft per year; Anderson and others, 1997). The river is of critical

importance to the economy of the state because it supplies irrigation water to farms of the Central Valley (the Sacramento Valley as shown in fig. 1 and the San Joaquin Valley, not shown), provides the greatest source of fresh water to San Francisco Bay and the Sacramento–San Joaquin Delta estuary (collectively referred to hereinafter as the Bay–Delta), and provides drinking water to millions of urban residents in both northern and southern California. Although the water quality of the Sacramento River is generally suitable for most uses, the river is impacted by mine drainage, urban runoff, point sources, and nonpoint sources such as agricultural runoff (California State Water Resources Control Board, 1992). The major water-quality impairments in the Sacramento River are attributed to metals and pesticides, although the causes of some aquatic toxicity in the watershed remain undetermined (Larsen, 1998).

One major source of metals to the Sacramento River is drainage from inactive mines in the Iron Mountain area of the West Shasta mining district. During mining and smelting activities from the 1880s to the 1960s, the acid mine drainage from Iron Mountain discharged directly to Spring Creek, a tributary to the Sacramento River upstream of Redding. The hydrology of the Sacramento River in the area upstream of Redding is affected considerably by several aspects of the Central Valley Project (CVP). Key features of the CVP and years completed are Shasta Dam, 1943–1945; Keswick Dam, 1950; Whiskeytown Lake, 1963; and the Spring Creek Power Plant (SCPP), 1963. The Spring Creek Debris Dam (SCDD) was completed in 1963 to prevent siltation in the tail race of the SCPP, and also to regulate the acid mine drainage in Spring Creek, which was a known threat to aquatic life (U.S. Environmental Protection Agency, 1992). At least 30 fish kills during the period 1940–1969 near Redding were associated with metal-rich, acid drainage from Iron Mountain by way of Spring Creek (Nordstrom and others, 1977). Limited treatment of Iron Mountain mine drainage to remove copper (Cu) by iron (Fe) cementation was done from the 1970s until the early 1990s, with variable success. An emergency lime-neutralization plant was required by the U.S. Environmental Protection Agency during 3 to 4 months of the wet season from 1989 to 1994. Since November 1994, the most concentrated acid discharges from the mines at Iron Mountain have been treated year-round by lime neutralization, removing

about 85 percent of the copper and about 90 percent of the zinc (Zn) and cadmium (Cd) compared with untreated loads (Richard Sugarek, U.S. Environmental Protection Agency, written commun., 1997).

Despite the ongoing water treatment at Iron Mountain, a significant reach of the Sacramento River—more than 200 river mi downstream of Keswick Dam—may be affected by elevated trace metal concentrations as a result of significant runoff events of acid mine drainage by way of Spring Creek. The Bureau of Reclamation manages releases of water from Spring Creek Reservoir under a 1980 Memorandum of Understanding (MOU) with several other agencies. Under the MOU, the primary goal of water management in the Spring Creek area has been to achieve compliance with water-quality standards for metals at a point immediately downstream of Keswick Dam. Compliance usually has been achieved by mixing water from Spring Creek Reservoir with water from Shasta Lake released from Shasta Dam and from Whiskeytown Lake, which flows into Keswick Reservoir by way of the Spring Creek Power Plant (fig. 2). On several occasions since 1963, the water level in Spring Creek Reservoir has exceeded the spillway elevation, causing uncontrolled release of acidic water to Keswick Reservoir and occasionally exceeding water-quality standards at Keswick Dam. The impacts of such metal releases on aquatic life in Keswick Reservoir and the Sacramento River below Keswick Dam have been documented to some extent in terms of acute toxicity to fish (U.S. Environmental Protection Agency, 1992). However, much less is known regarding the chronic impacts of metals on ecosystems or the downstream impacts and transport of the metals from mine drainage in this area.

Metals such as cadmium, copper, lead (Pb), and zinc enter Keswick Reservoir as part of the acid mine drainage from Spring Creek. Prior to part-time lime neutralization in 1989, the acid water of Spring Creek below the SCDD had pH values generally less than 3. During 1994–1998, pH values in Spring Creek below the SCDD have been commonly between 4 and 5. Where the Spring Creek waters mix with near-neutral, dilute waters of Keswick Reservoir, the pH rises to near 7 and the metals are partially to completely redistributed in the form of suspended colloids or other solid forms composed primarily of hydrous iron and aluminum oxides (Nordstrom and others, 1999). These solids and associated metals, and remaining dissolved metals, can be transported out of Keswick Reservoir

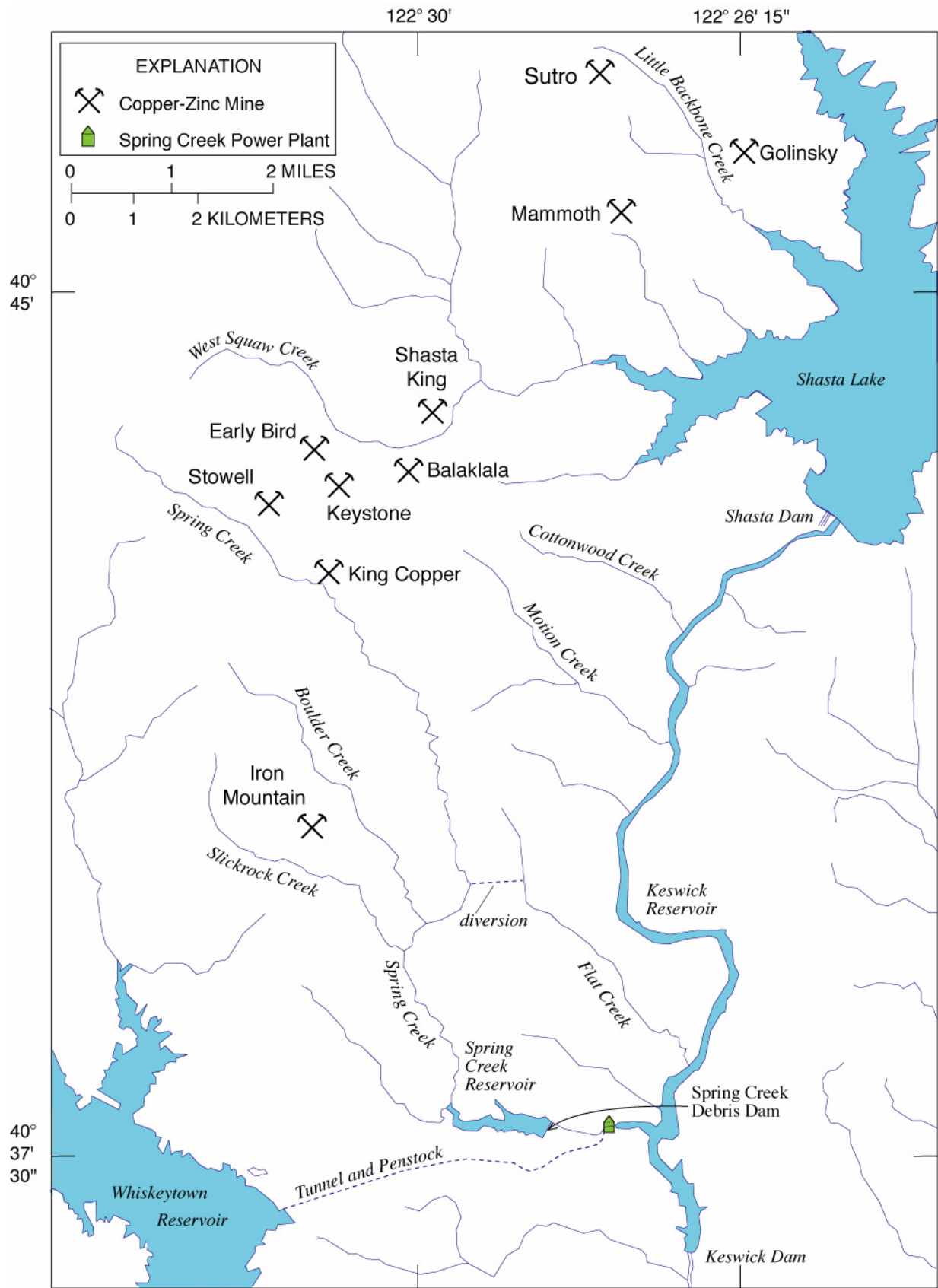


Figure 2. Location map of West Shasta mining district, Shasta County, California.

and into the Sacramento River, and then transported toward the Bay–Delta. In sufficiently high concentrations, the metals can be toxic to aquatic life; numerous fish kills have occurred in the reach of the Sacramento River below Keswick Reservoir. Monitoring programs for metals downstream of Keswick Reservoir have been designed primarily for the assessment of compliance with water-quality standards. Water samples collected by other federal and state agencies (and their contractors) for metal analyses have included both unfiltered and filtered samples. Unfiltered (whole water) samples typically have been subjected to total recoverable analysis (an incomplete digestion). Sample filtration typically is done using conventional 0.45- μm pore-size filters. Colloidal forms of metal are known to pass through conventional 0.45 μm pore-size filters (Kimball and others, 1995; Church and others, 1997). Therefore, neither the fate nor the transport of colloidal metals have been addressed quantitatively in these sampling programs. Knowledge of the fate of the colloidal metals is crucial in understanding sources of metals and how far downstream metals from mine drainage are transported, and in distinguishing metals originating from mine drainage from those with other sources, such as agricultural or urban runoff.

