Sources of Metal Loads to the Alamosa River and Estimation of Seasonal and Annual Metal Loads for the Alamosa River Basin, Colorado, 1995–97

By Roderick Ortiz, Patrick Edelmann, Sheryl Ferguson, and Robert Stogner, Sr.

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CONVERSION FACTORS, ABBREVIATED UNITS, AND ACRONYMS

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
foot (ft)	0.3048	meter (m)
inch	25.4	millimeter (mm)
mile	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)

Sea level: In this report, “sea level” refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929)—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Other abbreviation used in this report:

USGS	U.S. Geological Survey
USEPA	U.S. Environmental Protection Agency
ARL	Analytical reporting limit

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Abstract

Metal contamination in the upper Alamosa River Basin has occurred for decades from the Summitville Mine site, from other smaller mines, and from natural, metal-enriched acidic drainage in the basin. In 1995, the need to quantify contamination from various source areas in the basin and to quantify the spatial, seasonal, and annual metal loads in the basin was identified. Data collection occurred from 1995 through 1997 at numerous sites to address data gaps. Metal loads were calculated and the percentages of metal load contributions from tributaries to three risk exposure areas were determined. Additionally, a modified time-interval method was used to estimate seasonal and annual metal loads in the Alamosa River and Wightman Fork.

Sources of dissolved and total-recoverable aluminum, copper, iron, and zinc loads were determined for Exposure Areas 3a, 3b, and 3c. Alum Creek is the predominant contributor of aluminum, copper, iron, and zinc loads to Exposure Area 3a. In general, Wightman Fork was the predominant source of metals to Exposure Area 3b, particularly during the snowmelt and summer-flow periods. During the base-flow period, however, aluminum and iron loads from Exposure Area 3a were the dominant source of these metals to Exposure Area 3b. Jasper and Burnt Creeks generally contributed less than 10 percent of the metal loads to Exposure Area 3b. On a few occasions, however, Jasper and Burnt Creeks contributed a substantial percentage of the loads to the Alamosa River. The metal loads calculated for Exposure Area 3c result from upstream sources; the primary upstream sources are Wightman Fork, Alum Creek, and Iron Creek. Tributaries in Exposure Area 3c did not contribute substantially to the metal load in the Alamosa River.

In many instances, the percentage of dissolved and/or total-recoverable metal load contribution from a tributary or the combined percentage of metal load contribution was greater than 100 percent of the metal load at the nearest downstream site on the Alamosa River. These data indicate that metal partitioning and metal deposition from the water column to the streambed may be occurring in Exposure Areas 3a, 3b, and 3c. Metals that are deposited to the streambed probably are resuspended and transported downstream during high streamflow periods such as during snowmelt runoff and rainfall runoff.

Seasonal and annual dissolved and total-recoverable aluminum, copper, iron, and zinc loads for 1995–97 were estimated for Exposure Areas 1, 2, 3a, 3b, and 3c. During 1995–97, many tons of metals were transported annually through each exposure area. Generally, the largest estimated annual total-recoverable metal mass for most metals was in 1995. The smallest estimated annual total-recoverable metal mass was in 1996, which also had the smallest annual streamflow. In 1995 and 1997, more than 60 percent of the annual total-recoverable metal loads generally was transported through each exposure area during the snowmelt period. A comparison of the estimated storm load at each site to the corresponding annual load indicated that storms contribute less than 2 percent of the annual load at any site and about 5 to 20 percent of the load during the summer-flow period.

INTRODUCTION

The upper Alamosa River Basin is a heavily mineralized area located in the San Juan Mountains of southwestern Colorado (fig. 1). Metal contamination has occurred for decades from the Summitville Mine

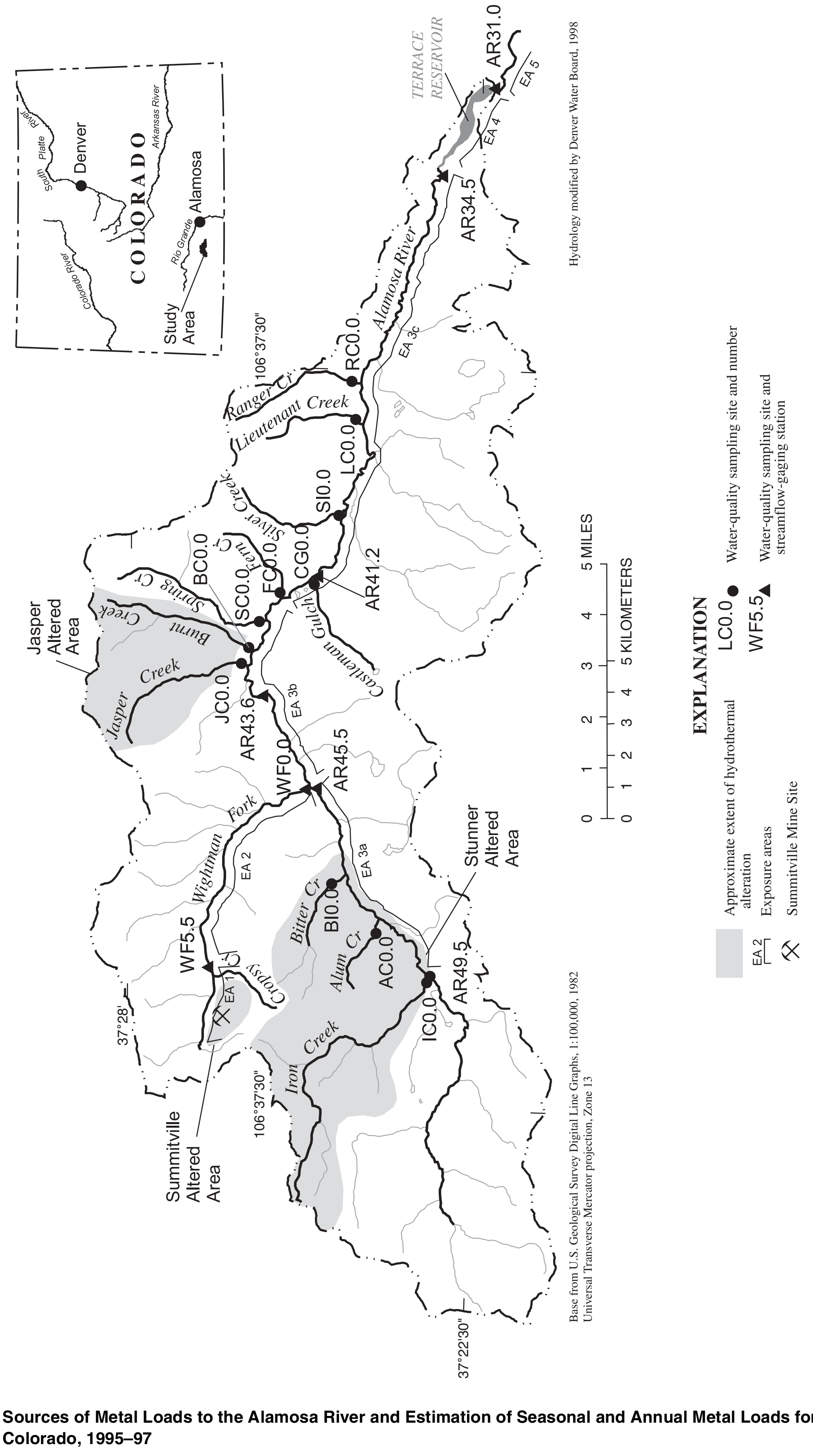

Figure 1. Location of study area, risk assessment exposure areas, and water-quality sampling sites in the Alamosa River Basin.

site, from other smaller mines, and from natural, metal-enriched acidic drainage in the basin (Miller and McHugh, 1994). Mining activities have occurred intermittently in the Summitville area since the late 1800's. Large-scale open-pit mining began at the Summitville Mine site in the mid-1980's and continued until the mine site was suddenly abandoned in late 1992. At that time, the State of Colorado requested the U.S. Environmental Protection Agency (USEPA) to assume site-maintenance responsibilities under the emergency response provisions of Superfund. Since 1992, the site has undergone substantial waste-pile consolidation, runoff rerouting, water treatment, and reclamation. In 1998, the State of Colorado assumed shared site responsibility of the Summitville site with the USEPA.

Data-collection activities by the U.S. Geological Survey (USGS) began in 1993 and included streamflow measurements and water-quality sampling at several surface-water sites on the Alamosa River and Wightman Fork. In 1994, investigative work by the USGS was limited to Terrace Reservoir and the inflow and outflow sites to the reservoir (fig. 1). In 1995, Morrison-Knudsen Corporation and ICF Kaiser Engineers (1995) identified multiple data gaps needed for ecological risk assessment of the Summitville Superfund site. Two of the data gaps identified were the need to quantify metal contamination from various source areas in the basin and the need to quantify the spatial, seasonal, and annual metal loads in the basin. As a result, the USGS developed a comprehensive data-collection plan for the basin to address these data gaps (Patrick Edelmann, U.S. Geological Survey, written commun., 1995). The plan included the use of several continuous streamflow gages and water-quality monitors. In addition, periodic water-quality sampling on the Alamosa River, Wightman Fork, and several other tributaries was established. Data collected from the network from 1995 through 1997 were used to address the data gaps identified in the risk assessment.

Purpose and Scope

The purposes of this report are (1) to quantify metal contamination and contribution from various source areas and (2) to estimate seasonal and annual metal loads at selected sites in the Alamosa River Basin from 1995 through 1997.

This study was done to address specific data gaps identified in the original risk assessment of the Summitville Superfund site. The risk assessment addendum (Camp Dresser and McKee Inc., 2000) will provide the results from this and several other studies to the USEPA so that informed decisions regarding the need for remedial actions can be made. As part of the risk assessment addendum, the potentially impacted region downstream from the Summitville Mine site was divided into six exposure areas to address risks related to specific contaminants of concern on an area-by-area basis. The locations of the six exposure areas are described in table 1 and are shown in figure 1. The contaminants of concern addressed in the risk assessment and in this report are dissolved and total-recoverable aluminum, copper, iron, and zinc.

Table 1. Ecological risk exposure areas, corresponding stream reach, and U.S. Geological Survey sampling sites

[EA, exposure area; USGS, U.S. Geological Survey]

Exposure area (see figure 1)	Stream reach	USGS sampling site within the exposure area (see figure 1)
EA1	Summitville Mine site	WF5.5
EA2	Wightman Fork downstream from WF5.5	WF0.0
EA3a	Alamosa River upstream from Wightman Fork	AR45.5
EA3b	Alamosa River from Wightman Fork to Fern Creek	AR43.6
EA3c	Alamosa River from Fern Creek to Terrace Reservoir	AR41.2 and AR34.5
EA4	Terrace Reservoir	Not addressed in this report
EA5	Alamosa River downstream from Terrace Reservoir	AR31.0

Description of Study Area

The upper Alamosa River Basin is located in the San Juan volcanic fields of southwest Colorado (fig. 1). The study area has a drainage area of approximately 110 square miles and extends from near the headwaters of the Alamosa River to just above Terrace Reservoir (Stogner and others, 1996). Elevations in the study area range from 8,400 feet to nearly 13,000 feet above sea level. Annual precipitation ranges from approximately 12 inches at the lower elevations to as much as 40 inches at the top of the highest peaks (Miller and McHugh, 1994). Most of the precipitation is in the form of snowfall. The Alamosa River upstream from Wightman Fork receives water from the Iron, Alum, and Bitter Creek drainages, which are geomorphically degraded and have been for nearly 5 million years (Bove and others, 1996). Low-pH water with high concentrations of trace metals from the Summitville Mine site adversely affects Wightman Fork and several miles of the Alamosa River downstream from the confluence with Wightman Fork. The oxidation of the ubiquitous pyrite stock in the area results in acidic water and the release of metals. The oxidation of pyrite is summarized in Wentz (1974) and in Nordstrom (1982). From the mouth of Wightman Fork, the Alamosa River flows east through the Alamosa Canyon for about 14 miles before reaching Terrace Reservoir. Several small tributary flows enter the Alamosa River along this reach including Jasper and Burnt Creeks, which drain hydrothermally altered areas. Terrace Reservoir is a small irrigation reservoir that supplies water for agricultural use in the San Luis valley (Ferguson and Edelmann, 1996).

METHODS OF DATA COLLECTION AND ANALYSIS

To meet the objectives of this study, the USGS collected instantaneous streamflow and periodic water-quality data at five sites on the Alamosa River (AR45.5, AR43.6, AR41.2, AR34.5, and AR31.0) and two sites on Wightman Fork (WF5.5 and WF0.0) from 1995 through 1997 (fig. 1). Site nomenclature uses a two-letter designation for the stream followed by a river mileage (in miles) from the mouth. Hence, WF5.5 is on Wightman Fork 5.5 miles upstream from the mouth of the Alamosa River. Routine water-quality samples were collected 8 to 12 times per year at these sites; figure 2 illustrates the temporal distribution of the sampling events over the 3 years of data collection. One additional site on the Alamosa River (AR49.5) was designated as a background site. Several other tributaries were sampled less often, based on their potential metal contribution to the Alamosa River. Tributaries that drain hydrothermally altered areas were sampled seven to nine times per year from April through October. These sites include Iron Creek (IC0.0), Alum Creek (AC0.0), Bitter Creek (BI0.0), Jasper Creek (JC0.0) and Burnt Creek (BC0.0) (fig. 1). Other tributaries that drained areas unaffected by mining were sampled four to five times per year, primarily during the snowmelt and summer flow. These tributaries were Spring Creek (SC0.0), Fern Creek (FC0.0), Castleman Gulch (CG0.0), Silver Creek (SI0.0), Lieutenant Creek (LC0.0), and Ranger Creek (RC0.0). The samples were collected as described by Horowitz and others (1994) and in the USGS comprehensive data-collection plan (Patrick Edelmann, U.S. Geological Survey, written commun., 1995). Streamflow measurements were done at all tributary sites at the time of sample collection.

The concentration and streamflow data used in the analyses of this report are available from the Colorado Department of Public Health and Environment, Hazardous Materials and Waste Management Division, 4300 Cherry Creek Drive South, Denver, CO, 80222–1530. The data include all instantaneous streamflow values from 1995 through 1997. In addition, the data include dissolved and total-recoverable metal concentrations for grab samples, discrete samples collected using automatic samplers, and flow-weighted composite samples collected during the same period. Water-quality data collected during storm events also are included. Grab samples (discrete and equal-width increment), composite, and storm samples can be found in the data base under the general heading of "sample type."