Previous Work and Related Ongoing Studies

One of the more extensive monitoring programs for metals in the Sacramento River Watershed is located in Sacramento County and is called the Coordinated Monitoring Program (CMP). Participating agencies in the CMP are the Sacramento Regional County Sanitation District (a cooperating agency on this study), the Sacramento County Water Agency, and the City of Sacramento. This program began in 1991 (Larry Walker Associates and Brown and Caldwell, 1994). Sampling sites were chosen on the Sacramento River both upstream and downstream of the City of Sacramento. The American River, just below Folsom Dam (fig.1) and just before the confluence with the Sacramento River, also was sampled. Another comprehensive monitoring program in the watershed, the Sacramento River Watershed Program, is administered by the Sacramento Regional County Sanitation District and is designed to assess toxicity of metals and pesticides to aquatic organisms in the Sacramento River and to quantify metal loads to the Bay–Delta.

The California Regional Water Quality Control Board (hereinafter called the Regional Water Board) has recently completed a study of metal concentrations and loads in the Sacramento River system (Connor and Clark, 1999) on the basis of sampling during 1993–1995. That study showed that metal loads were greatest during wet-season run-off conditions. Studies of aquatic toxicity by the Regional Water Board (Connor and others, 1994; Larsen, 1998; Larsen and others, 1998) on the basis of water sampling during 1993–1997 indicate that metals generally did not cause toxicity to aquatic organisms downstream of Shasta Dam. However, in the Upper Sacramento River, upstream of Shasta Lake (fig. 1), these studies found that nickel (Ni) caused toxicity to *Ceriodaphnia dubia*.

Trace metals are monitored in the Sacramento River Basin as part of the United States Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program (Domagalski and others, 1998). An intensive period of monthly sampling for that program occurred from February 1996 to February 1998 at 12 sites in the Sacramento River Basin, including 4 sites on the Sacramento River: Bend Bridge, Colusa, Verona, and Freeport (fig. 1). A less intensive period of monthly sampling at only the Freeport site has continued since March 1998. Water samples from the NAWQA Program taken for analysis of trace metals are filtered through 0.45- μm pore-size capsule (Gelman) filters. The detection limit for most trace metal determinations using the standard methods of the USGS's National Water Quality Laboratory (NWQL) during the intensive sampling period was 1 $\mu\text{g/L}$. Although barely suitable for some metals, such as copper and zinc, this relatively high detection limit commonly result in nondetections for many trace metals of interest in filtered samples, including cadmium and lead.

Studies of metal transport in other watersheds have provided important information regarding the role of colloids, especially in other waterbodies that receive metal-rich, acidic drainage from historic mining areas. Extensive colloid transport of metals was documented in the upper Arkansas River, downstream of Leadville, Colorado (Kimball and others, 1995). Similar effects were seen in a detailed study of metal transport in the upper Animas Basin, which includes Silverton, Colorado (Church and others, 1997).

Purpose and Scope

Because of limitations in trace metal detection limits of the USGS's standard NAWQA protocols and the relatively limited extent of the NAWQA sampling network in the Sacramento River watershed, the present study was designed to assess metals transport in the Sacramento River. Water samples were taken during six sampling periods between July 1996 and June 1997, and were processed using tangential-flow ultrafiltration techniques to separate colloidal solids from the aqueous phase, resulting in better estimates for dissolved metals. A related report (Volume 1 [Alpers and others, 2000]) describes the methods and the quality assurance and quality control aspects of the USGS metals transport study, and gives the results of metal concentration data. The present report (Volume 2) contains interpretations of metals transport in the Sacramento River system in terms of metal loads. The metal loads are computed for dissolved and colloidal fractions of the water, as well as for whole-water samples using a partial digestion related to total-recoverable metals (Alpers and others, 2000).

The scope of this report (Volume 2) is limited to interpretation of loads for six metals: aluminum (Al), cadmium, copper, iron, lead, and zinc. Information from this study on mercury (Hg) loads in the Sacramento River watershed are discussed in a separate report (David Roth, U.S. Geological Survey, written commun., 1999). Another companion report from this study (Cain and others, 2000) describes metal bioaccumulation in caddisfly larvae taken from five sampling sites on the Sacramento River between Keswick Dam and Tehama plus a site on a tributary, Cottonwood Creek (fig. 1). The chemistry of streambed sediments from these six sites was documented in a previous report (Alpers and others, 2000).

Appendix 1 of this report contains tables of data with loads of selected metals (Al, Cd, Cu, Fe, Pb, Hg, and Zn) in dissolved form, colloidal form, and whole water (total recoverable analyses). In Appendix 2, metal loads at each sampling point are compared with the sum of the loads at Freeport and the Yolo Bypass. Tables of load data used in mass balance calculations are given in Appendix 3 (Spring Creek arm of Keswick Reservoir) and Appendix 4 (Keswick Reservoir). Other appendixes include plots of dissolved and colloidal loads for miscellaneous metals (Appendix 5) and hydrographs for selected sampling

periods showing variations in discharge in relation to the time of sampling (Appendix 6).

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Computation of Metal Loads

The instantaneous load of a given constituent transported by a river is the product of the concentration of that constituent at a given time and the instantaneous discharge of the river at that same time. In practice, it is usually difficult, if not impossible, to obtain truly instantaneous water-quality samples and discharge measurements, but most river systems do not change appreciably over the course of

a day; so, what is commonly calculated is an average load expressed in kilograms per day (kg/d). The assumptions made by this approach are that both the concentration of the constituent and the discharge of the river remain relatively constant for the day in which the measurements are made. The actual formula is:

$$\text{Load (kg/d)} = \text{Concentration } (\mu\text{g/L}) \times \text{Discharge (m}^3\text{/s)} \times 0.0864 \quad (1)$$

Discharge

The flow regime of the Sacramento River is highly seasonal, in response to the mediterranean climate of northern California. The wet season in the watershed ranges typically from November to May, with snowmelt occurring normally during April through June; warm rains earlier in the winter have been known to cause extensive melting associated with extremely high discharge such as the New Year's flood of 1997 (Hunrichs and others, 1998). The six sampling periods for the present study were chosen to span a variety of flow conditions. The sampling periods in July, September, and November 1996 and during May–June 1997 occurred during relatively low-flow conditions whereas the sampling periods during December 1996 and January 1997 were during high-flow conditions (fig. 3).

Discharge in the Sacramento River and its major tributaries is managed for the purposes of flood control, irrigation, and aquatic habitat. Several water diversions affecting the Sacramento River cause significant seasonal changes in the flow regime. Diversions for agricultural use include the Tehama–Colusa and Glenn–Colusa canals (fig. 3). Return flows from irrigation on the western side of the Sacramento River are collected in the Colusa Basin Drain (figs. 1 and 3), which enters the Sacramento River downstream of Colusa and upstream of the confluence of the Sacramento River with the Feather River. On the eastern side of the valley, agricultural return flows are collected in the Sacramento Slough (figs. 1 and 3). The agricultural diversions are most active during irrigation season, typically May through October. Flood control diversions in the Sacramento River system include the Sutter and Yolo bypasses, which are typically most active during December through April (figs. 3D, 3E).

As a result of the various diversions and water management practices, the flow regime on the

Sacramento River was somewhat different during each of the six sampling periods in this study. The diagrams in figure 3 indicate the relative discharge of the Sacramento River and its tributaries and a distributary (the Yolo Bypass) for each of the sampling periods. During all six sampling periods, the discharge of the Sacramento River decreased between Red Bluff and Colusa. During low-flow conditions this decrease was primarily because of agricultural diversions, whereas during high-flow conditions this decrease resulted from flood-control diversions.

Dissolved Loads

Tables of load data (Appendix 1) were calculated according to the formula in Equation (1) using the concentration and discharge data from Alpers and others (2000). Dissolved loads were computed using concentration data from the tangential-flow ultrafiltrates that were derived using 10,000 daltons, or Nominal Molecular Weight Limit (NMWL) membranes, equivalent to an effective pore-size diameter of 0.005 μm (Millipore Corporation, 1993). Other studies typically have measured concentrations using 0.45- μm pore-size filters, which tend to yield higher values than the ultrafilters.

Conventional filtrates were also produced using a 0.45- μm pore-size capsule filter (Gelman) and a 0.40- μm pore-size membrane filter (Nuclepore). Metal concentrations in these conventional filtrates were generally higher than those observed in the ultrafiltrates, especially for such elements as aluminum, iron, and lead, which are associated with fine-grained colloids. It is very important to recognize these differences if the “dissolved” data reported here are to be compared with “dissolved” loads based on conventional filtrates from other studies.

Colloidal Loads

Colloidal loads were calculated in a manner similar to that used for dissolved loads, by multiplying the discharge of the river or creek by the equivalent colloid concentration of the constituent. The equivalent colloid concentration is directly analogous to the dissolved concentration of a constituent; both use units of micrograms per liter (or milligrams per liter), and both represent the mass of the constituent present per unit volume of water. The dissolved concentration represents the amount of the constituent

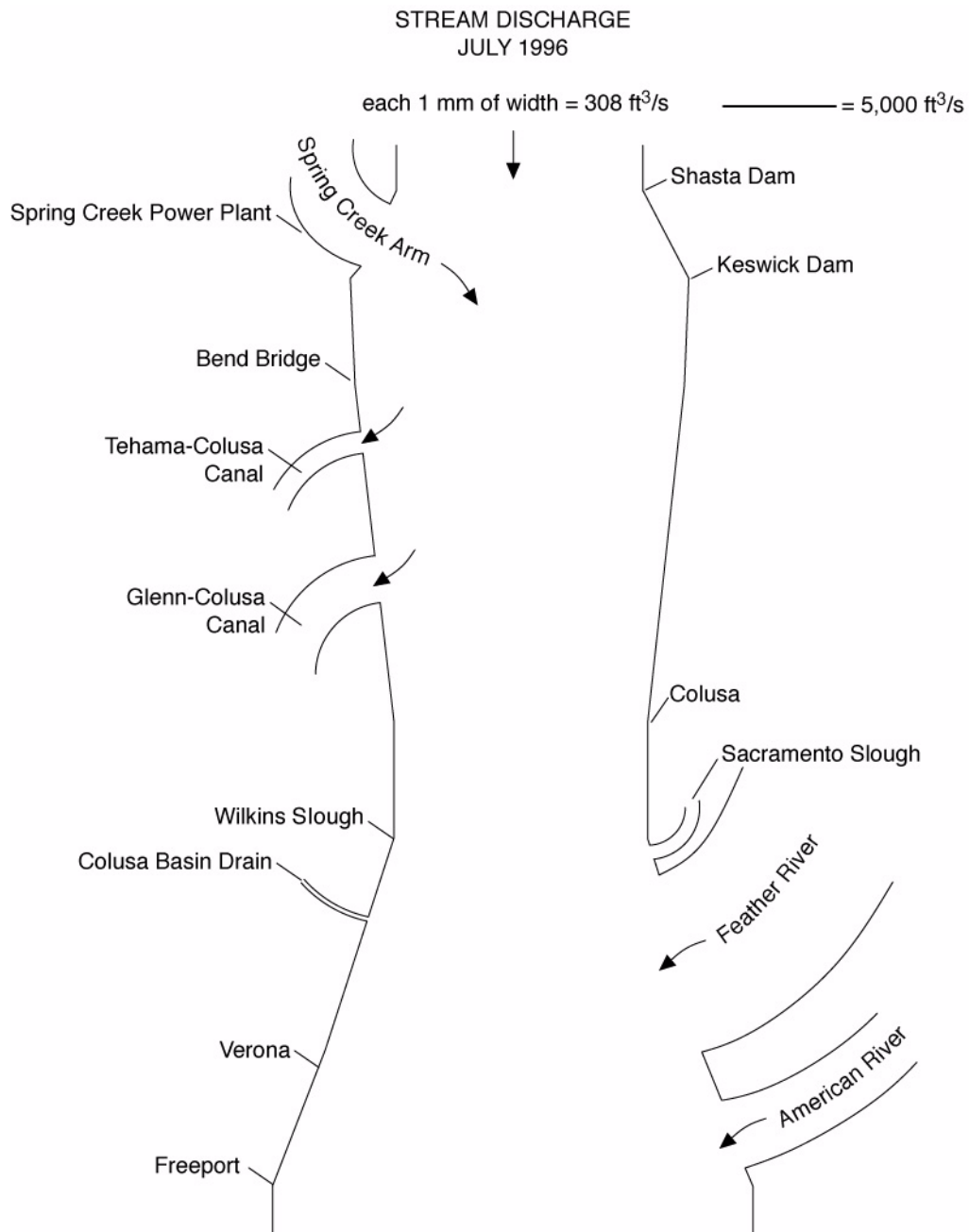


Figure 3A. Diagram showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the July 11–18, 1996 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

that is dissolved, whereas the equivalent colloid concentration represents the amount of the constituent that is contained in or on the colloids. The equivalent colloid concentration of a constituent in a colloidal sample (in micrograms per liter) was computed as the product of the suspended colloid concentration (in milligrams per liter) and the concentration of the

constituent of interest in the colloid sample (in micrograms per milligram). The method used to calculate the suspended colloid concentration using aluminum concentrations in colloidal and whole water samples is described by Alpers and others (2000). The colloidal loads in Appendix 1 of this report were calculated using Eq. 1, where the concentration is the

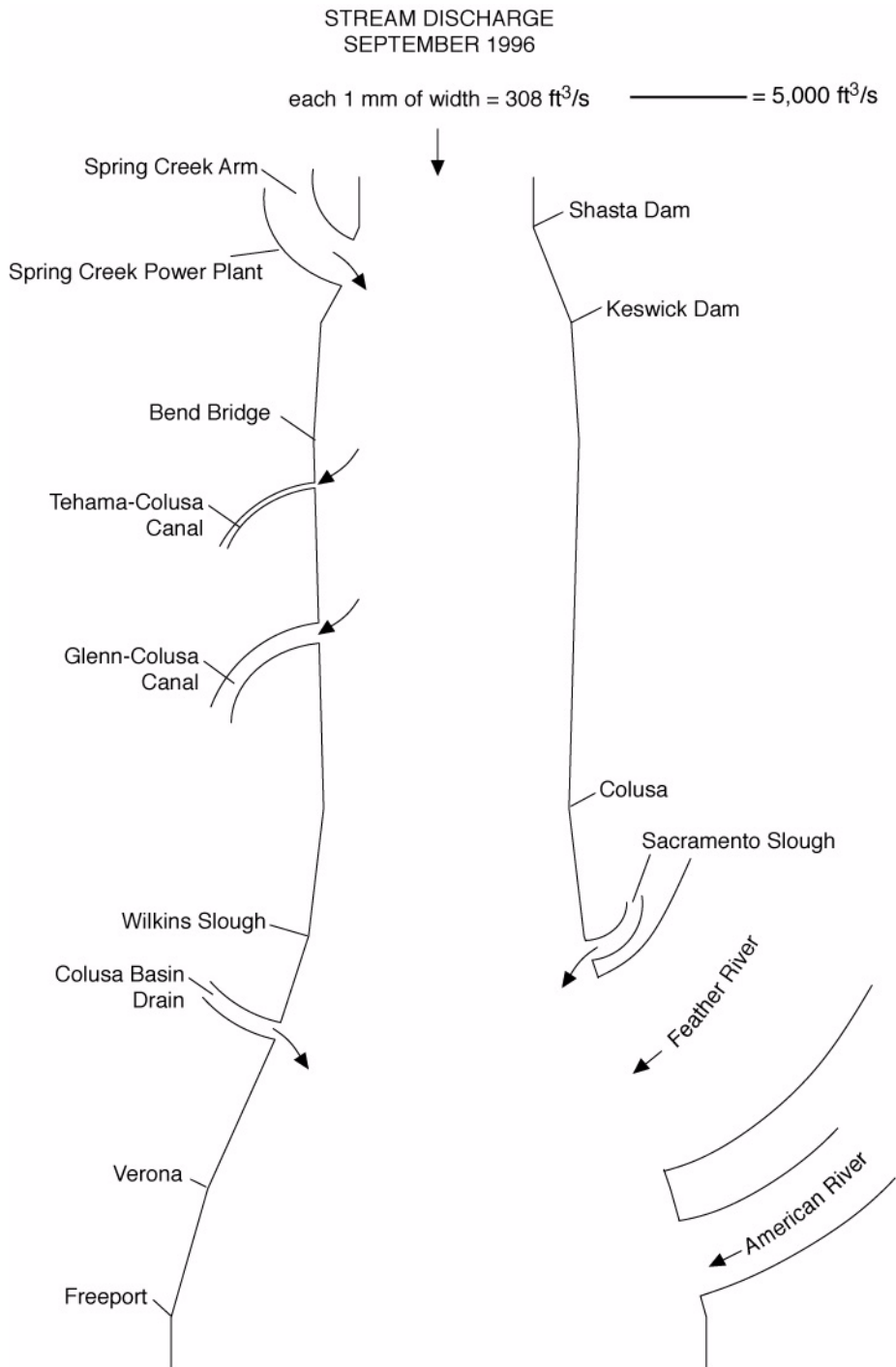


Figure 3B. Diagram showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the September 18–26, 1996 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

equivalent colloid concentration, equal to the product of colloid concentration and the concentration of the constituent associated with the colloids, using data listed in Appendix 5 of Alpers and others (2000).