The annual hydrograph has four distinct seasonal flow regimes or flow periods: base flow, early snowmelt, snowmelt, and summer flow (fig. 2). The timing and duration of these flow periods vary from year to year depending on the weather conditions and the available snowpack at the higher elevations

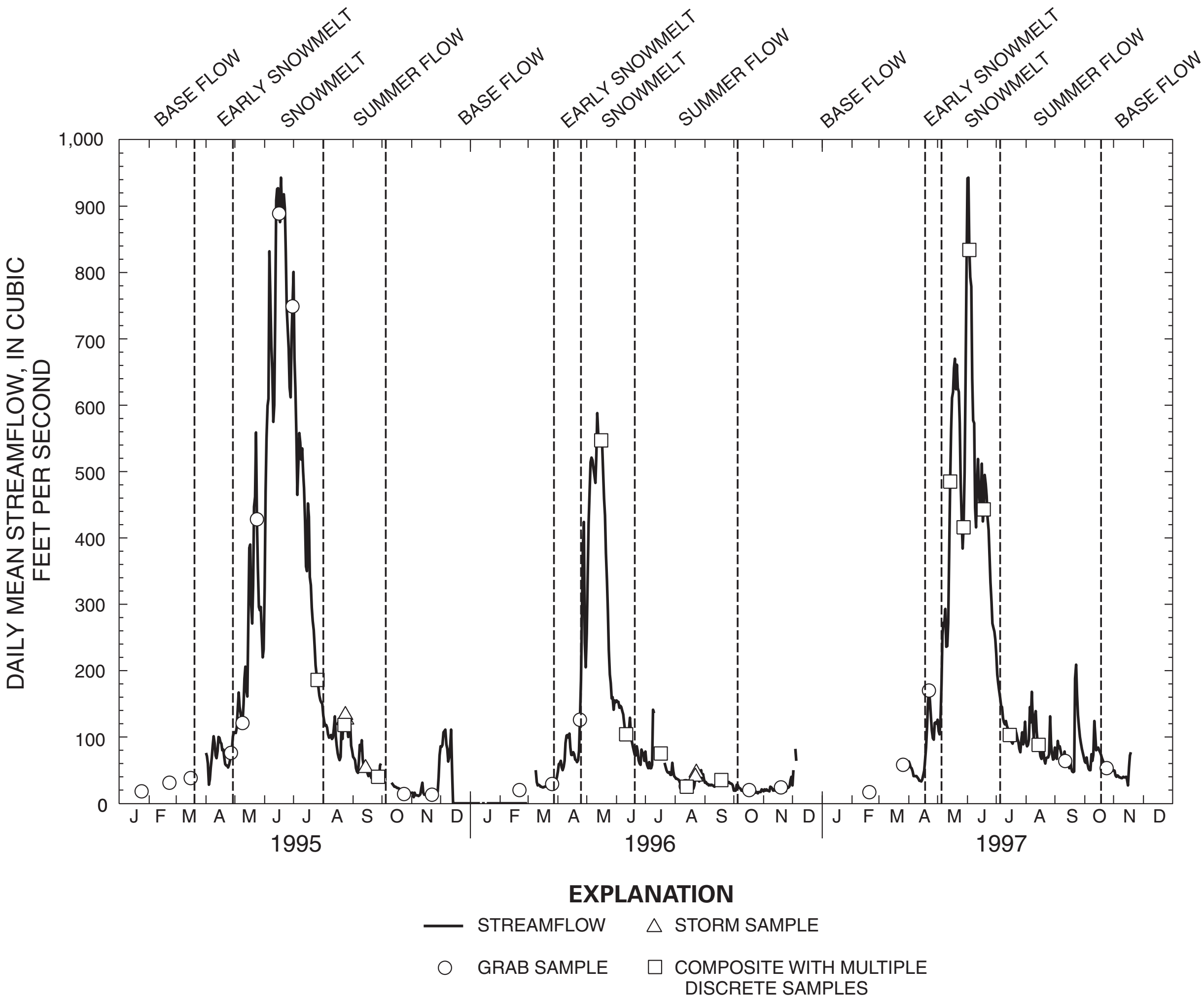

Figure 2. Daily mean streamflow and number of water-quality samples collected at AR34.5, 1995–97.

(table 2). The water-quality data were analyzed and summarized for each of these four flow periods. The base-flow period is characterized by relatively steady-state low-flow conditions. Typically, base flow extends from early October through early April. The early snowmelt flow regime is delineated by a departure from base flow as the first substantial snowmelt conditions become apparent. This "first flush" period is relatively short in duration but can be associated with large metal loading to the river. The snowmelt-flow regime is characterized by the annual peak streamflow and provides the largest percentage of the annual streamflow in the river. The extent of the snowmelt period in the basin from 1995 to 1997 was highly variable depending on the amount of snowpack and the prevailing weather patterns. The summer-flow regime is delineated by a decrease in streamflow and a gradual return to base-flow conditions; nearly all significant rainfall events occur during this period.

Methods of Collection and Analysis Used to Quantify Contamination from Various Source Areas

Selected water-quality and streamflow data collected from all sites were used to quantify contamination and assess the metal contribution from various exposure areas in the basin. Metal concentrations from analysis of water-quality samples and corresponding streamflow measurements were used to calculate metal loads at each sampling site for each sampling date. The following equation was used to compute metal loads:

$$\text{Load} = (C_{metal} \times Q_{site}) \times M$$

where

Load is mass of metal, in tons per day,

C_{metal} is concentration of metal, in micrograms per liter,

Q_{site} is streamflow, in cubic feet per second, and

M is conversion factor of 26.98×10^{-7}.

Generally, less than 3 percent of the total-recoverable concentrations at gaged stations were less than the reporting limit. Less-than values were more prevalent among dissolved concentrations but most were associated with aluminum values. If censored concentration data were reported, the reporting limit was substituted for the analytical value in the analysis. AR45.5 had the largest overall percentage of less-than values among the gaged sites.

Table 2. Flow periods and duration of flow periods in the Alamosa River Basin, 1995–97

Flow periods	Date range	Duration, (in days)
	1995	
Base flow	January 1–March 20	79
Early snowmelt	March 21–April 29	40
Snowmelt	April 30–August 1	94
Summer flow	August 2–October 5	65
	1995–1996	
Base flow	October 6–March 28	175
Early snowmelt	March 29–April 25	28
Snowmelt	April 26–June 20	56
Summer flow	June 21–October 5	107
	1996–1997	
Base flow	October 6–April 18	195
Early snowmelt	April 19–May 5	17
Snowmelt	May 6–July 5	61
Summer flow	July 6–October 18	105

Percentages of metal load contributions from tributaries were determined for each sample collected by dividing the metal load at the tributary site by the metal load at the nearest downstream Alamosa River site. For example, the percentage of metal load contribution from Alum Creek to AR45.5 was determined by dividing the metal load at Alum Creek by the metal load from the corresponding sample collected at AR45.5. The formula is as follows:

$$\frac{[Load(AC0.0)]}{[Load(AR45.5)]} \times 100 = \text{percentage of metal load contribution from Alum Creek}$$

Percentages of metal load contributions were calculated for each tributary and flow period and grouped by exposure area.

During base-flow conditions, water-quality samples were collected only once at each site during a sampling event because relatively little diurnal variation in metal load was expected between October and March. Water-quality samples generally were collected from all Alamosa River sites, Wightman Fork sites, and sites on Iron, Alum, Bitter, Jasper, and Burnt Creeks. Instantaneous streamflow measurements were done at all sites during base flow. Dissolved and total-recoverable aluminum, copper, iron, and zinc loads were calculated and percentage of contributions to downstream sites were calculated as described previously.

During nonsteady-state streamflow conditions, large diurnal variations in streamflow and metal concentrations occur in the Alamosa River and Wightman Fork (Ortiz and Stogner, 2000). Consequently, large variations in metal loads also occur during these periods. In an effort to collect comparable samples, multiple water-quality samples were collected at WF5.5, WF0.0, AR45.5, AR43.6, AR41.2, and AR34.5 using automatic samplers. The automatic samplers were programmed to collect as many as six discrete sample sets at each site during a diurnal period (24 hours). The first sample at each site was collected from the same parcel of water as the parcel moved downstream from the Summitville Mine to Terrace Reservoir; samples at WF0.0 and AR45.5 were collected at the same time because of the close proximity of the two sites (fig. 1). The other sets of samples accomplished in the same manner but on different parts of the hydrograph (fig. 3). The specific timing of the sample collection at each site was determined just prior to the start of sampling by using satellite-transmitted streamflow data from each gaging station to compare and determine traveltimes between downstream sites. A description of these methods used can be found in Ortiz and Stogner (2000).

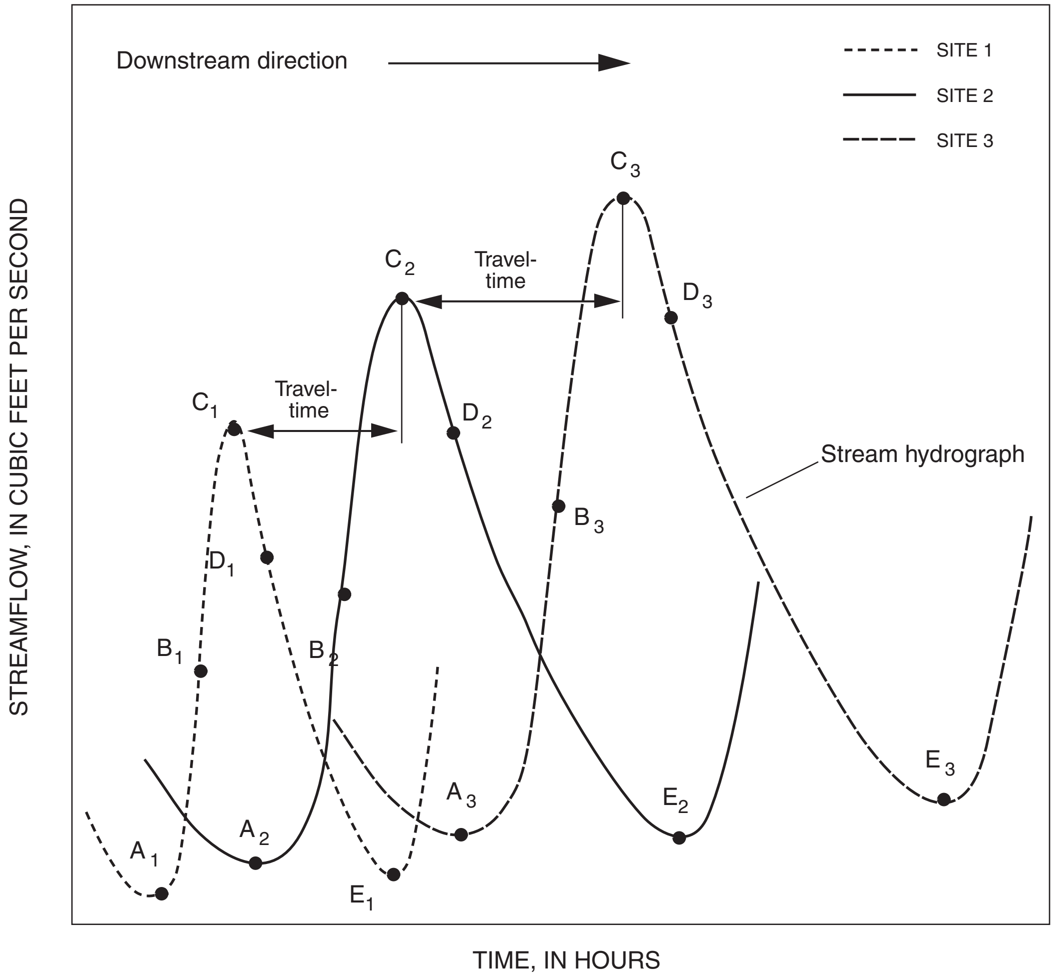

Figure 3. Depiction of hypothetical hydrographs showing selected sample points and estimated traveltime of theoretical parcel of water between downstream sites.

Sites AR49.5 and AR31.0 were not equipped with automatic samplers and were only sampled once during each sampling event. The background site, AR49.5, was sampled upstream from its confluence with Iron Creek at approximately the same time as IC0.0 (Iron Creek). The loads from AR49.5 were used to determine the contribution of metal loads entering Exposure Area 3a. Hereafter in this report, Exposure Area will be designated as "EA." The metal load at AR31.0 (Alamosa River below Terrace Reservoir) was not expected to change throughout a diurnal cycle and, as such, a single sample was deemed representative of the daily mean concentration.

Water-quality samples also were collected from tributaries other than Wightman Fork during each sampling event. Typically, only one sample was collected at each tributary site. The tributary sites were located at or near the mouth of (in downstream order) Iron Creek, Alum Creek, Bitter Creek, Jasper Creek, Burnt Creek, Spring Creek, Fern Creek, Castleman Gulch, Silver Creek, Lieutenant Creek, and Ranger Creek (fig. 1).

Sources of metals to the Alamosa River were evaluated using data collected from a specific parcel of water as it flowed through the study area. The specific parcel was identified from those sites equipped with automatic samplers and was chosen to coincide with the approximate traveltime of water sampled at tributary sites. Generally, tributary sites were collected within a 6-hour period around noon. Occasionally, tributaries were not sampled on the same day as the sites equipped with automatic samplers. In these cases, an effort was made to ensure that the data used from the automatic samplers were collected at approximately the same time of day that the tributaries were sampled and that no major changes in streamflow had occurred. Storm samples were not included in the data set when evaluating loads and percentage of contributions from source areas.

Streamflow data accompanied most water-quality samples collected during nonsteady-state periods. Generally, instantaneous data were retrieved from the data loggers at gaged sites providing the gage was operational. Streamflow measurements were not made at AR41.2, AR43.6, AR45.5, WF0.0, and WF5.5 from April through June 1995 because streamflow gages had not been installed and high streamflow conditions were unwadeable. As a result, load calculations, could not be made for these samples. Streamflow measurements were done in conjunction with water-quality samples collected at tributary sites.

Methods of Collection and Analysis Used to Estimate Seasonal and Annual Metal Loads

Several methods can be used to compute seasonal and annual metal loads. Estimates using regression equations can be used where there are strong correlations between constituents. In the Alamosa River, however, relations between the logarithms of metal concentrations and streamflow generally were not statistically significant ($p<0.10$). Standard time-interval methods divide the data record into discrete intervals and estimate load as the product of the concentration for that discrete period and the sum of the streamflow for that period (Scheider and others, 1979). For the purposes of this report, a modified time-interval method was used to estimate metal loads. In the modified time-interval method, the data record is divided into several discrete time intervals based on changes in streamflow or flow periods. The mean concentration of the values that occurred during each flow period was multiplied by the total streamflow for the period to determine metal loads for the flow period. Estimates of the metal loads for each flow period were summed to estimate annual metal loads.

Grab samples collected during steady-state streamflow conditions and flow-weighted composite samples collected during nonsteady-state streamflow conditions were used to compute an average metal concentration at each site for each flow period from 1995 through 1997. Methods for processing flow-weighted composite samples were consistent with those described by the USEPA (1991). Appropriate concentration data were logarithmically transformed (log base 10) and averaged. The averages then were retransformed (antilog of the transformed averages) to obtain nonskewed, estimated average metal concentrations. This type of data transformation is commonly used with water-quality data because of the generally log-normal distribution of the positively skewed data (Helsel and Hirsch, 1992). However, the statistical certainties of the average concentrations determined by this method are unknown because of the small number of samples collected during each flow period (fig. 2).

Streamflow for each flow period was determined by summing the reported daily streamflow for the flow period at each gaged site. Streamflow gages at sites AR34.5 and AR31.0 were operated throughout much of the year by the Colorado Division of Water Resources (McDonald, 1996, 1997, and 1998). Streamflow gages at sites WF5.5, WF0.0, AR45.5, AR43.6, and AR41.2 were installed by the USGS in mid- to late July 1995. The USGS-gaged streamflow records are reported in the annual water-resources data reports for Colorado (Crowfoot and others, 1996, 1997, and 1998). Table 3 shows the periods of operation for all the gages from 1995 to 1997.

In certain cases, daily streamflow was not available at a site and was estimated by computing the proportion of instantaneous streamflow measured at the site during the flow period to the streamflow measured at AR34.5. Depending on the number of instantaneous measurements made during the flow period, either one proportion or multiple proportions were used to estimate the cumulative or total streamflow for the flow period for the ungaged period at the site.

Metal concentrations associated with rainstorm runoff were not used to compute the average metal concentrations for the summer-flow period because too few storm samples were collected to adequately characterize metal concentrations at each site during storms. As a result, the average metal concentrations and, therefore, loads may be underestimated for the summer-flow period. The available storm data, however, were analyzed and a semiquantitative discussion of seasonal and annual storm load contribution is presented. First, the storm data were grouped by site and a log-transformed average was computed as

Table 3. Approximate periods of operation for streamflow gages on the Alamosa River and Wightman Fork, 1995–97

[1234, denotes approximate number of weeks during a month; -, denotes inactive; x, denotes active]

Site	Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234	1234
1995												
AR31.0	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR34.5	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR41.2	----	----	----	----	----	----	-xxx	xxxx	xxxx	xx--	----	----
AR43.6	----	----	----	----	----	----	-xxx	xxxx	xxxx	xx--	----	----
AR45.5	----	----	----	----	----	----	--xx	xxxx	xxxx	xx--	----	----
WF0.0	----	----	----	----	----	----	--xx	xxxx	xxxx	xx--	----	----
WF5.5	----	----	----	----	----	----	--xx	xxxx	xxxx	xx--	----	----
1996												
AR31.0	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
AR34.5	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
AR41.2	----	----	----	-xxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
AR43.6	----	----	----	-xxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
AR45.5	----	----	----	-xxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
WF0.0	----	----	----	-xxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
WF5.5	----	----	----	-xxx	xxxx	xxxx	xxxx	xxxx	xxxx	x---	----	----
1997												
AR31.0	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR34.5	----	----	---	xxxx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR41.2	----	----	----	--xx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR43.6	----	----	----	--xx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
AR45.5	----	----	----	--xx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
WF0.0	----	----	----	--xx	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----
WF5.5	----	----	----	----	xxxx	xxxx	xxxx	xxxx	xxxx	xx--	----	----

described previously. The average concentrations were multiplied by the median change in streamflow and the median duration of a storm as presented by Rupert (2001). The product (load in tons per day) was multiplied by the number of rainstorm runoff events per year to estimate the load contributed by storms. Generally, 18 storms were identified during the summer period for each year (Rupert, 2001). A comparison of the estimated storm load at each site to the corresponding annual load indicated that storms contribute less than 2 percent of the annual load at any site. When compared to the summer load, storms appeared to contribute from 5 to 20 percent of the load. The highest percentage of contribution was for total-recoverable aluminum and iron.

In addition to the underestimation of loads due to storms, the Summitville Mine treatment plant periodically released water with high metal concentrations and low pH that was not sampled (Rupert, 2001). The releases were generally associated with variations in the operations at the mine site. These releases affect the accuracy of the estimates of metal loads used in this report.

SOURCES OF METAL LOADS TO THE ALAMOSA RIVER

Sources of dissolved and total-recoverable aluminum, copper, iron, and zinc loads were determined for Exposure Areas 3a, 3b, and 3c (fig. 1) by computing the percentage of contribution of metal load for each site relative to the downstream main-stem site. The equation to calculate the percentage of contribution of metal load from each tributary was described in a previous section of this report. In addition, the percentage of contribution of metal load from the upstream main-stem site to the closest downstream main-stem site was calculated in the same manner. This provides a percentage of contribution of the metal load that can be attributed to the Alamosa River upstream from the exposure areas. The percentage of contribution of metal loads determined in this manner provides an estimate of the contribution of metals from a particular area. In some instances, the percentage of contribution of metal loads from the tributary site(s) or the upstream main-stem site is larger than 100 percent of the metal load measured at the downstream main-stem site. This indicates that some reaction or process occurred within the stream reach that decreased the dissolved and/or total-recoverable metal load in the water column. Iron and aluminum hydroxide precipitates are commonly found on the stream bottom in certain areas of the Alamosa River and Wightman Fork. The following sections present the data as boxplots, which show the variation around the median value of the data. An example of a boxplot is given in figure 4.

Alamosa River Upstream from Wightman Fork (Exposure Area 3a)

Sources of metals to the Alamosa River upstream from Wightman Fork, EA3a, were determined for each flow period: base flow, early snowmelt, snowmelt, and summer flow. The source area evaluated in EA3a includes the Stunner hydrothermally altered area (fig. 1). The water-quality sites evaluated for EA3a were: AR49.5 (Alamosa River upstream from Iron Creek), IC0.0 (Iron Creek at the mouth), AC0.0 (Alum Creek at the mouth), and BI0.0 (Bitter Creek at the mouth). The percentage of contribution of metal loads from each of these sites is shown in figures 5–8. The percentage of contribution of metal loads for AR49.5, IC0.0, AC0.0, and BI0.0 were

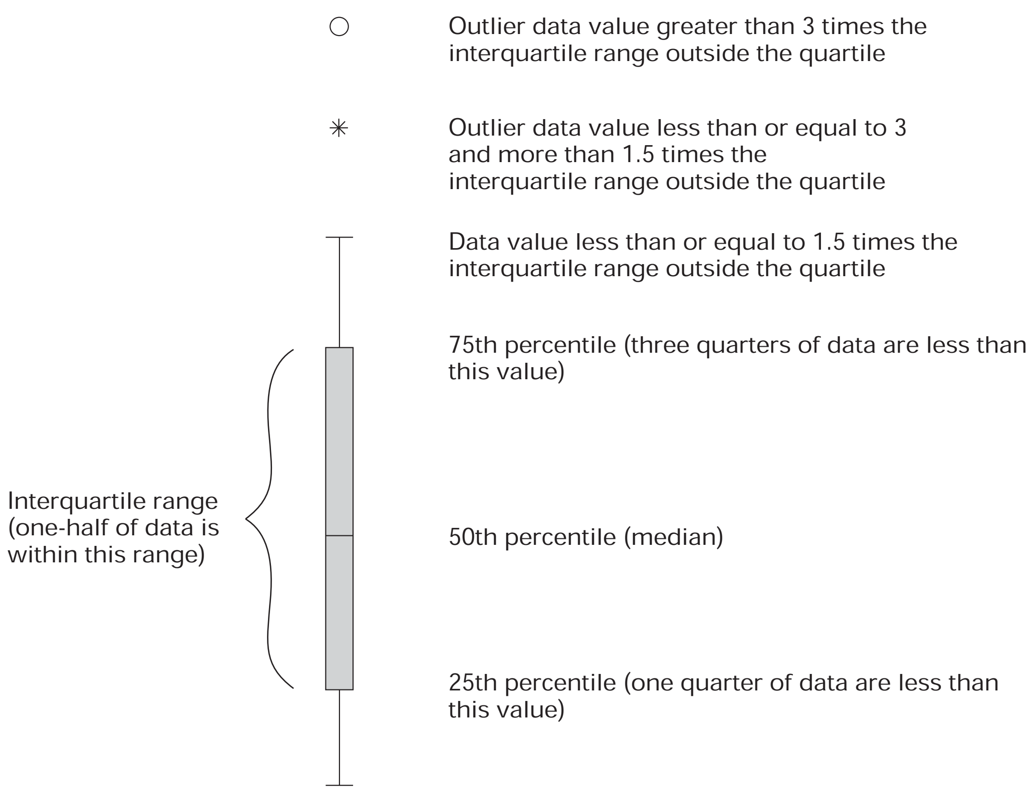

Figure 4. Example diagram of a boxplot.

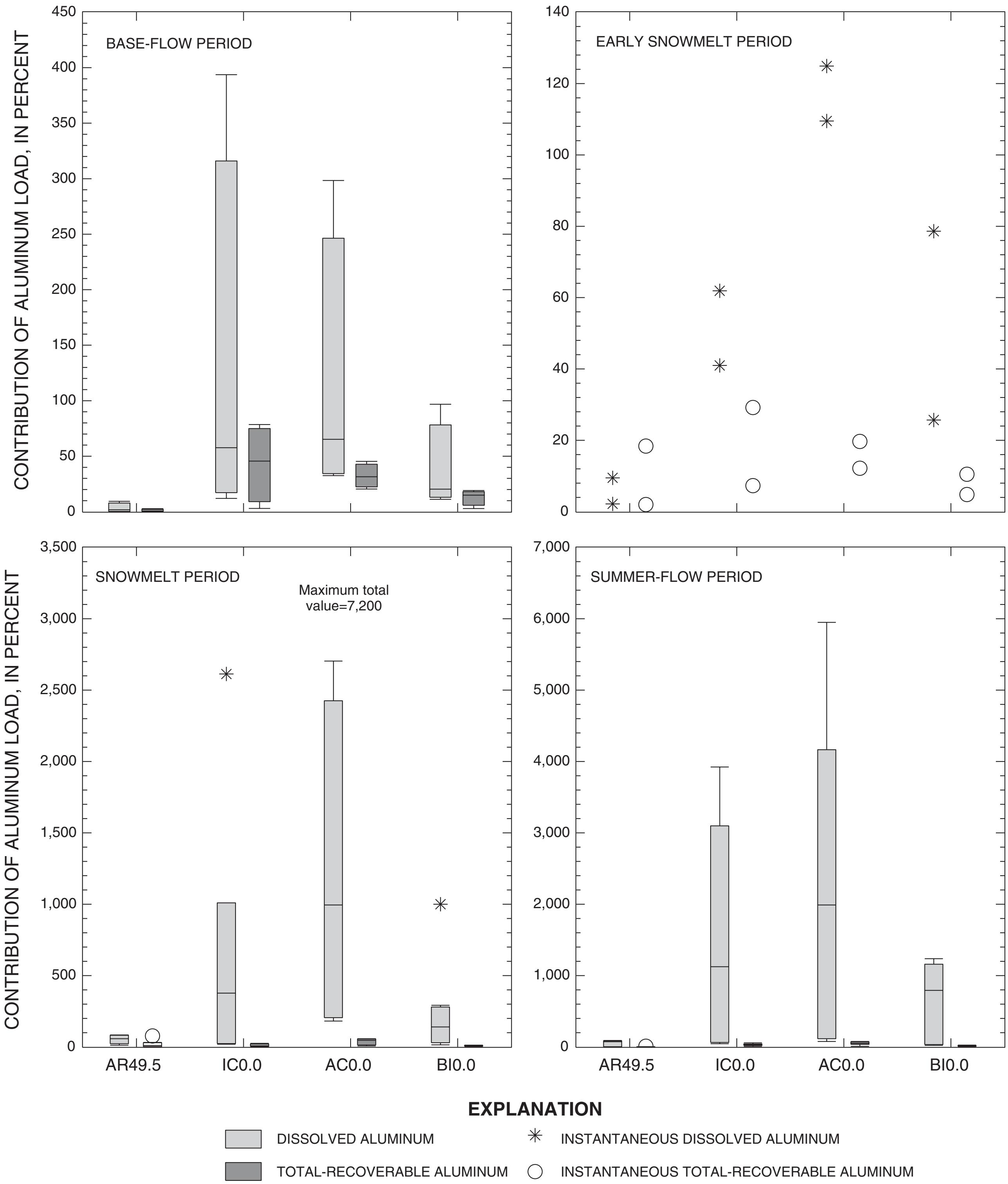

Figure 5. Percentage of contribution of aluminum load from Exposure Area 3a (Alamosa River and tributary sites upstream from Wightman Fork), 1995–97.

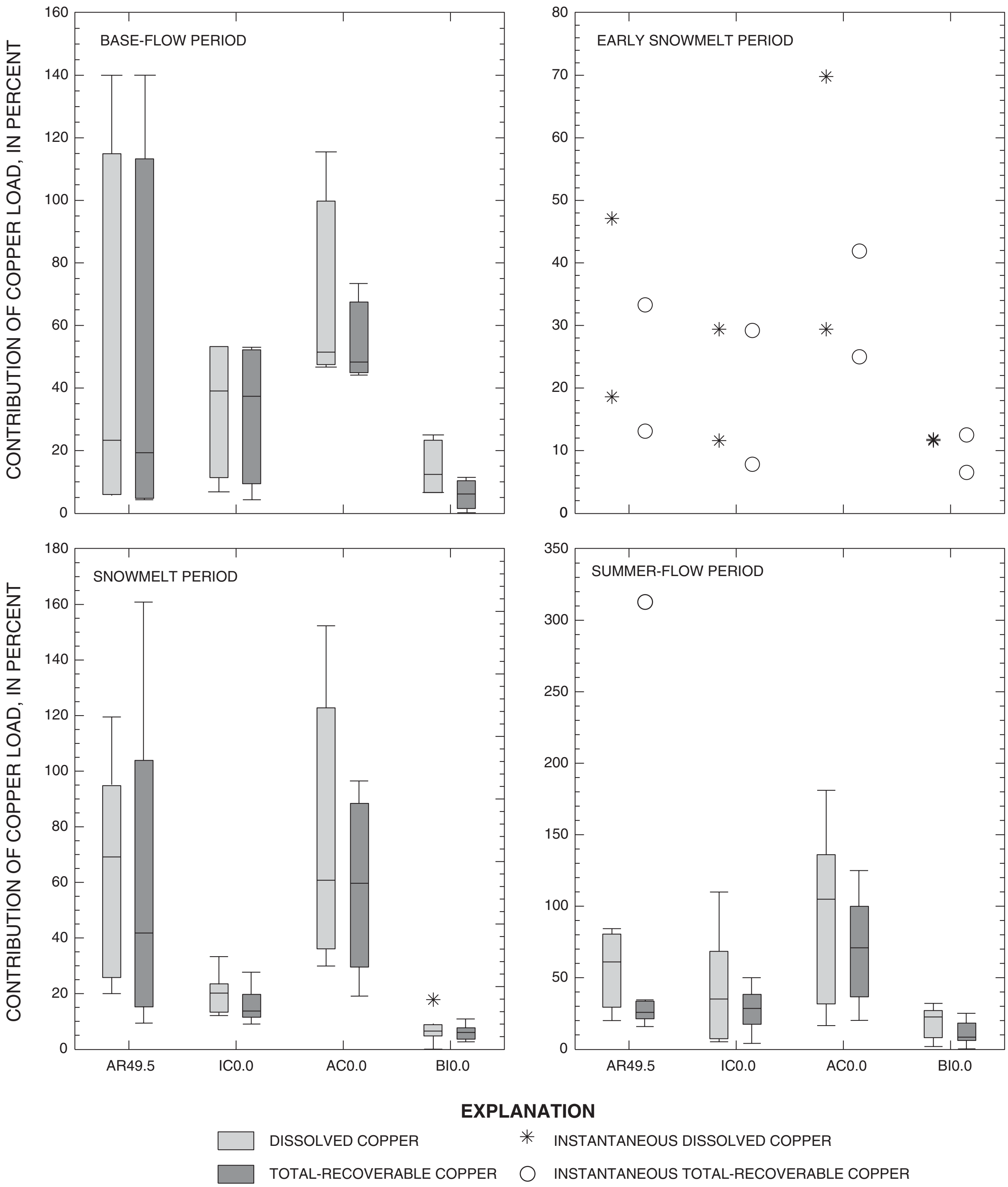

Figure 6. Percentage of contribution of copper load from Exposure Area 3a (Alamosa River and tributary sites upstream from Wightman Fork), 1995–97.

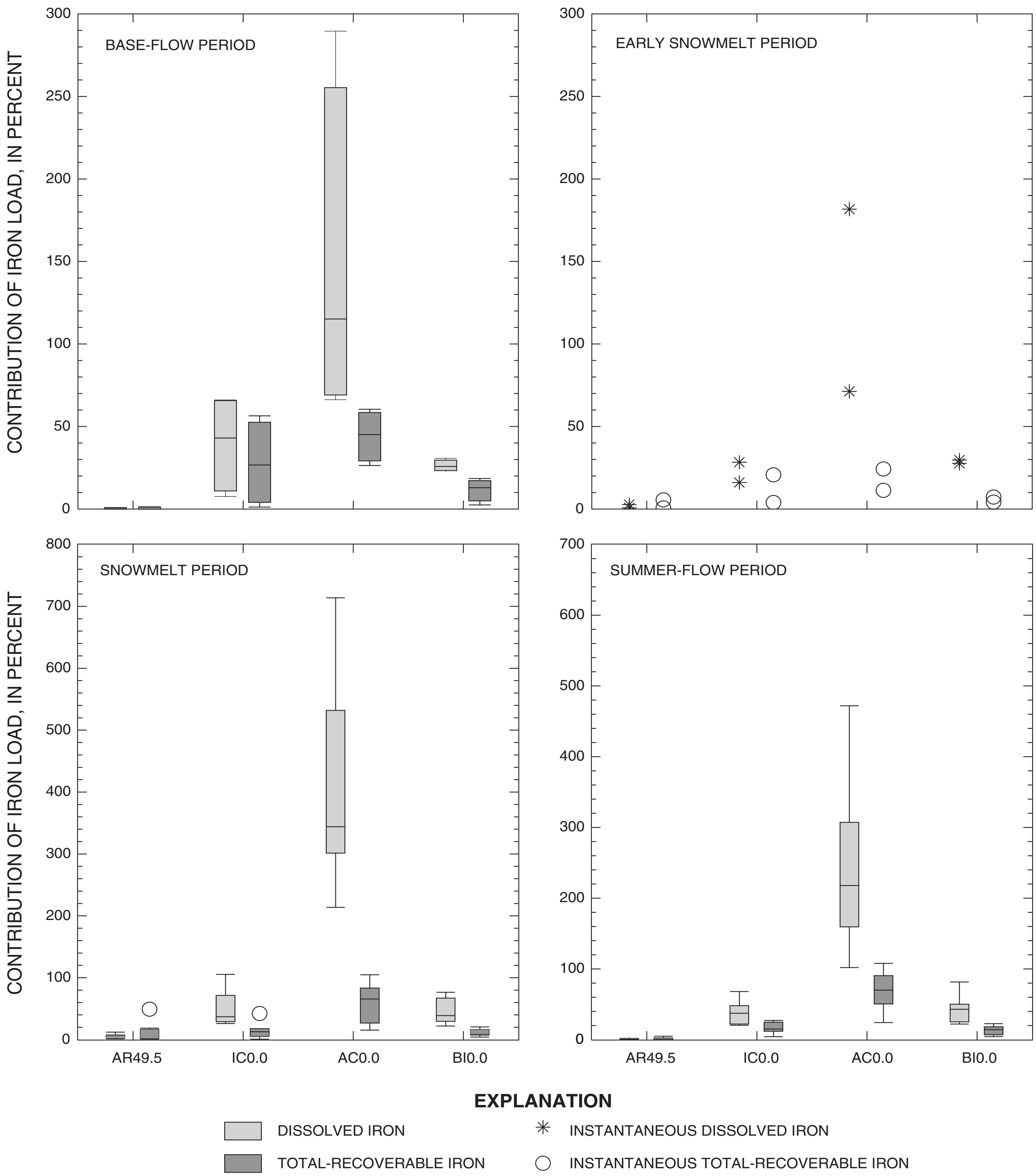

Figure 7. Percentage of contribution of iron load from Exposure Area 3a (Alamosa River and tributary sites upstream from Wightman Fork), 1995–97.