For colloid samples with speciation data from sequential extractions, the speciated colloid loads were calculated in exactly the same way as described above, substituting the speciation concentration data

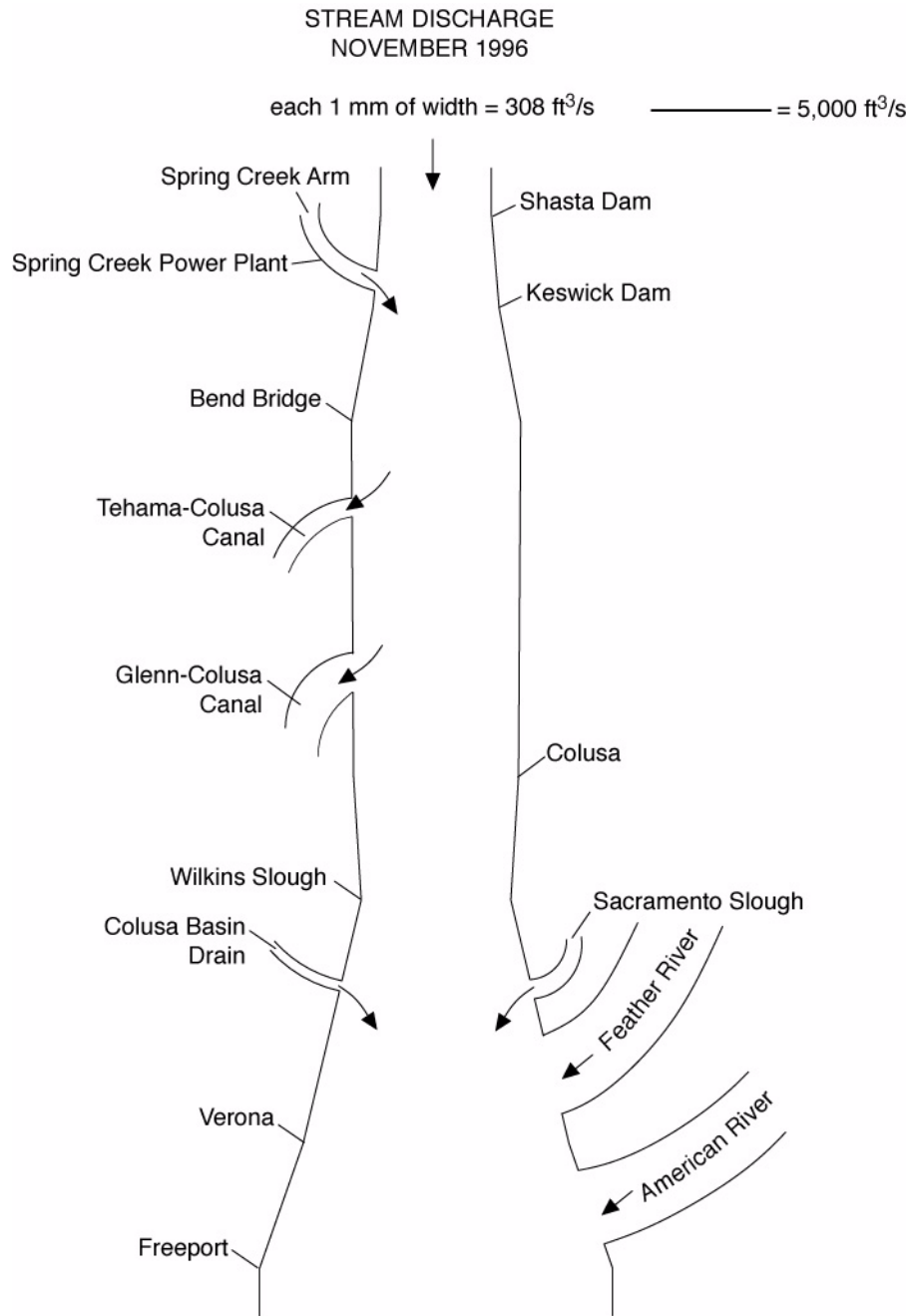


Figure 3C. Diagram showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the November 12–22, 1996 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

(Appendix 5 in Alpers and others, 2000) for the concentration of the constituent in the colloid sample.

Transport Plots

The bar plots in figures 4 through 9 display the dissolved and colloidal loads of Al, Cd, Cu, Fe, Pb, and Zn (respectively) for mainstem Sacramento River sampling sites, during each of the six sampling

periods, in downstream order from left to right. These plots have a break in the y-axis, about two-thirds of the distance from the x-axis, above which the scale changes from linear to logarithmic. The bars that cross this axis break are also broken, so that it is easy to distinguish the points plotted on the logarithmic scale. The reason for this construction is that the loads for each metal typically varied over three to four orders of magnitude between the smallest and largest

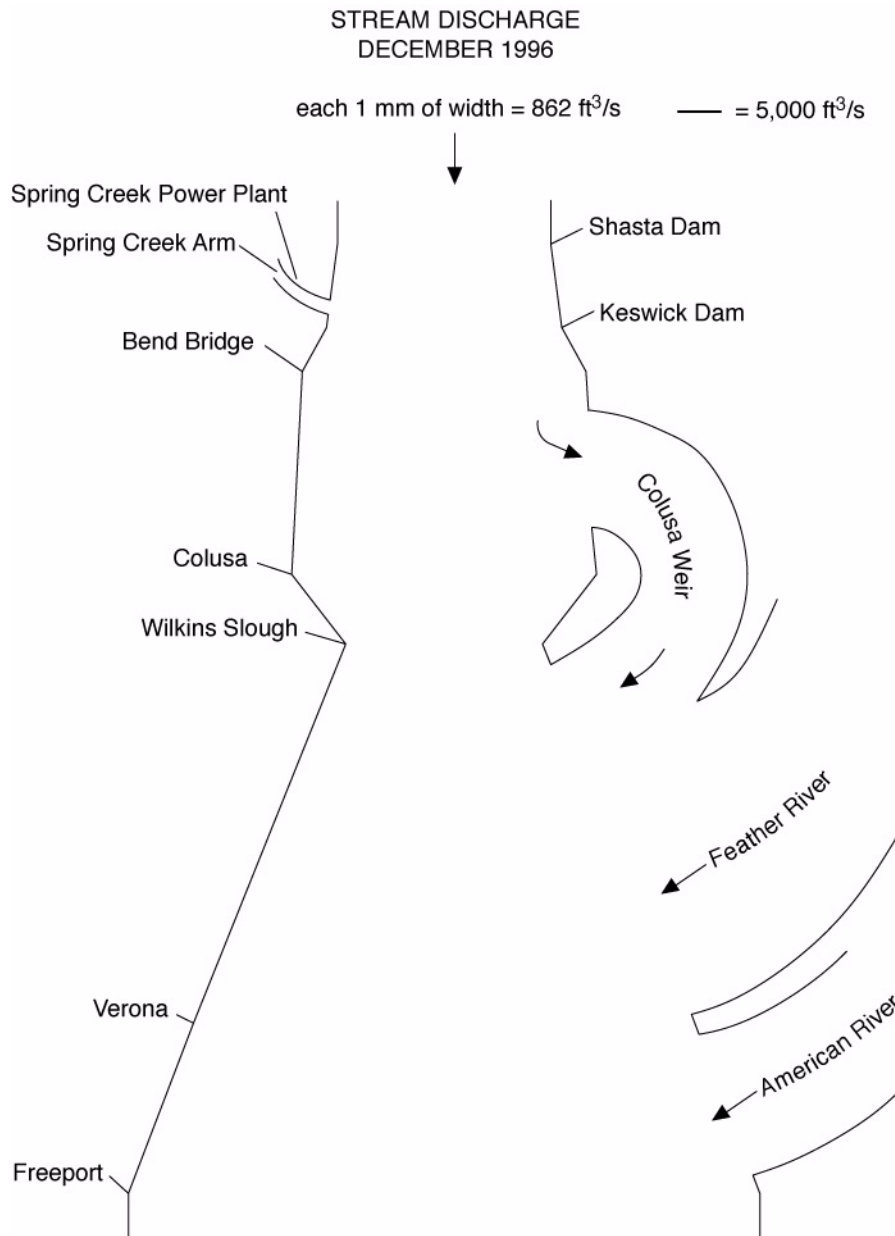


Figure 3D. Diagrams showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the December 11–18, 1996 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

measurements. To make direct comparisons between the low-discharge sampling periods (for example, November 1996) and the high-discharge period of January 1997, the broken axis, linear-log plot was chosen.

A complementary group of plots (figs. 10 through 15) shows the transport for each element with a set of six graphs, one for each sampling period. On these graphs, the measured (or estimated) discharges, the calculated concentrations of suspended colloids, and the metal concentrations in the colloid

concentrates are shown. Superimposed on each of these graphs is a series of stacked bar graphs denoting the dissolved and colloidal metal loads for each site on a linear scale. The overall heights of the bars are proportional to the total (dissolved plus colloidal) metal load, with the number above the bar denoting the value of the total load, in kilograms per day. It is important to note that each of the six graphs for a given element may have a different vertical scale for each of the three parameters plotted. Whereas figures 4 through 9 compare the various loads at different times

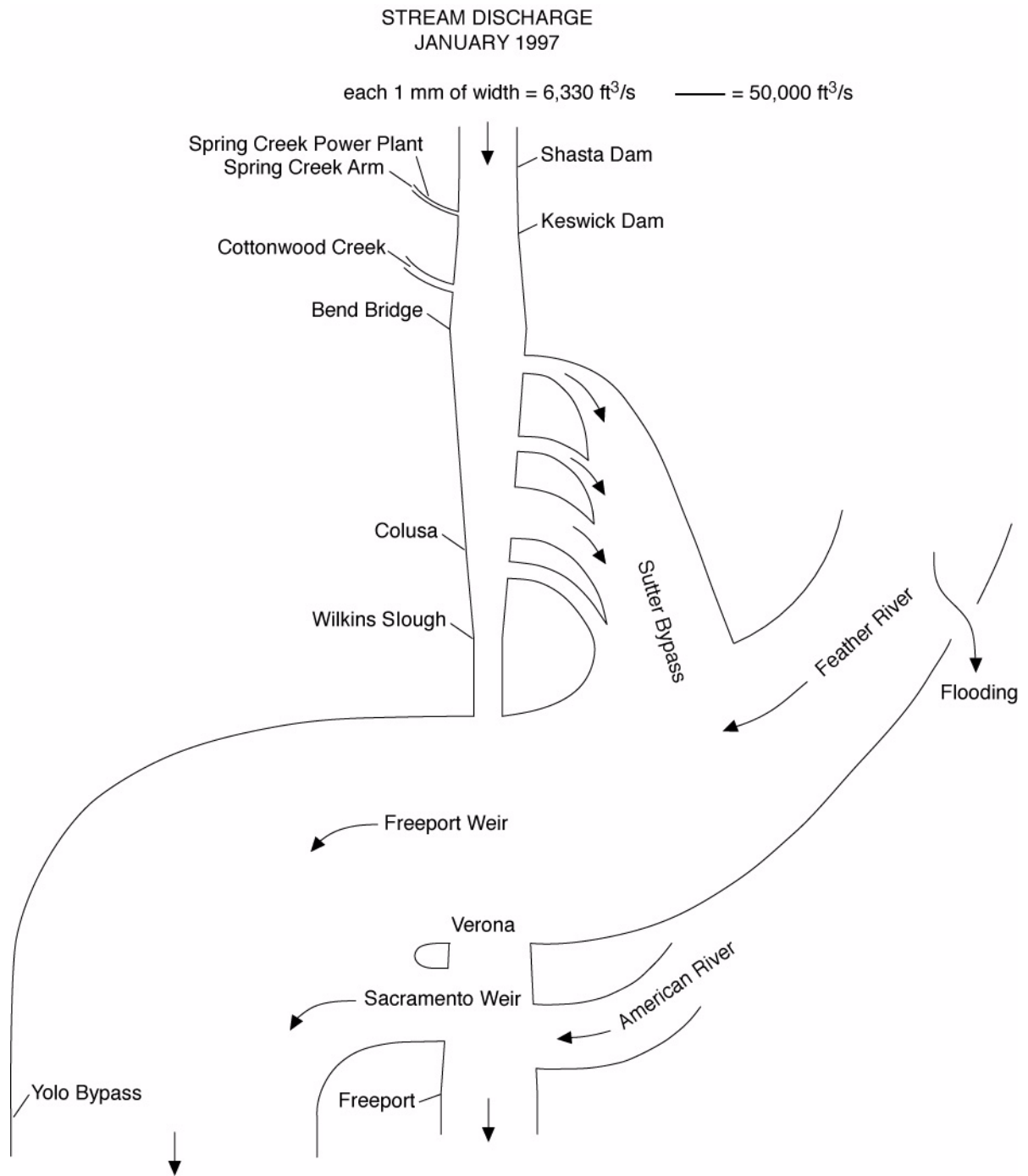


Figure 3E. Diagrams showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the January 2–8, 1997 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

of year, figures 10 through 15 show how the loads varied with discharge and colloid concentration, and how the proportion of dissolved loads varied with time and site. The trends and features of these transport graphs are discussed further in later sections of this report.

Load graphs for several other trace elements (chromium [Cr], cobalt [Co], nickel, and yttrium [Y]) are provided for general information in Appendix 5 of this report. The various features of the plots for these other elements are not discussed in this report.

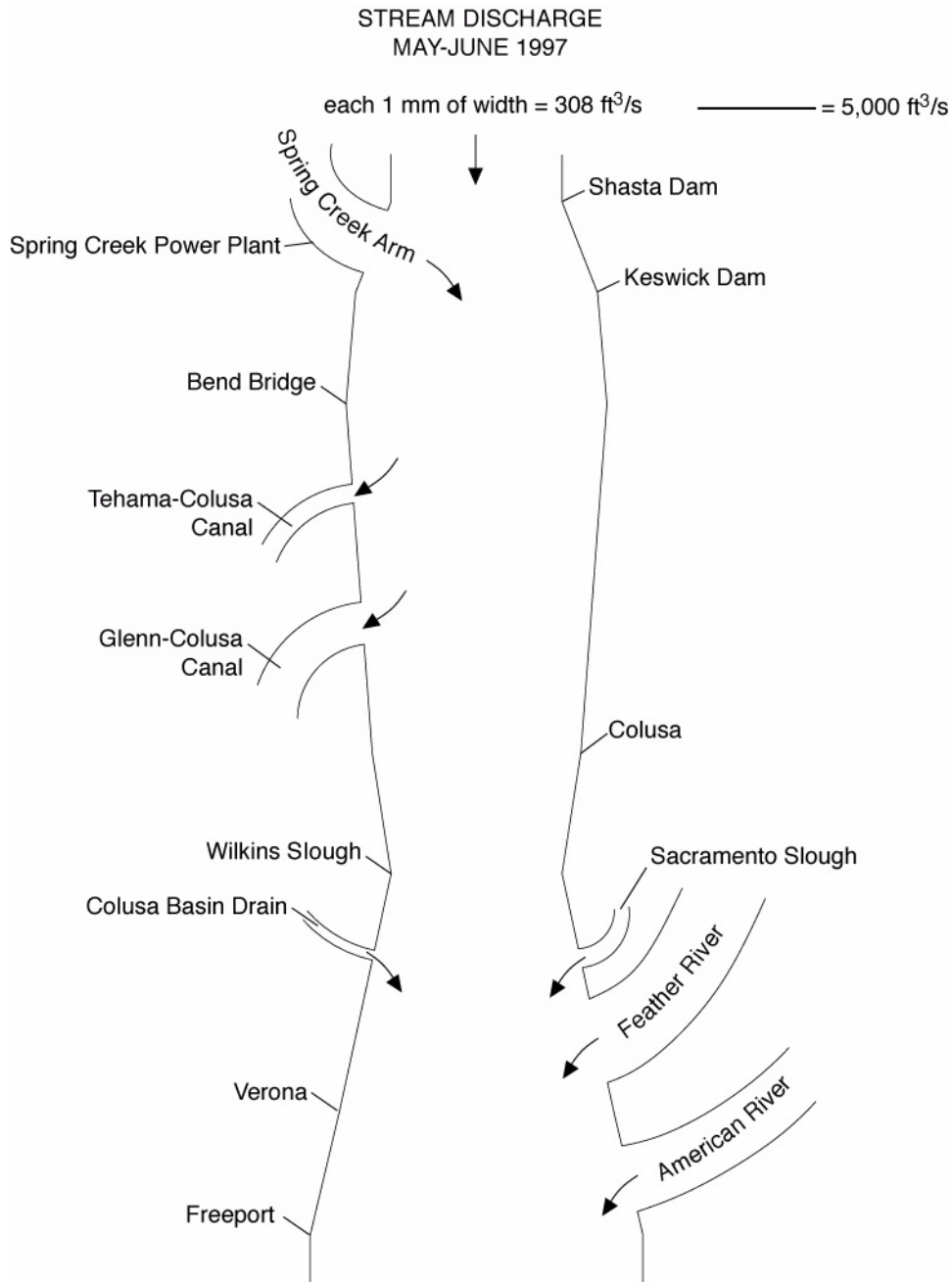


Figure 3F. Diagrams showing magnitude of mean discharge in the Sacramento River, California, relative to major tributaries and diversions during the May 28–June 6, 1997 sampling period. The width of the river is proportional to discharge. ft³/s, cubic feet per second; mm, millimeter.