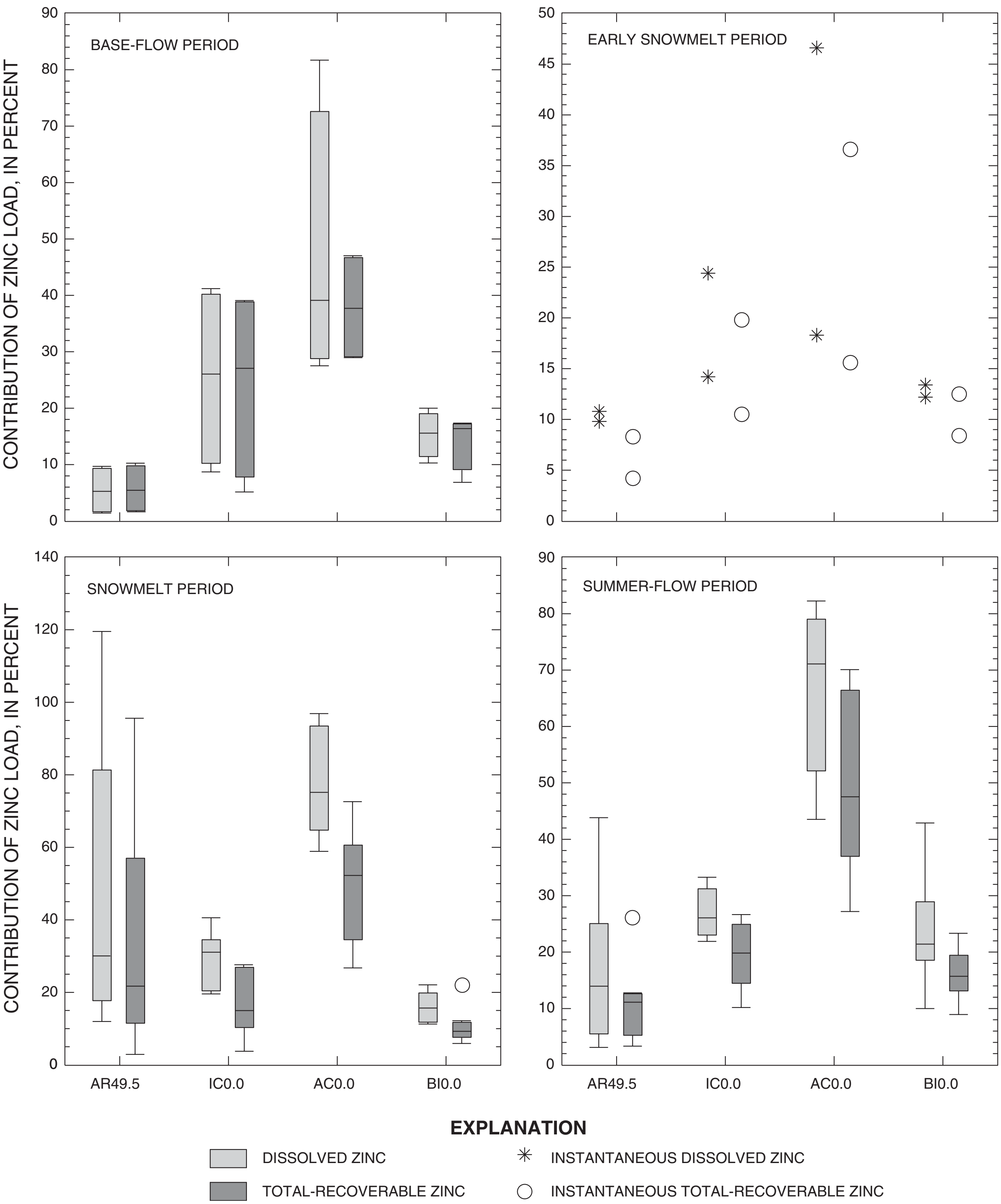

Figure 8. Percentage of contribution of zinc load from Exposure Area 3a (Alamosa River and tributary sites upstream from Wightman Fork), 1995–97.

computed relative to the metal loads measured at AR45.5.

Alum, Iron, and Bitter Creeks contribute substantially to the metal loads in EA3a. The predominant contributor of dissolved and total-recoverable aluminum, copper, iron, and zinc loads to EA3a is Alum Creek. Frequently, the percentage of contribution of metal loads from Alum Creek was greater than the combined metal load contribution from Iron Creek and Bitter Creek. Generally, Iron Creek was a greater source of metals to EA3a than Bitter Creek. The Alamosa River upstream from Iron Creek (AR49.5) is shown to contribute a fair percentage of copper and zinc for some flow regimes or periods. It should be noted that much of the copper and zinc concentration data at AR49.5 were reported as less than the analytical reporting limit (ARL). A decision was made to use the ARL when calculating loads because, generally, the ARL was representative of other reported concentrations. As such, the use of the ARL to calculate loads at AR49.5 provides a relatively good estimate, albeit a slightly higher estimate, of the copper and zinc load contribution to EA3a.

As shown in figures 5–8, there were several instances where the percentage of metal load contribution from a tributary or several tributaries was greater than 100 percent of the measured metal load at AR45.5. This indicates that, with respect to dissolved metal loads, the dissolved metal partitioned to the suspended or particulate phase within the exposure area; and with respect to total-recoverable metal loads, the suspended or particulate metal settled from the water column to the streambed within the exposure area. Metals that are deposited to the streambed are probably resuspended and transported downstream during high streamflow associated with snowmelt runoff and during rainfall runoff in the summer.

Alamosa River from Wightman Fork to Fern Creek (Exposure Area 3b)

Sources of metals to the Alamosa River from Wightman Fork to Fern Creek, EA3b, were determined for each flow period: base flow, early snowmelt, snowmelt, and summer flow. The source areas evaluated in EA3b include Wightman Fork and the Jasper hydrothermally altered area (fig. 1). The water-quality sites evaluated for EA3b were: AR45.5 (Alamosa River upstream from Wightman Fork), WF0.0 (Wightman Fork at mouth), AR43.6 (Alamosa River upstream from Jasper), JC0.0 (Jasper Creek at the mouth), BC0.0 (Burnt Creek at the mouth), and SC0.0 (Spring Creek at the mouth). The percentage of contribution of metal loads from each of these sites are shown in figures 9–12. The percentage of contribution of metal loads from AR45.5 and WF0.0 were computed relative to the metal loads measured at AR43.6, and the percentage of contribution of metal loads from AR43.6, JC0.0, BC0.0, and SC0.0 were computed relative to AR41.2.

During the base-flow period, the pH of the Alamosa River at AR45.5 was at its annual minimum and the pH of the Wightman Fork generally was at its annual maximum. During this period, the predominant contribution of dissolved and total-recoverable aluminum and iron loads to EA3b was from EA3a, as indicated by the metal loads at AR45.5 (figs. 9 and 11). Additionally, EA3a generally contributed more than 30 percent of the dissolved and total-recoverable zinc loads to EA3b during base flow (fig. 12). EA3a generally was the predominant contributor of total-recoverable iron load to EA3b during the early snowmelt period (fig. 11).

During early snowmelt, snowmelt, and summer-flow periods, Wightman Fork was the predominant contributor of dissolved aluminum. Wightman Fork was the predominant contributor of dissolved iron load to AR43.6 during snowmelt periods. During base flow, early snowmelt, snowmelt, and summer flow, Wightman Fork was the predominant contributor of dissolved and total-recoverable copper loads. Throughout the year, Wightman Fork was the predominant contributor of dissolved and total-recoverable zinc loads. There were several instances where the percentages of dissolved aluminum, copper, iron, and zinc loads and total-recoverable copper and zinc loads from Wightman Fork were greater than 100 percent of the metal load at AR43.6. Additionally, there were occurrences where the dissolved and total-recoverable aluminum and iron loads at AR45.5 were greater than 100 percent of the metal load at AR43.6. These data indicate that, during certain times, metal partitioning and metal deposition from the water column to the streambed may be occurring in the reach between Wightman Fork and AR43.6, a distance of 2.1 miles.

Downstream from AR43.6, Jasper and Burnt Creeks generally contributed less than 10 percent of the metal loads relative to AR41.2. However, on a few occasions, Burnt Creek contributed a substantial

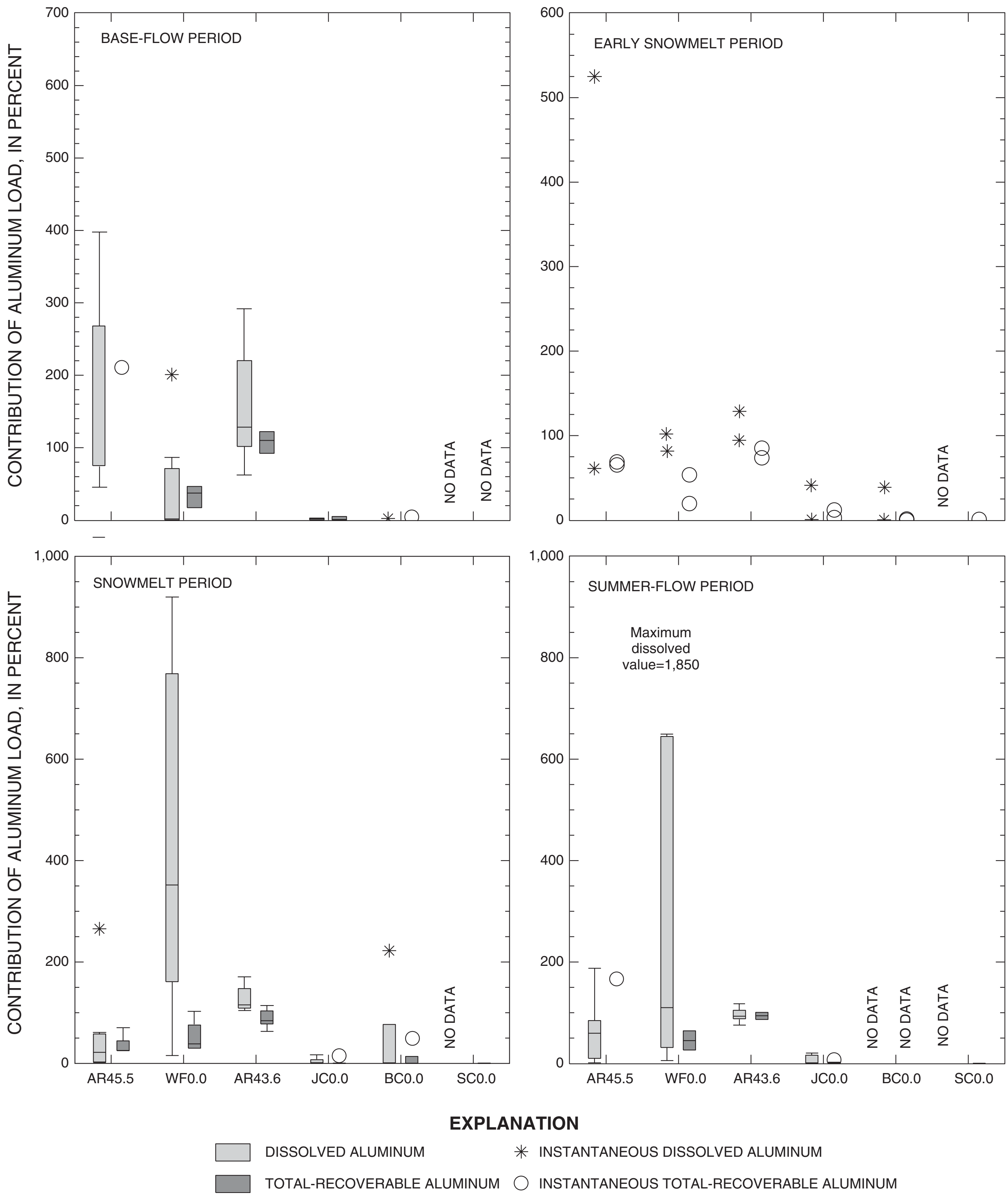

Figure 9. Percentage of contribution of aluminum load from Exposure Area 3b (Alamosa River and tributary sites from Wightman Fork to Fern Creek), 1995–97.

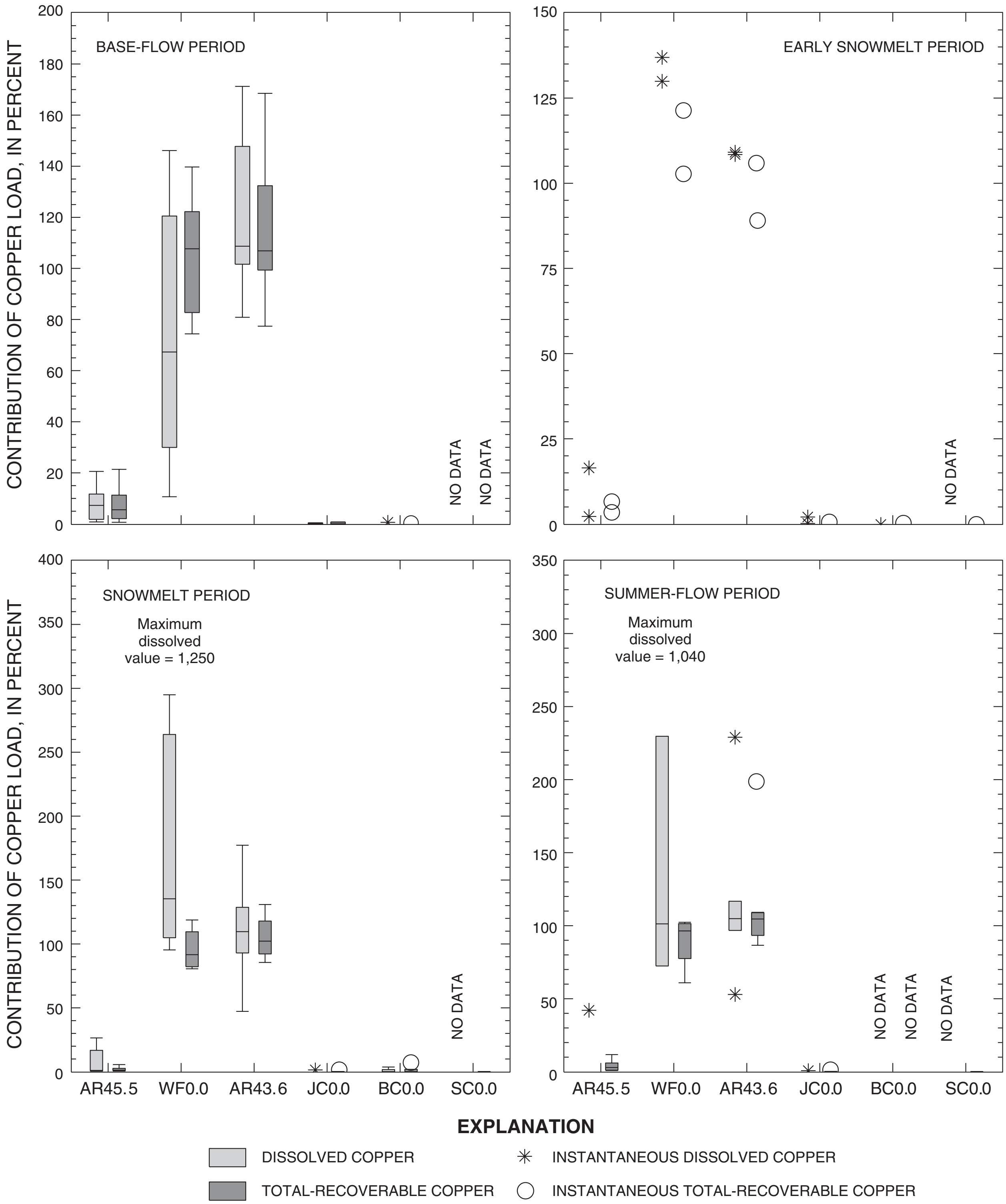

Figure 10. Percentage of contribution of copper load from Exposure Area 3b (Alamosa River and tributary sites from Wightman Fork to Fern Creek), 1995–97.