Total Recoverable Loads

Total recoverable loads that are based on partial digestions of whole-water samples were calculated in a similar manner to the loads for dissolved and colloidal data. The whole-water concentrations and

discharge measurements were taken from Appendices 3 and 4 of the report by Alpers and others (2000). The computed total recoverable (whole-water) loads are tabulated in Appendix 1 of this report.

Metal concentrations from total recoverable analyses of whole-water samples and the sum of the

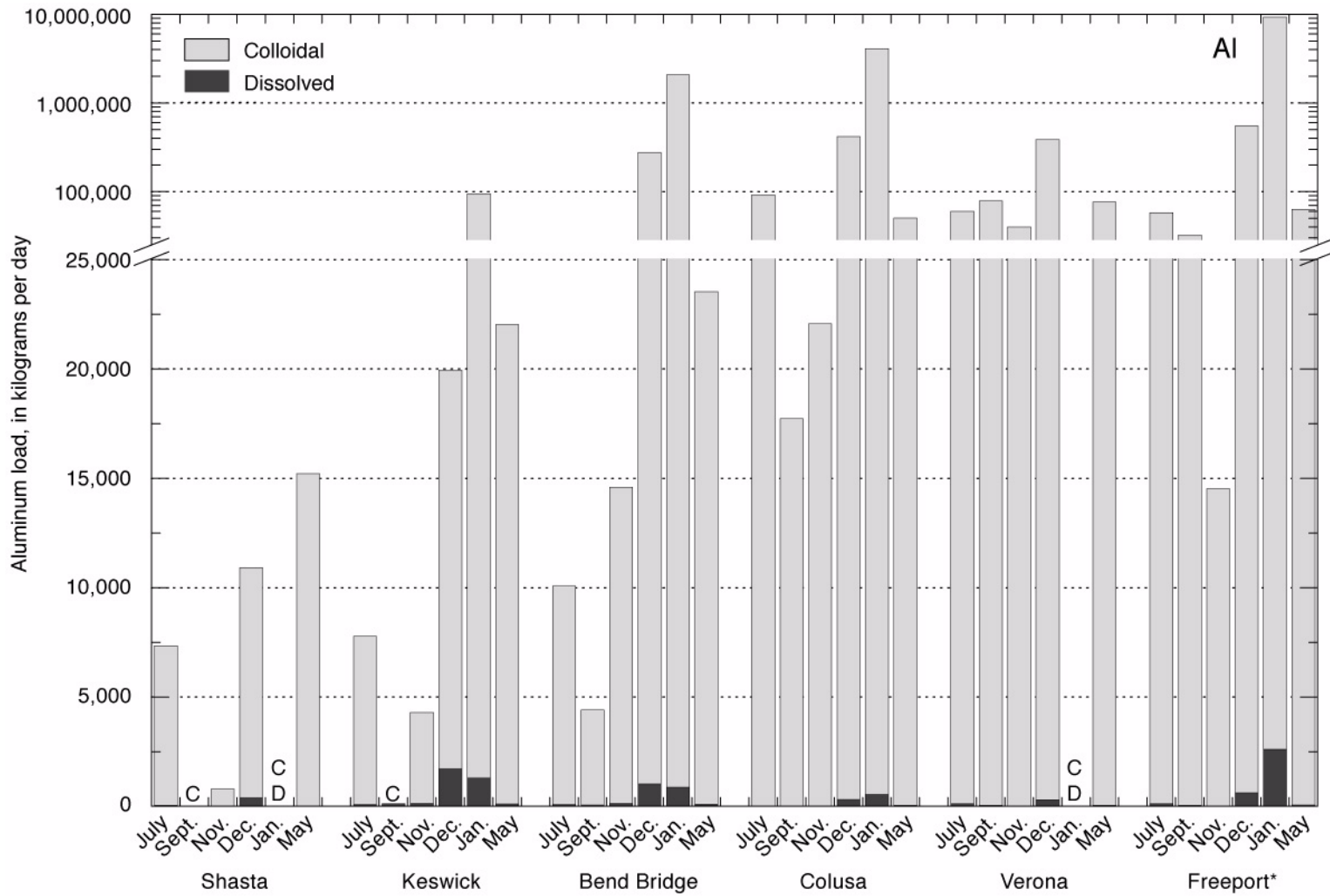


Figure 4. Plot of dissolved and colloidal aluminum loads, July 1996 to May-June (labeled as May on graph) 1997, Sacramento River, California. Al, aluminum; C, no colloidal load data available; D, no dissolved load data available. Freeport data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.

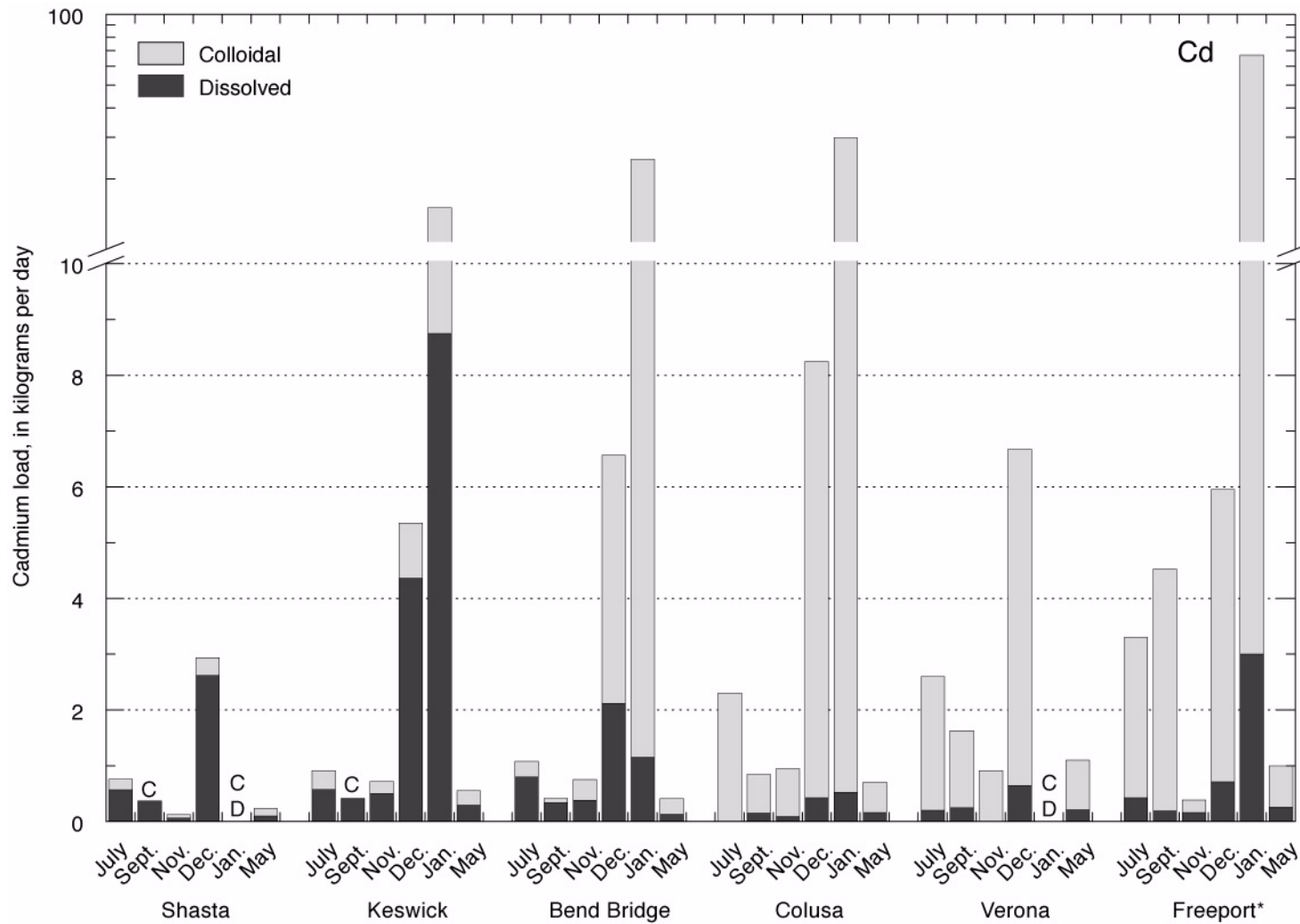


Figure 5. Plot of dissolved and colloidal cadmium loads, July 1996 to May–June (labeled as May on graph) 1997, Sacramento River, California. Cd, cadmium; C, no colloidal load data available; D, no dissolved load data available. Freeport data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.