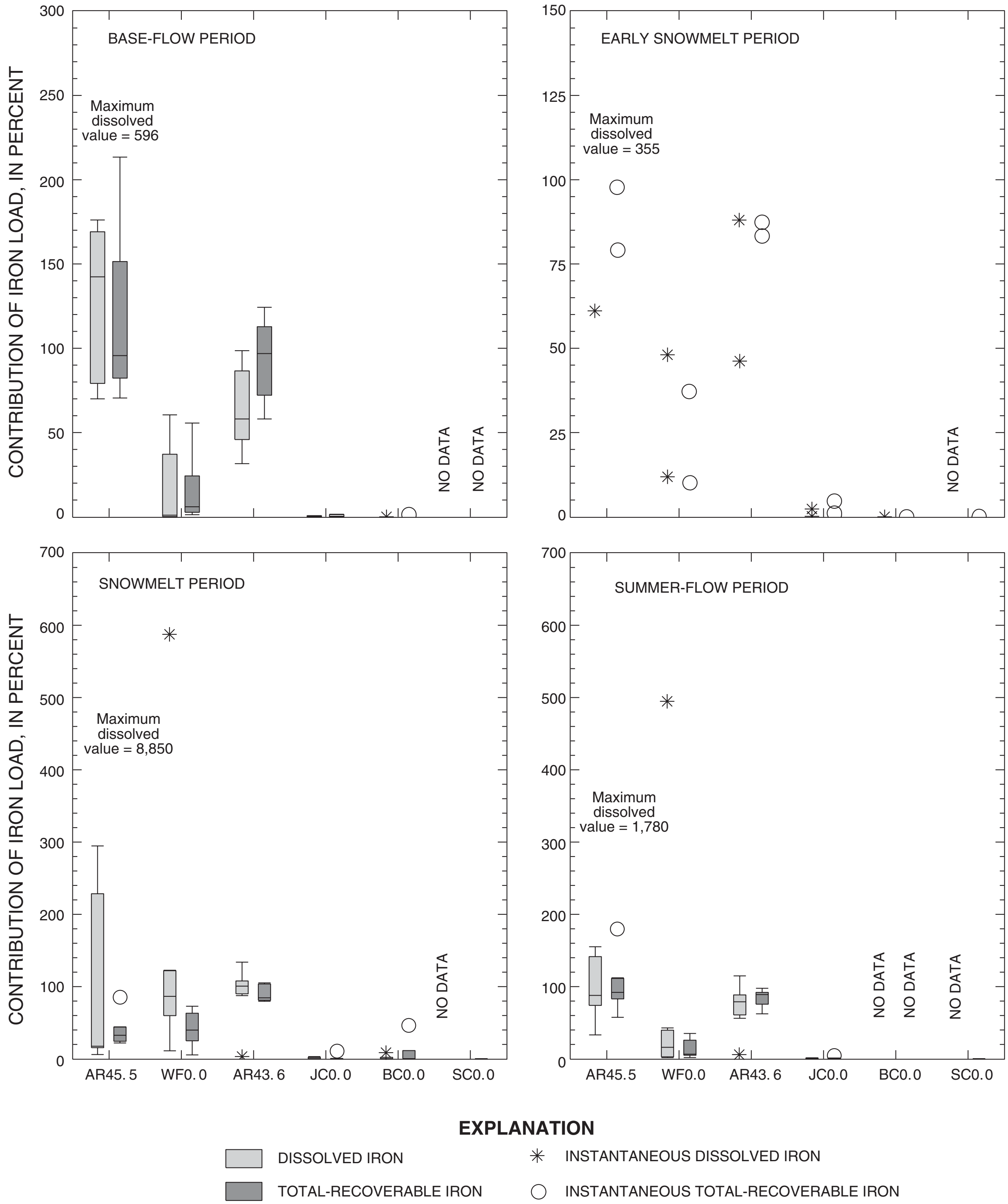

Figure 11. Percentage of contribution of iron load from Exposure Area 3b (Alamosa River and tributary sites from Wightman Fork to Fern Creek), 1995–97.

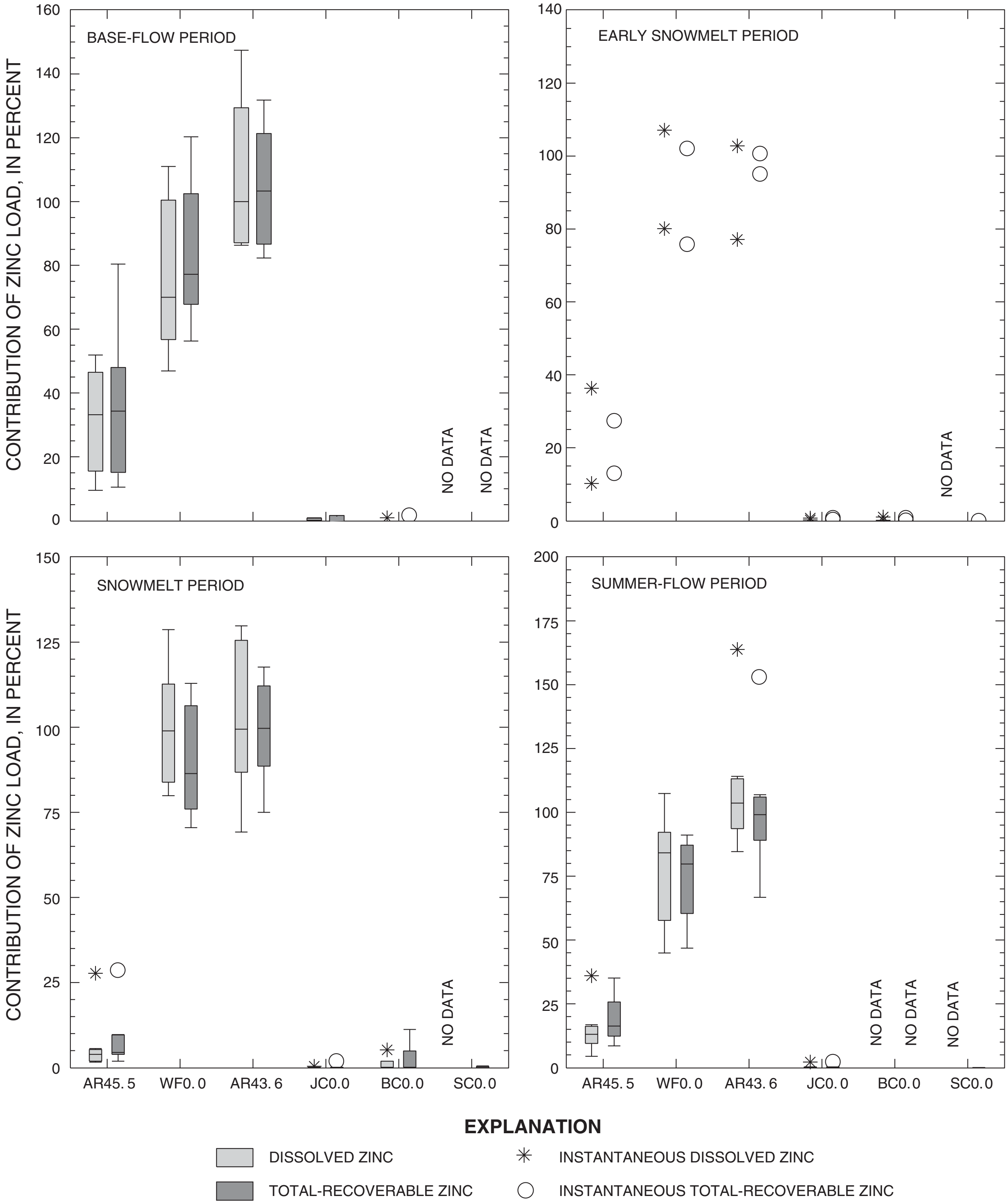

Figure 12. Percentage of contribution of zinc load from Exposure Area 3b (Alamosa River and tributary sites from Wightman Fork to Fern Creek), 1995–97.

percentage of the dissolved aluminum load and the dissolved and total-recoverable iron loads to the Alamosa River in EA3b. Also, on a few occasions, Jasper Creek contributed a substantial percentage of the dissolved and total-recoverable iron loads to the Alamosa River in EA3b. Spring Creek did not contribute substantially to the metal loading of the Alamosa River in EA3b.

Alamosa River from Fern Creek to Terrace Reservoir (Exposure Area 3c)

Sources of metals to the Alamosa River from Fern Creek to Terrace Reservoir, EA3c, were determined for each flow period—base flow, early snowmelt, snowmelt, and summer flow. The tributaries evaluated in EA3c do not drain any hydrothermally altered areas (fig. 1). The water-quality sites evaluated for EA3c are FC0.0 (Fern Creek at mouth), CG0.0 (Castleman Gulch at the mouth), AR41.2 (Alamosa River downstream from Castleman Gulch), SI0.0 (Silver Creek at the mouth), LC0.0 (Lieutenant Creek at the mouth), and RC0.0 (Ranger Creek at the mouth). The percentages of contribution of metal loads from each of these sites are shown in figures 13–16. The percentage of contribution of metal loads from FC0.0 and CG0.0 were computed relative to the metal loads measured at AR41.2, and the percentage of contribution of metal loads from AR41.2, SI0.0, LC0.0, and RC0.0 were computed relative to AR34.5.

None of the five tributaries sampled in EA3c contributed substantially to dissolved or total-recoverable aluminum, copper, iron, and zinc loads. The combined streamflow for these tributaries contributed less than 2 percent of the streamflow to EA3c. Therefore, the tributaries do not provide substantial dilution to the metal loads measured in EA3c. The metal loads in EA3c result from upstream sources; the primary upstream sources are Wightman Fork in EA1 and Alum and Iron Creeks in EA3a.

Throughout the year, the contributions of dissolved aluminum, copper, iron, and zinc loads and total-recoverable copper and iron loads at AR41.2 were frequently greater than 100 percent of the respective metal loads at AR34.5. Except during the early snowmelt period, total-recoverable zinc loads (fig. 16) were frequently greater than 100 percent of the respective metal loads at AR34.5. These data indicate that metal partitioning and metal deposition from the water column to the streambed may be occurring in the last 8.5 miles of EA3c.

ESTIMATION OF SEASONAL AND ANNUAL METAL LOADS AT SELECTED SITES

Seasonal and annual dissolved and total-recoverable aluminum, copper, iron, and zinc loads for 1995–97 were estimated for Exposure Areas 1, 2, 3a, 3b, and 3c. As indicated in table 2, the duration of flow varied from year to year for the same flow period. For example, the base-flow period for 1995 had a duration of 79 days, the base-flow period for 1996 had a duration of 175 days, and the base-flow period for 1997 had a duration of 195 days. The duration of the flow period affects the mass of metals estimated for each flow period. Therefore, it is important to remember this when making year-to-year comparisons of metal loads for the same flow period. Additionally, the magnitude of streamflow varied from year to year; 1995 and 1997 were above-normal flow years, whereas 1996 was a below-normal flow year. The streamflow in 1995 had the highest total flow with a 94-day snowmelt period, and the streamflow in 1996 had the lowest total flow with a 56-day snowmelt period.

Wightman Fork at WF5.5 (Exposure Area 1)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes (flow periods) and the annual streamflow and metal mass for 1995–97 at WF5.5 are presented in figures 17–19. In 1995, streamflow measurements and water-quality samples were not collected from WF5.5 until the snowmelt period. Therefore, metal loads were not estimated for the 1995 base flow and early snowmelt periods. The annual streamflow and estimates of metal mass shown for 1995 in figures 17–19 were based on partial year records and included estimates only for the snowmelt and summer-flow periods.

Many tons of metals were transported past WF5.5 from 1995 through 1997. Between 49 and 246 tons of total-recoverable aluminum (fig. 18), between 6 and 44 tons of total-recoverable copper

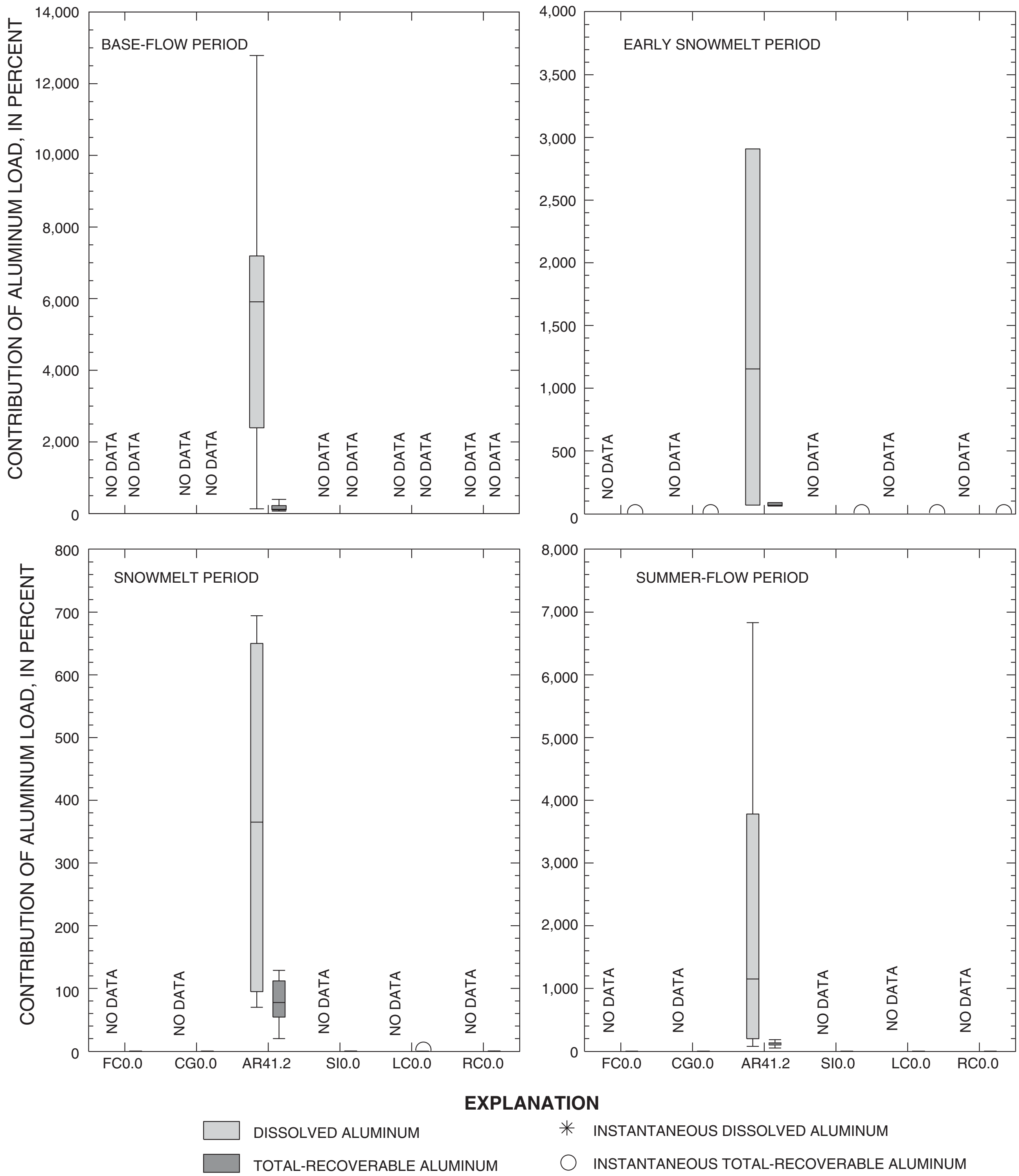

Figure 13. Percentage of contribution of aluminum load from Exposure Area 3c (Alamosa River and tributary sites from Fern Creek to Terrace Reservoir), 1995–97.

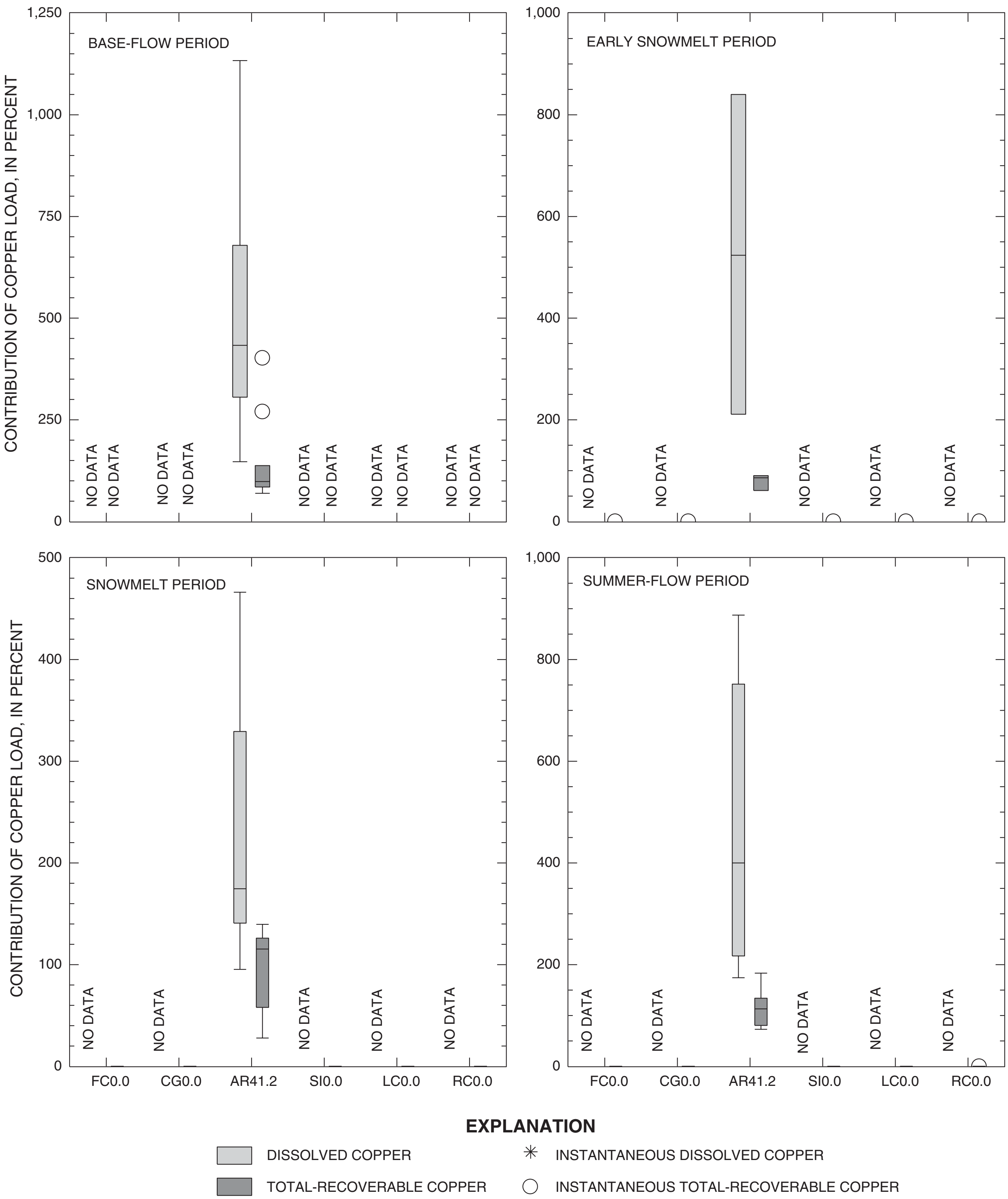

Figure 14. Percentage of contribution of copper load from Exposure Area 3c (Alamosa River and tributary sites from Fern Creek to Terrace Reservoir), 1995–97.

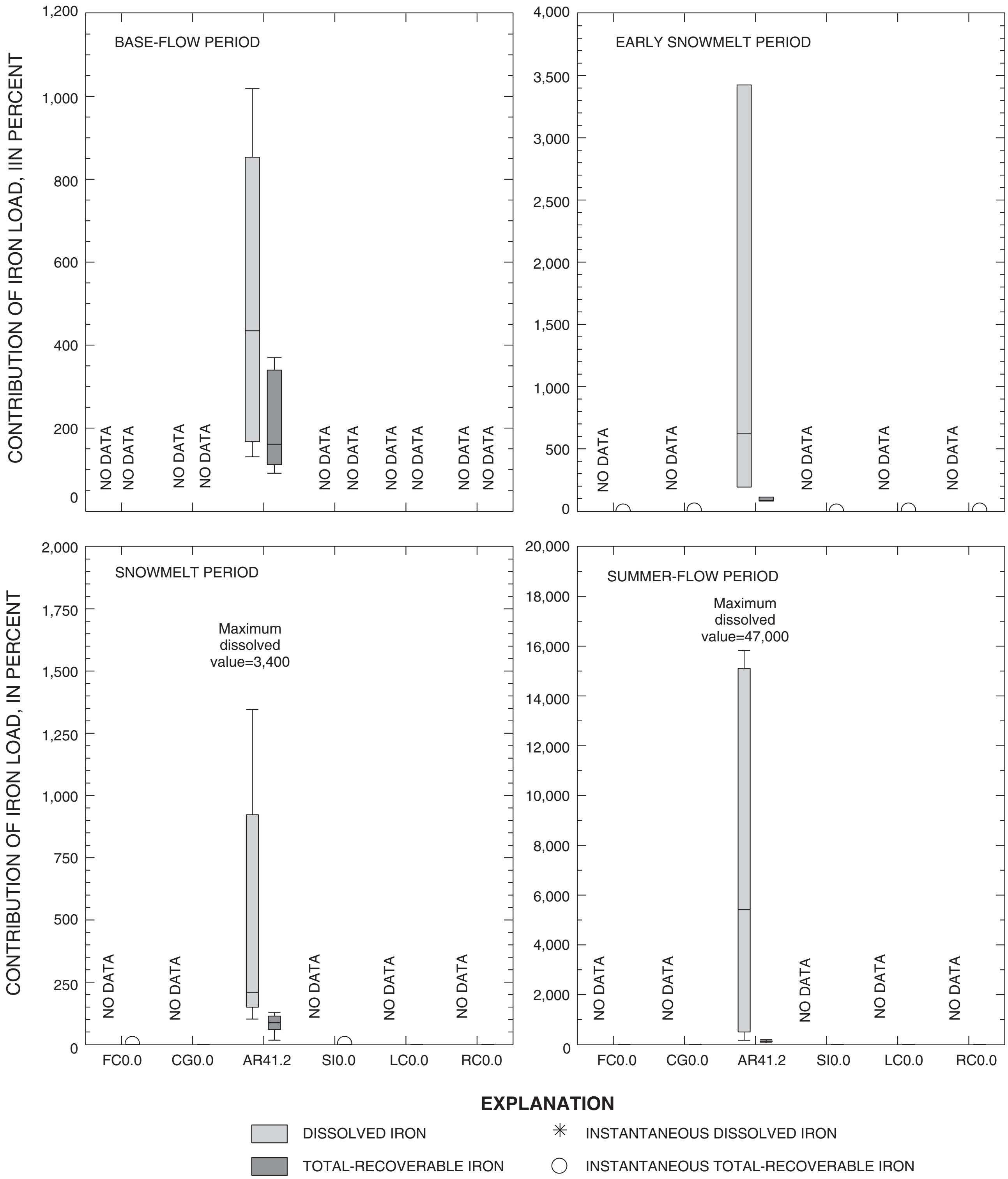

Figure 15. Percentage of contribution of iron load from Exposure Area 3c (Alamosa River and tributary sites from Fern Creek to Terrace Reservoir), 1995–97.

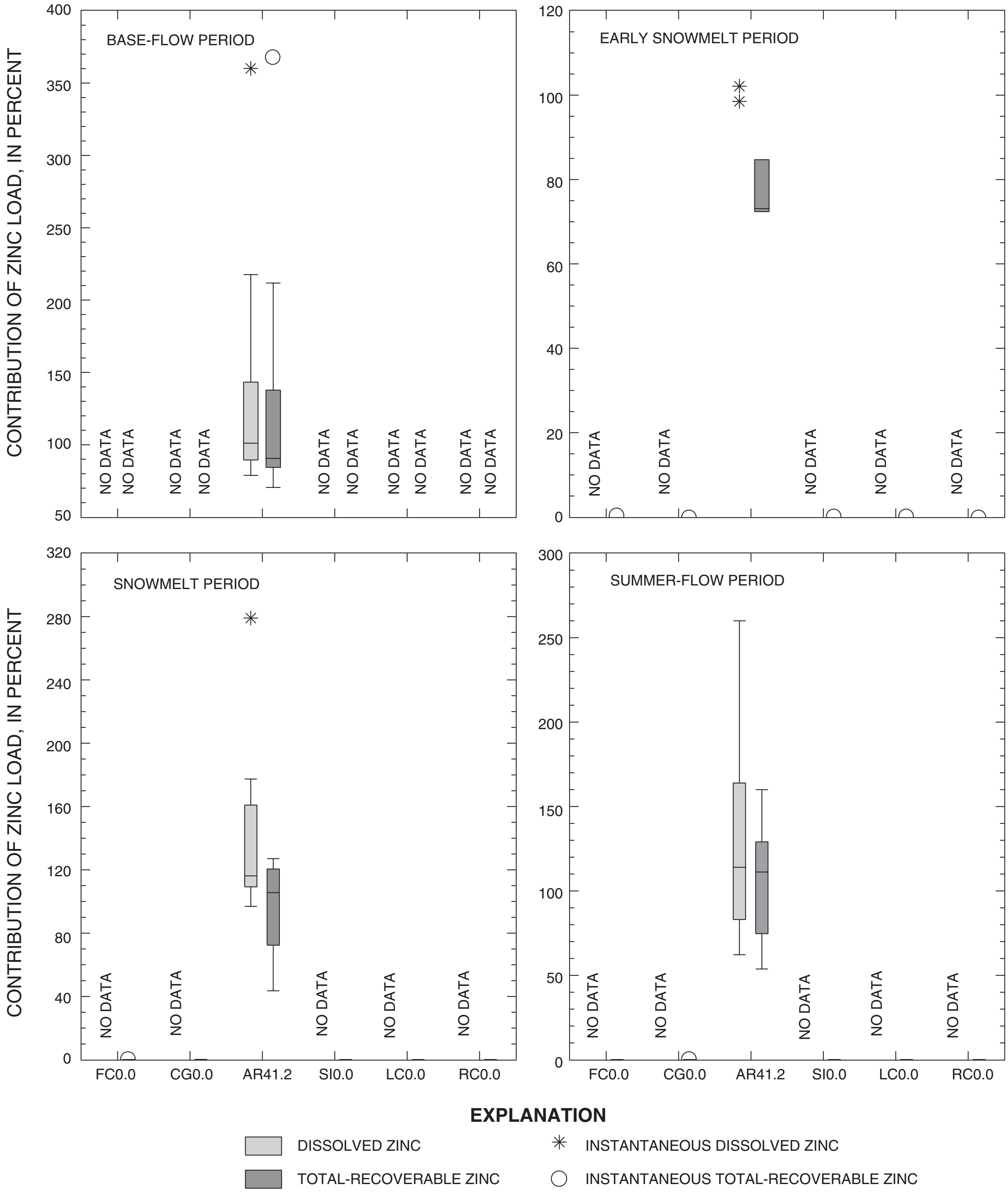

Figure 16. Percentage of contribution of zinc load from Exposure Area 3c (Alamosa River and tributary sites from Fern Creek to Terrace Reservoir), 1995–97.

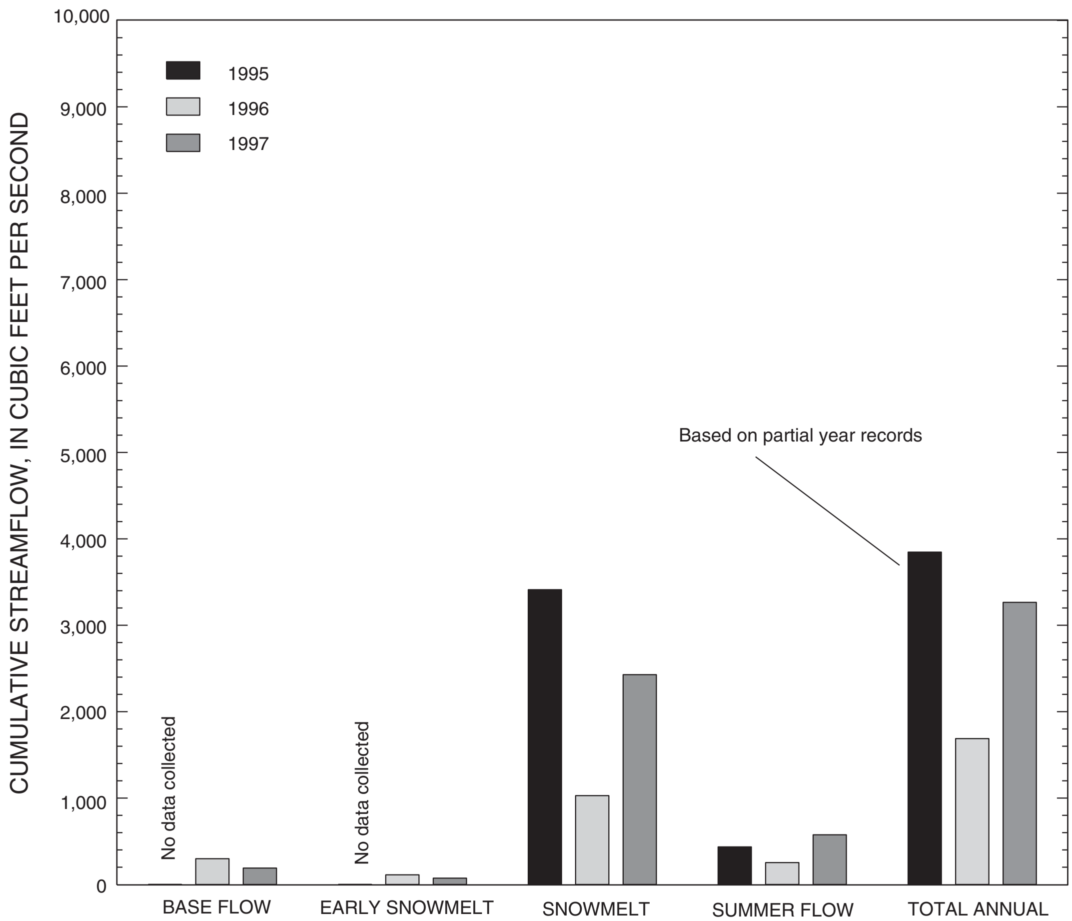

Figure 17. Cumulative streamflow for selected flow periods, Exposure Area 1 (site WF5.5), 1995–97.

(fig. 18), between 39 and 342 tons of total-recoverable iron (fig. 19), and between 4 and 20 tons of total-recoverable zinc (fig. 19) were estimated to have been transported annually past WF5.5 from 1995 through 1997. The largest estimated annual mass for dissolved and total-recoverable aluminum, copper, iron, and zinc occurred in 1995. The annual metal mass estimated for 1995 was between 5 and 10 times larger than the annual metal mass estimated for 1996 and about 2 times the annual metal mass estimated for 1997. The annual mass of dissolved aluminum, copper, iron, and zinc substantially decreased after 1995.

More than 60 percent of the annual streamflow occurred during the 8 to 13 weeks of the snowmelt period (fig. 17). For 1995 and 1997, the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc transported during the snowmelt period generally constituted between about 70 and 90 percent of the corresponding annual metal mass. During 1996, the metal mass transported during the snowmelt period generally constituted between 25 and 50 percent of the annual metal mass.

From 1995 through 1997, generally more than 95 percent of the annual copper and zinc mass was transported past WF5.5 in the dissolved fraction. In 1995 and 1997, 85 percent of the annual aluminum mass was transported past WF5.5 in the dissolved fraction; in 1996, about 40 percent of the annual aluminum mass was transported past WF5.5 in the dissolved fraction. Between 1995 and 1997, between 40 and 60 percent of the annual iron mass was transported past WF5.5 in the dissolved fraction.