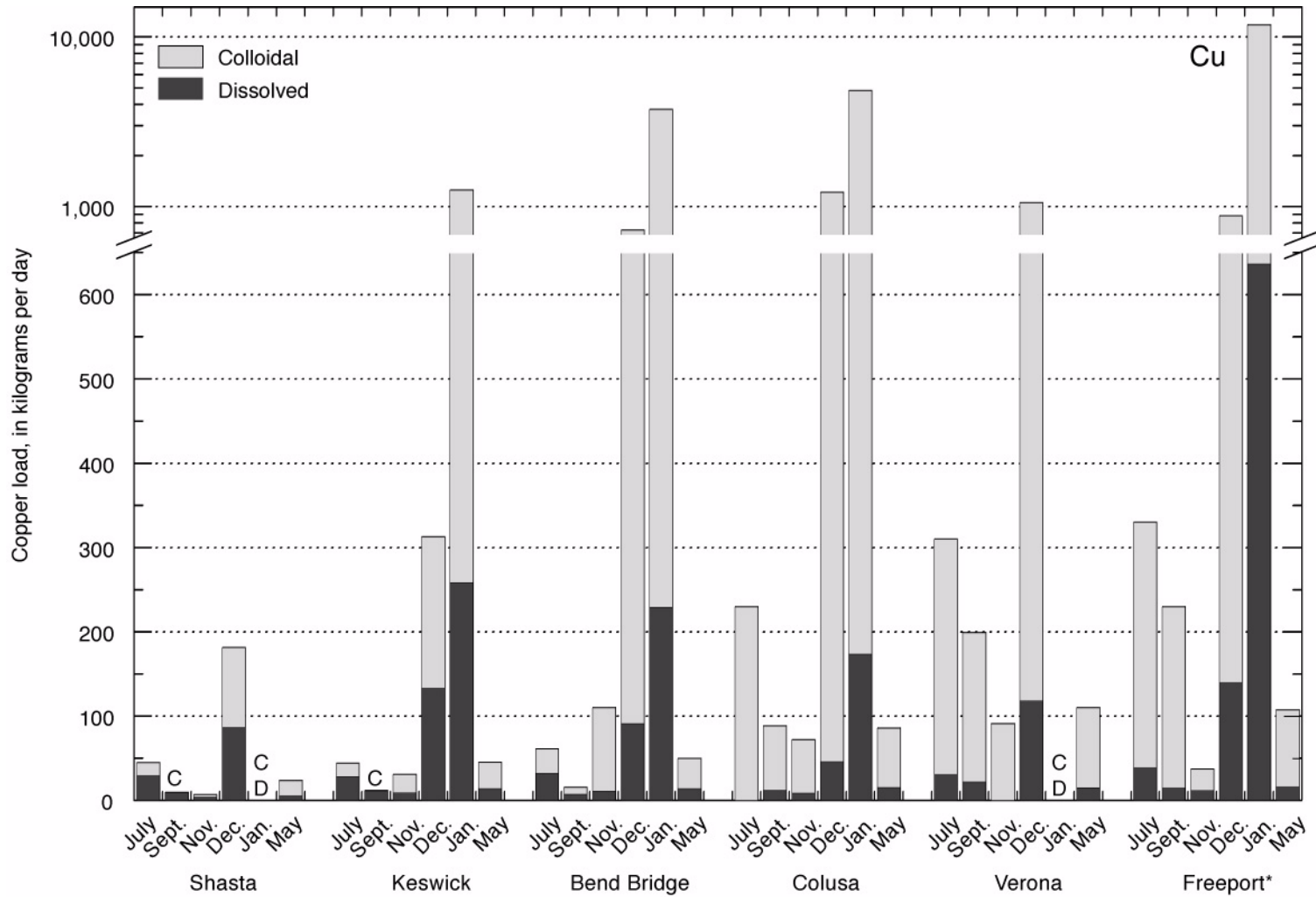


Figure 6. Plot of dissolved and colloidal copper loads, July 1996 to May–June (labeled as May on graph) 1997, Sacramento River, California. Cu, copper; C, no colloidal load data available; D, no dissolved load data available. Freeport data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.

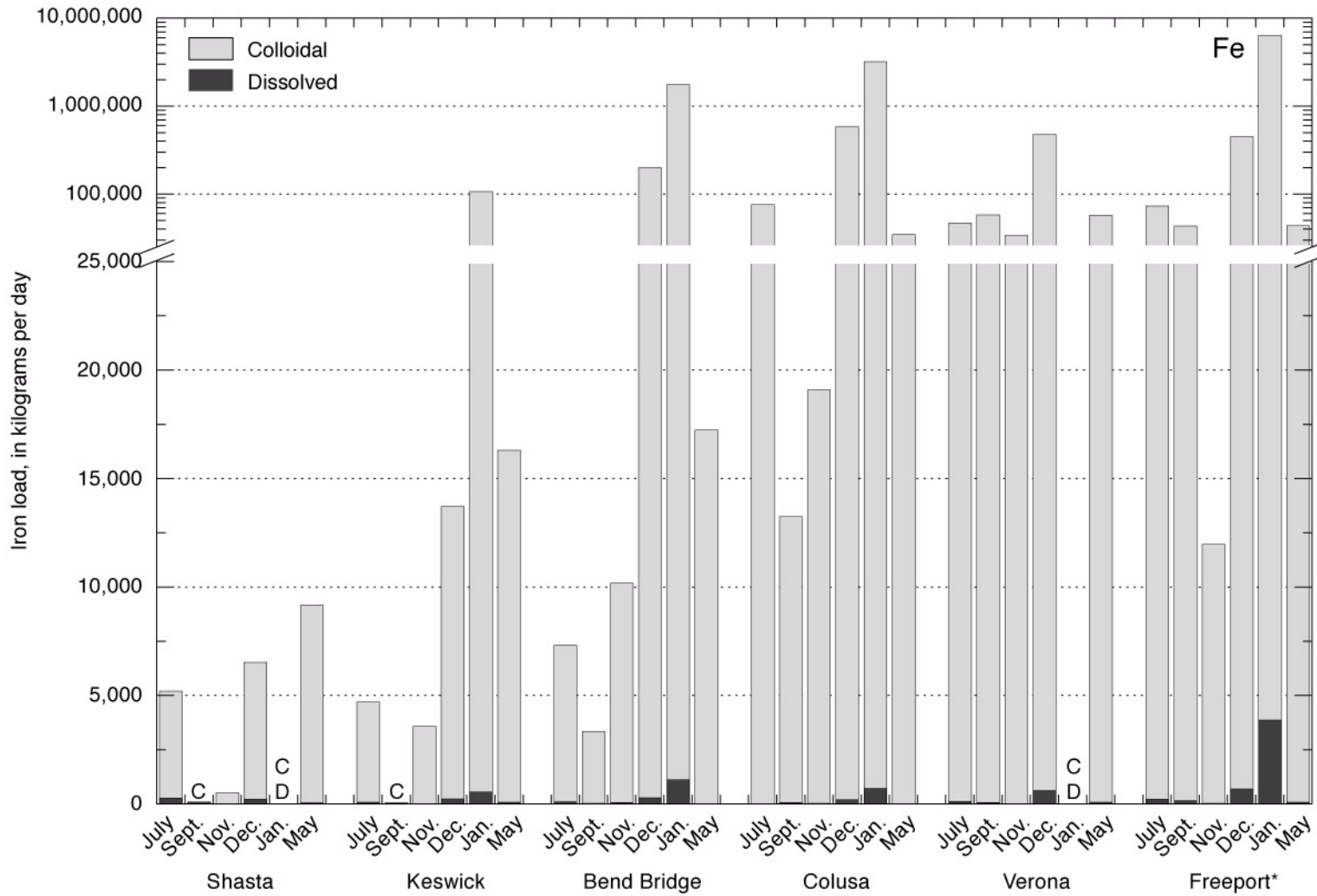


Figure 7. Plot of dissolved and colloidal iron loads, July 1996 to May–June (labeled as May on graph) 1997, Sacramento River, California. Fe, iron; C, no colloidal load data available; D, no dissolved load data available. Freepoort data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.