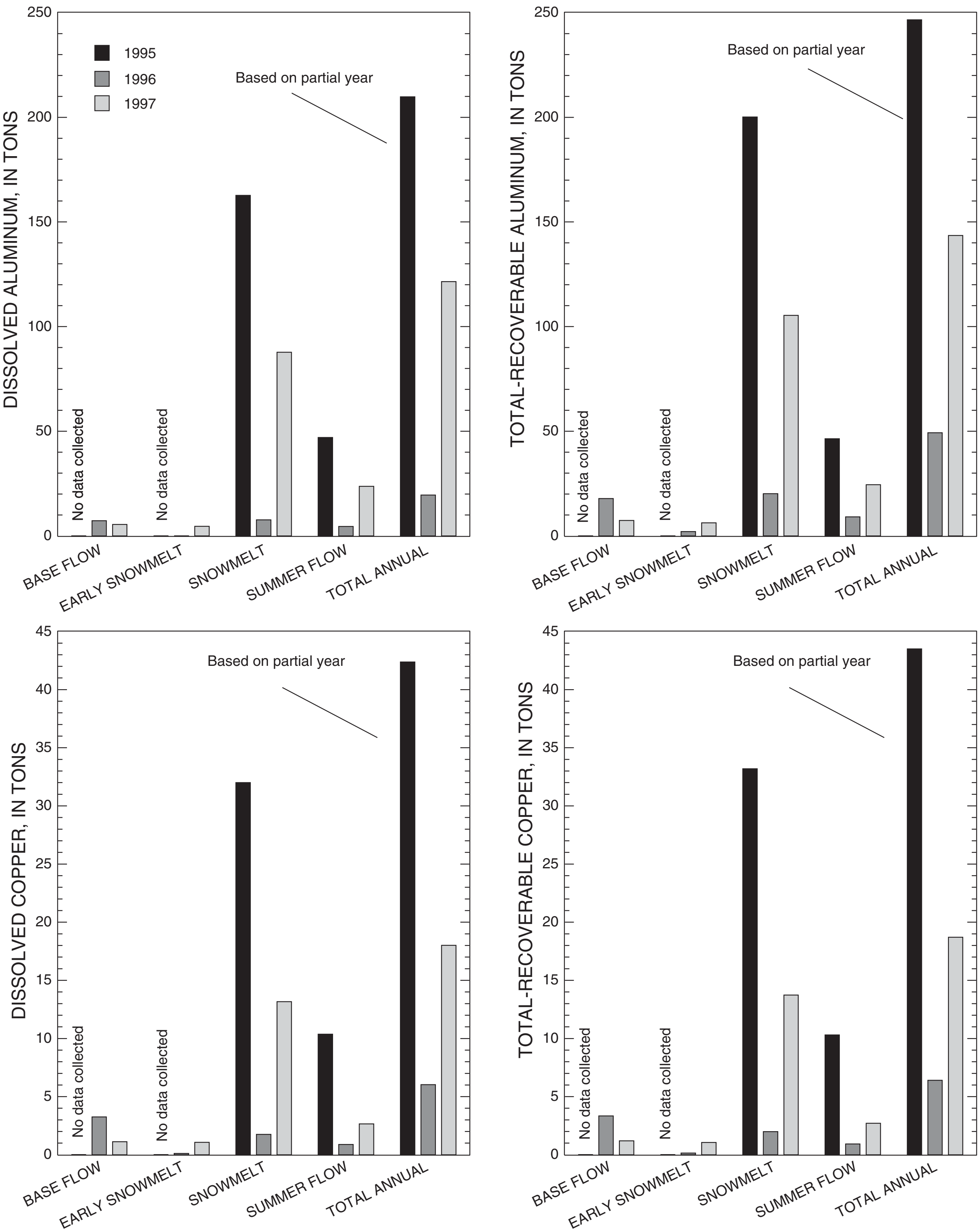

Figure 18. Mass of aluminum and copper for selected flow periods, Exposure Area 1 (site WF5.5), 1995–97.

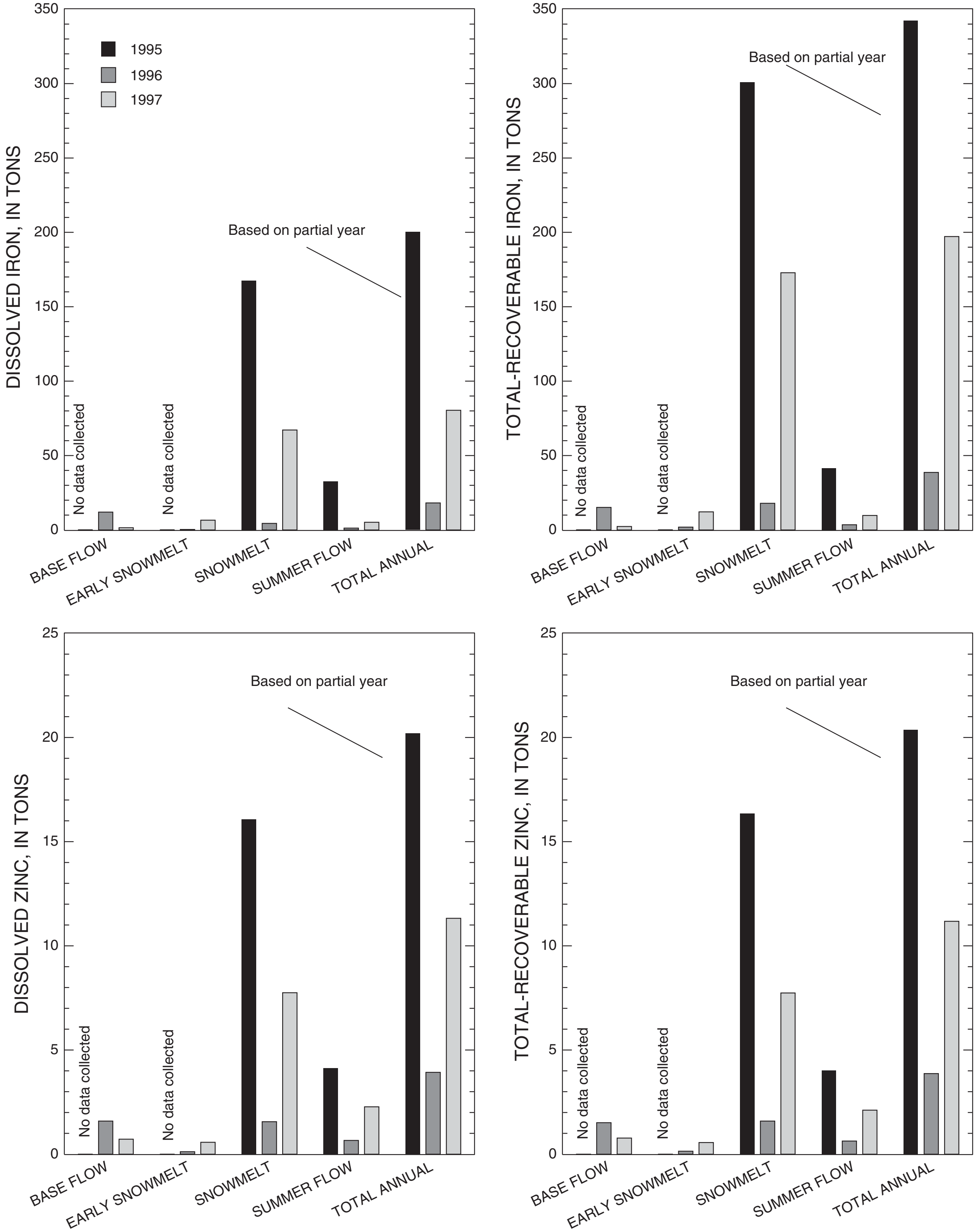

Figure 19. Mass of iron and zinc for selected flow periods, Exposure Area 1 (site WF5.5), 1995–97.

Wightman Fork at WF0.0 (Exposure Area 2)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes (flow periods) and the annual streamflow and metal mass for 1995–97 at WF0.0 are presented in figures 20–22.

Many tons of metals were transported past WF0.0 from 1995 through 1997. Between 55 and 220 tons of total-recoverable aluminum (fig. 21), between about 8 and 42 tons of total-recoverable copper (fig. 21), between 40 and 240 tons of total-recoverable iron (fig. 22), and between about 5 and 19 tons of total-recoverable zinc (fig. 22) were estimated to have been transported annually past WF0.0 from 1995 through 1997. The largest estimated annual mass for dissolved and total-recoverable aluminum, copper, iron, and zinc occurred in 1995. The annual metal mass estimated for 1995 was between 3 and 6 times larger than the annual metal mass estimated for 1996 and generally was between about 1 and 2 times the annual metal mass estimated for 1997. The annual mass of dissolved copper, iron, and zinc substantially decreased after 1995. However, the estimated annual

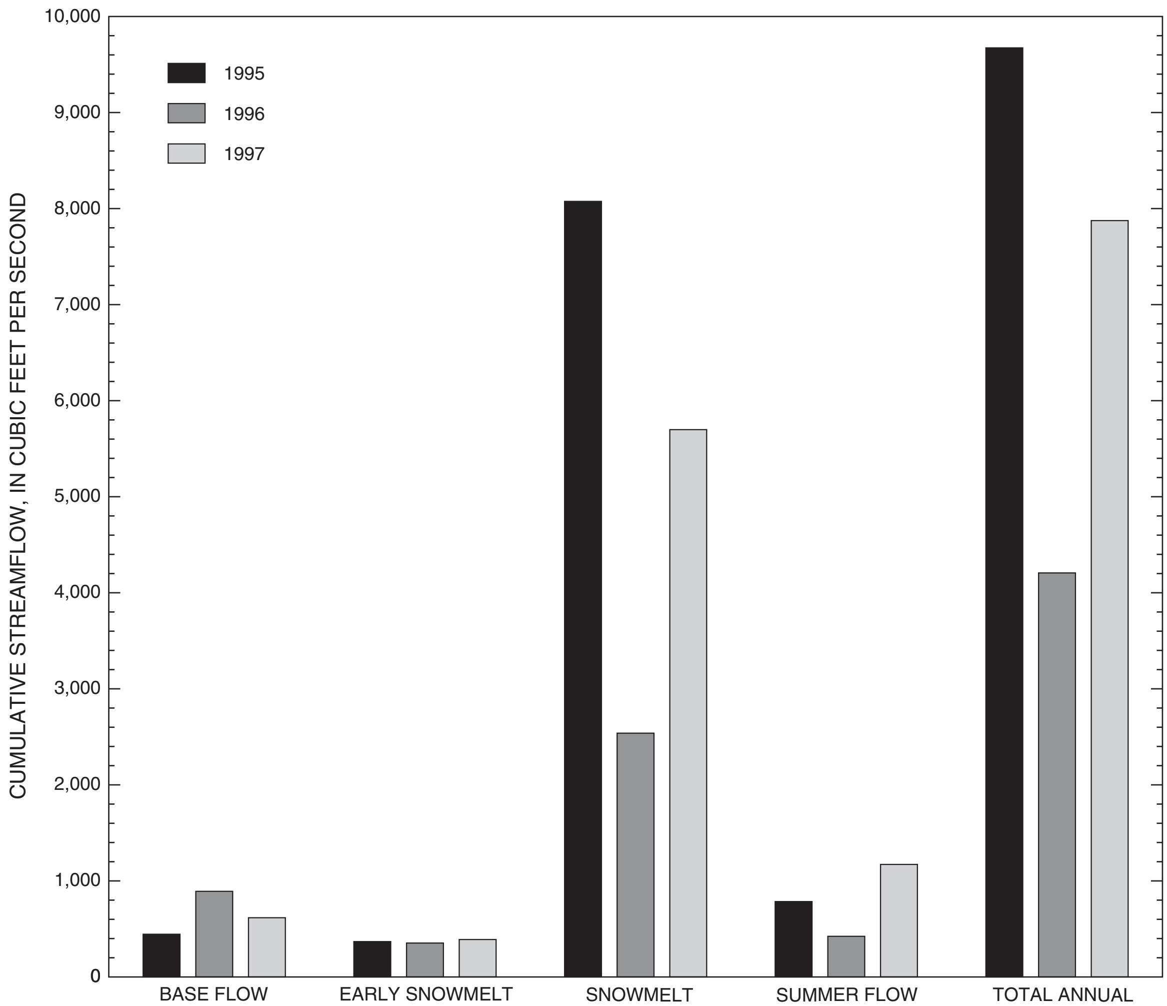

Figure 20. Cumulative streamflow for selected flow periods, Exposure Area 2 (site WF0.0), 1995–97.

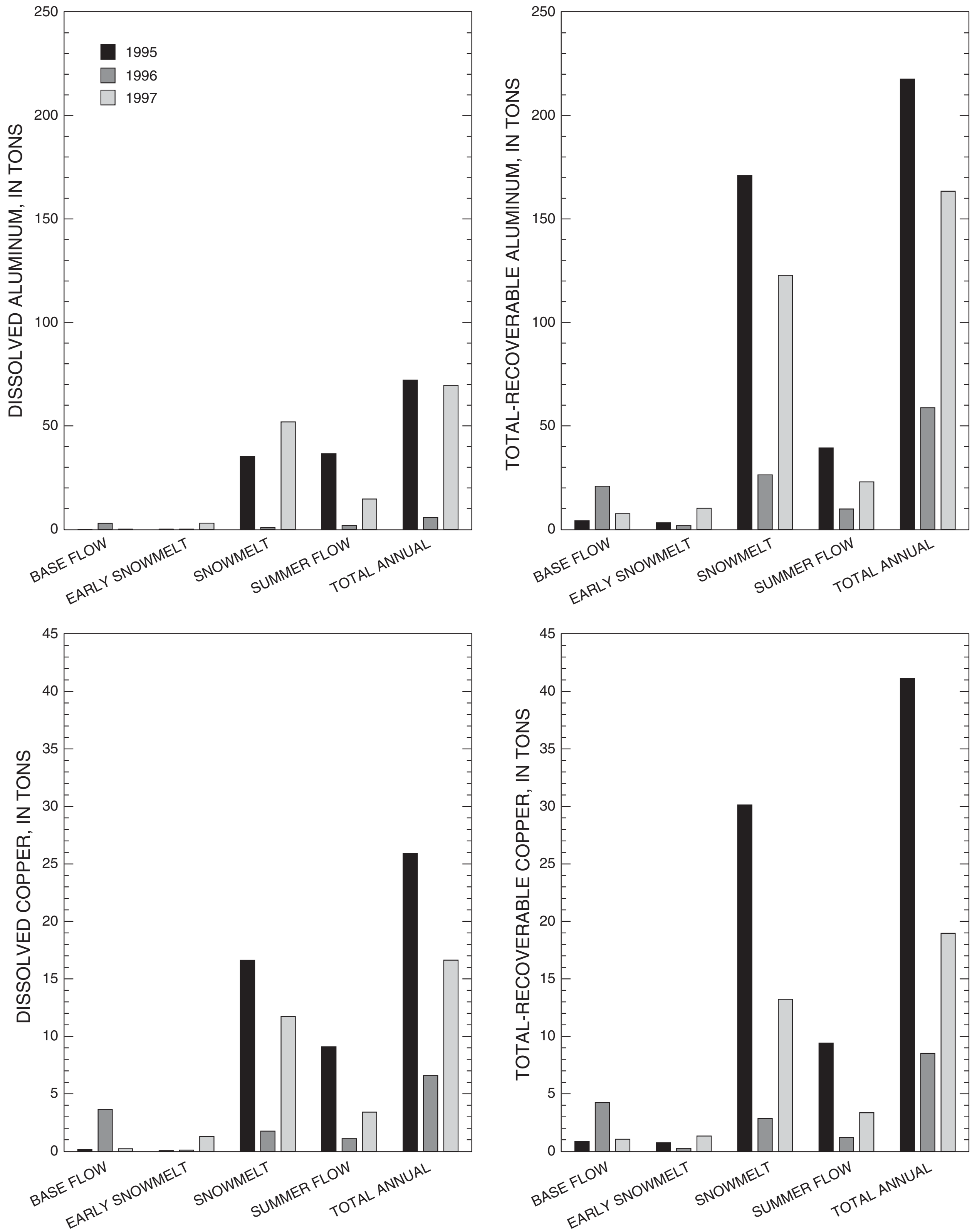

Figure 21. Mass of aluminum and copper for selected flow periods, Exposure Area 2 (site WF0.0), 1995–97.