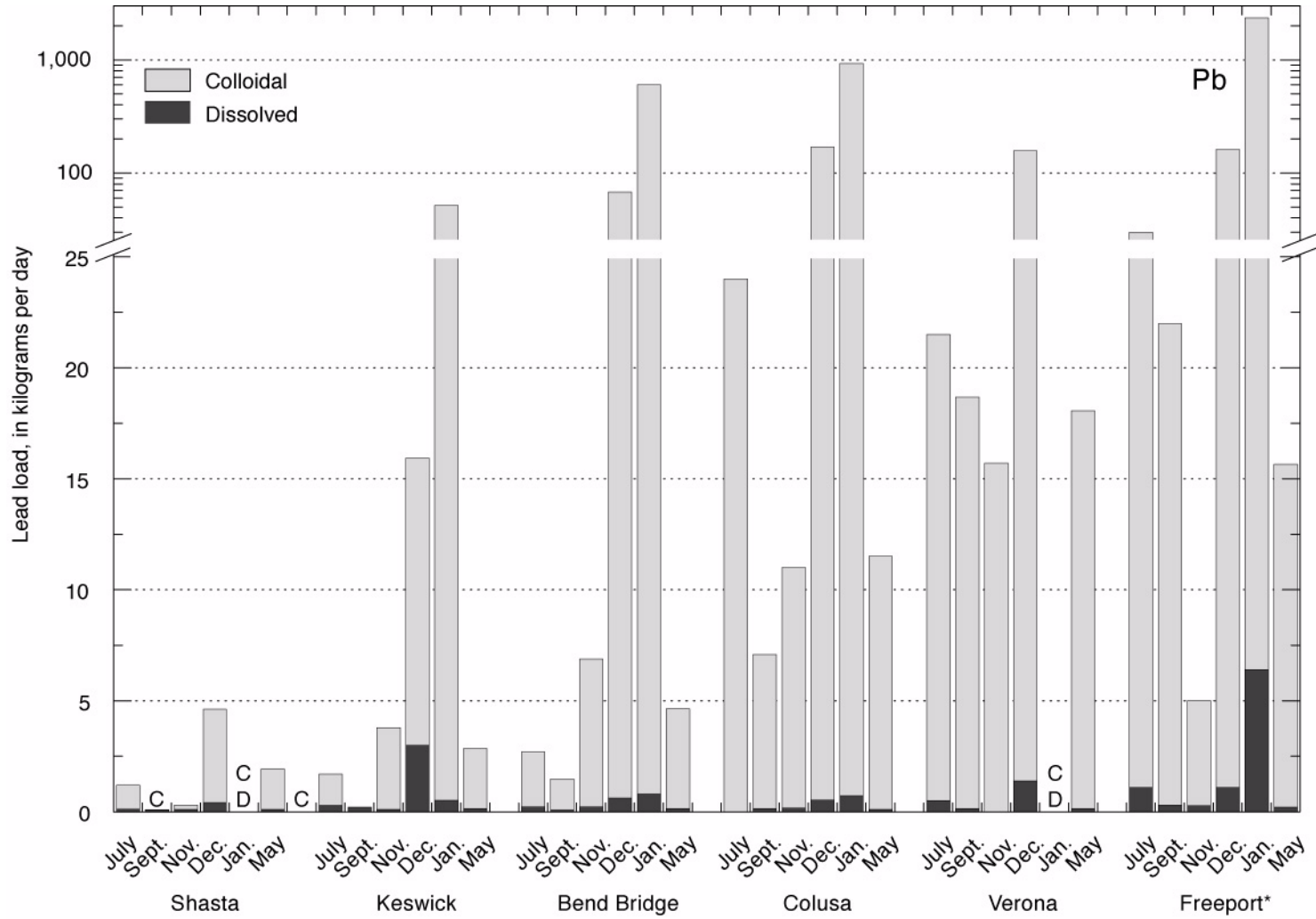


Figure 8. Plot of dissolved and colloidal lead loads, July 1996 to May–June (labeled as May on graph) 1997, Sacramento River, California. Pb, lead; C, no colloidal load data available; D, no dissolved load data available. Freeport data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.

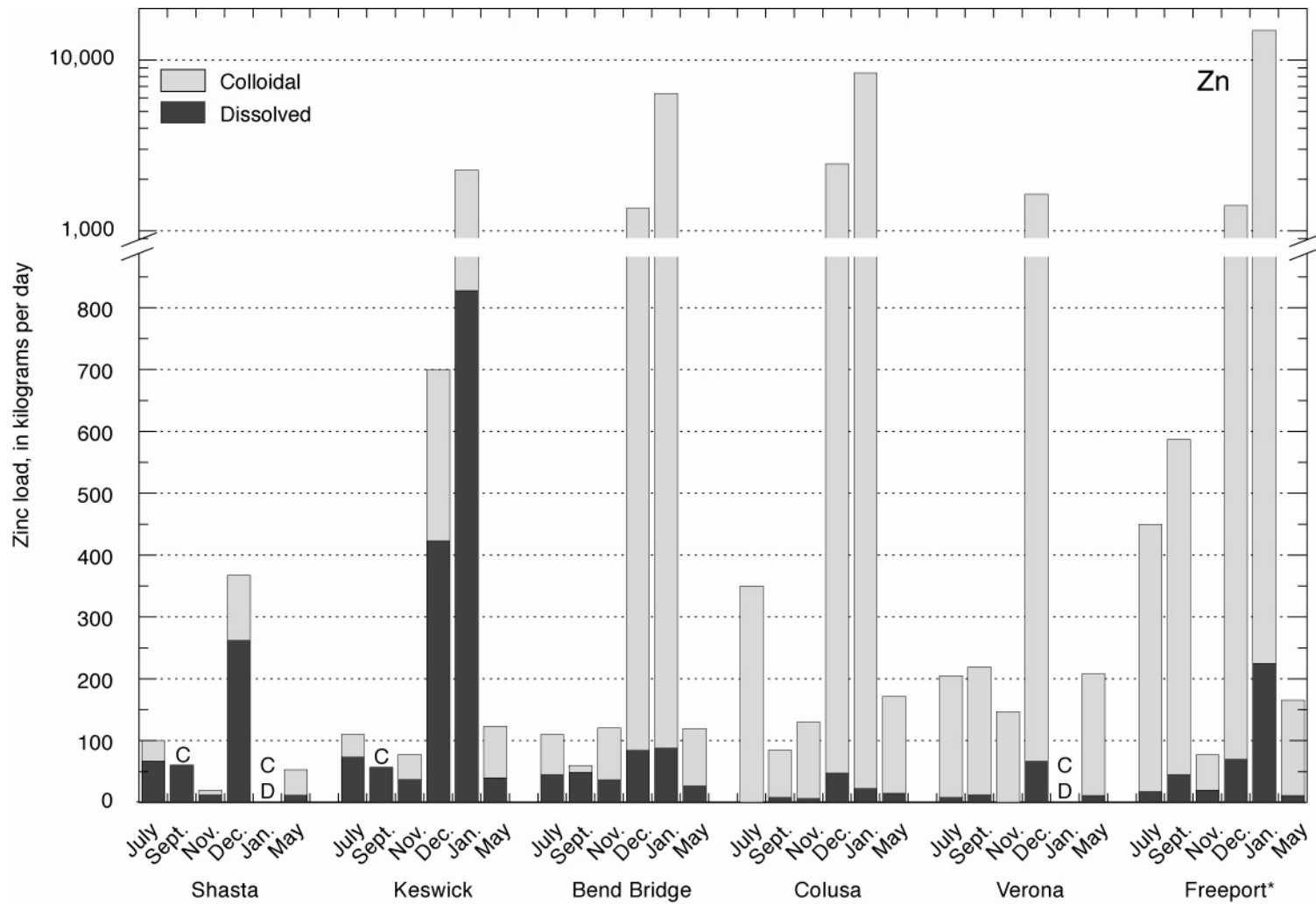


Figure 9. Plot of dissolved and colloidal zinc loads, July 1996 to May–June (labeled as May on graph) 1997, Sacramento River, California. Zn, zinc; C, no colloidal load data available; D, no dissolved load data available. Freeport data for January 1997 is the sum of loads from the Sacramento River at Tower Bridge plus the Yolo Bypass.