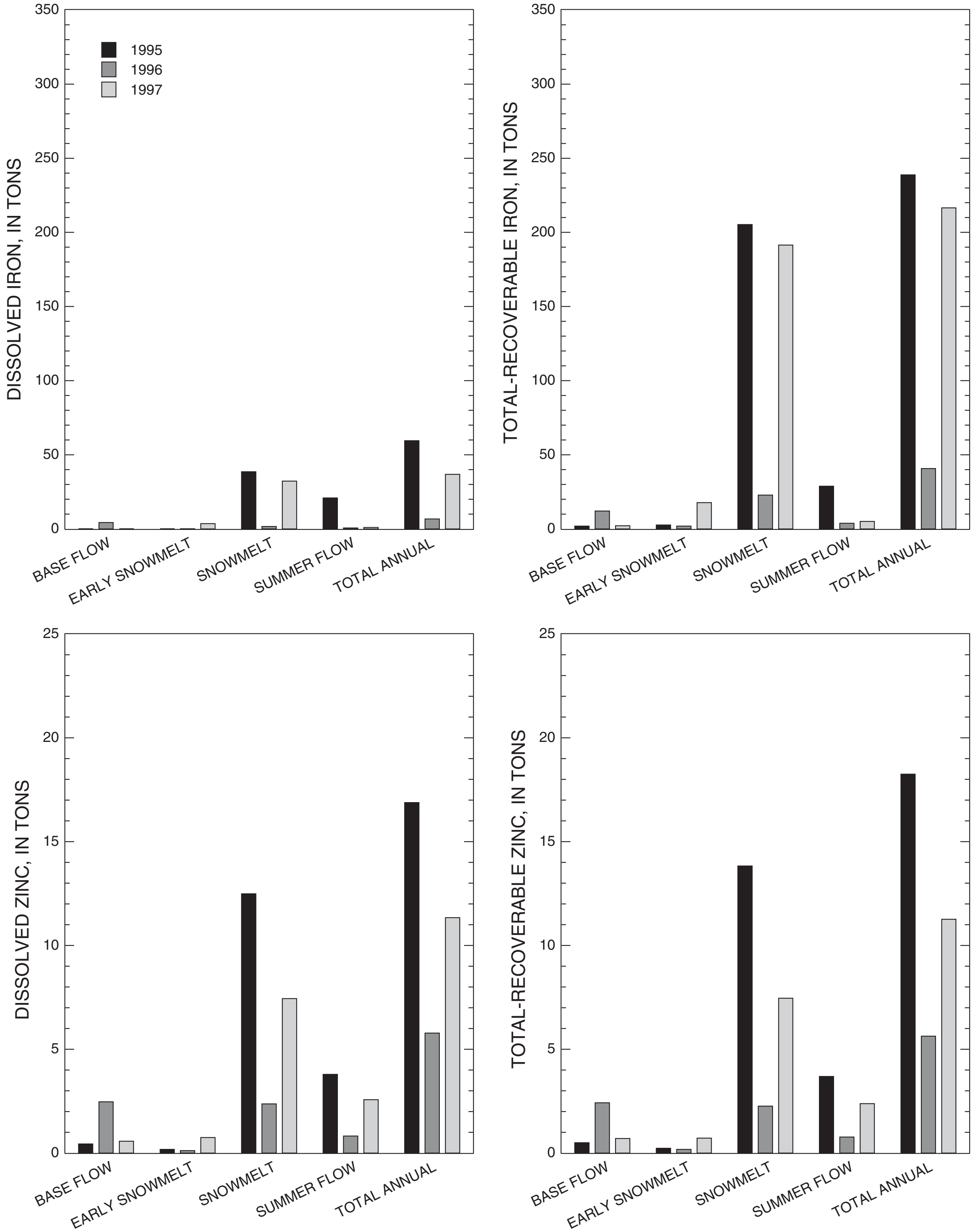

Figure 22. Mass of iron and zinc for selected flow periods, Exposure Area 2 (site WF0.0), 1995–97.

mass of dissolved aluminum was similar in 1995 and 1997.

More than 60 percent of the annual streamflow occurred during the snowmelt period (fig. 20). For 1995 and 1997, the mass of aluminum, copper, iron, and zinc transported during the snowmelt period generally constituted between 50 and 90 percent of the annual metal mass. During 1996, the metal mass transported during the snowmelt period constituted between 14 and 56 percent of the annual metal mass.

From 1995 through 1997, between 10 and approximately 45 percent of the annual aluminum mass, between 60 and 90 percent of the annual copper mass, between 17 and 25 percent of the annual iron mass, and between 90 and 100 percent of the annual zinc mass were transported past WF0.0 in the dissolved fraction. The dissolved fraction of aluminum, copper, and iron mass tended to be smaller at WF0.0 than the dissolved-metal mass fraction at WF5.5, indicating that the dissolved fraction of aluminum, copper, and iron partitioned to the solid phase in the intervening reach between WF5.5 and WF0.0. There was no appreciable change to the dissolved zinc fraction between WF5.5 and WF0.0, indicating that little metal partitioning of zinc occurred.

A comparison of the annual streamflow at WF0.0 to the annual streamflow at WF5.5 showed that about 40 percent of the annual streamflow at WF0.0 was attributable to WF5.5, indicating that the intervening 11.7 square miles of drainage between WF5.5 and WF0.0 contributed about 60 percent of the annual streamflow. However, a comparison of the annual metal mass at WF0.0 and WF5.5 in 1995 and 1997 indicated that estimates of annual mass of total-recoverable aluminum, copper, iron, and zinc were generally equivalent. Based on data collected from tributaries to the Wightman Fork in the reach between WF5.5 and WF0.0 during 1998 and 1999 (K. Nordstrom, U.S. Geological Survey, written commun., 2000), it appears unlikely that there are any appreciable sources of metals downstream from WF5.5 along Wightman Fork. In 1996, however, the estimates of annual mass of total-recoverable metals at WF5.5 were 84 percent (aluminum), 75 percent (copper), 95 percent (iron), and 69 percent (zinc) of the annual mass of metals estimated at WF0.0. Additionally, the annual dissolved aluminum and iron masses were larger at WF5.5 than at WF0.0, indicating that these metals partitioned to the solid phase. However, the annual dissolved copper and zinc masses were smaller at WF5.5 than at WF0.0, indicating that other sources of metals contributed to the metal mass at WF0.0 during 1996. A plausible explanation is that metal loads associated with instream sources or storm runoff during 1996 contributed to the increases in estimated metal mass at WF0.0. Also, potential estimation errors could account for the estimated differences in metal loads.

Alamosa River at AR45.5 (Exposure Area 3a)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes and the annual streamflow and metal mass for 1995–97 at AR45.5 are presented in figures 23–25.

Many tons of total-recoverable aluminum and iron were transported past AR45.5 between 1995 and 1997. Between 120 and 185 tons of total-recoverable aluminum (fig. 24), and between 230 and 400 tons of total-recoverable iron (fig. 25) were estimated to have been transported annually past AR45.5 from 1995 through 1997. A relatively small mass of total-recoverable copper and zinc was transported past AR45.5 during 1995–97. Less than 1 ton of total-recoverable copper (fig. 24) and less than 2 tons of total-recoverable zinc (fig. 25) were estimated to have been transported annually past AR45.5 from 1995 through 1997. The estimated annual mass for total-recoverable aluminum, copper, iron, and zinc was similar in 1995 and 1997; the estimated annual mass for total-recoverable aluminum, copper, and iron in 1996 was about 60 to 70 percent of the respective annual metal mass estimated for 1995 and 1997. The estimated annual mass of dissolved copper, iron, and zinc substantially decreased after 1995.

Less than 14 percent of the annual streamflow occurred during the base flow period. However, during this flow regime, the pH of the Alamosa River at AR45.5 generally is at its annual minimum and most of the annual dissolved aluminum and iron, and a considerable portion of the annual dissolved copper and zinc, were transported during the 1996 and 1997 base-flow period. More than 65 percent of the annual

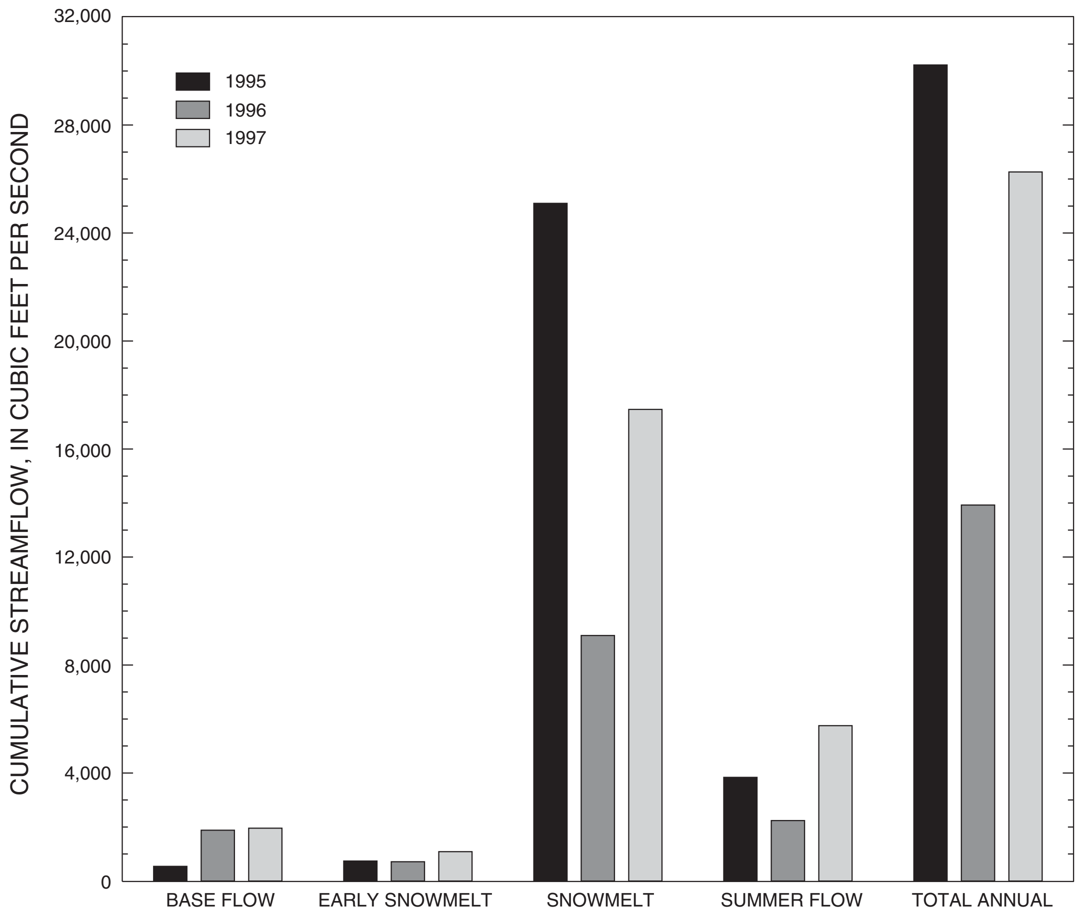

Figure 23. Cumulative streamflow for selected flow periods, Exposure Area 3a (site AR45.5), 1995–97.

streamflow occurred during the snowmelt period (fig. 23), and the largest mass of total-recoverable aluminum, copper, iron, and zinc generally was transported during this period. However in 1996, the mass of total-recoverable aluminum, copper, iron, and zinc transported during the snowmelt period constituted of less than one-third of the annual metal mass. In 1995 and 1997, the mass of total-recoverable aluminum, copper, iron, and zinc transported during the snowmelt period constituted between about 40 and 71 percent of the annual metal mass.

From 1995 through 1997, between 15 and about 30 percent of the annual aluminum mass and between about 15 and 25 percent of the annual iron mass was transported past AR45.5 in the dissolved fraction. More than 50 percent of the annual copper and zinc mass was in the dissolved fraction. This indicated that, with the exception of zinc and copper, the vast majority of metals transported past AR45.5 was in the particulate or suspended fraction. However, as stated earlier, a large dissolved metal fraction was transported during the base-flow period.

Alamosa River at AR43.6 (Exposure Area 3b)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes and the annual streamflow and metal mass for 1995–97 at AR43.6 are presented in figures 26–28. In 1995, streamflow measurements and water-quality samples were not collected from AR43.6 until the snowmelt period. Therefore, metal loads were not estimated for the 1995 base-flow and early snowmelt periods. The annual streamflow and estimates of

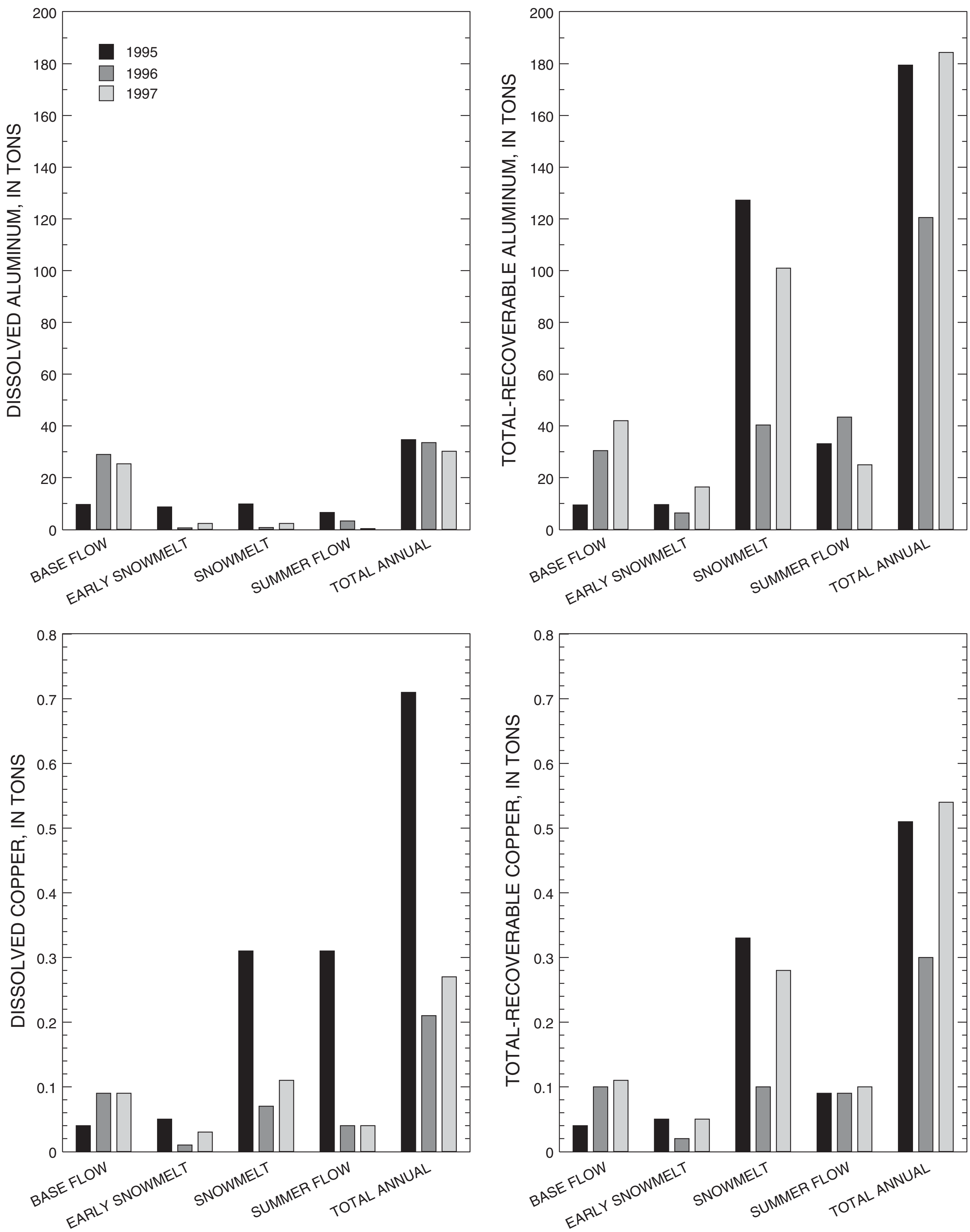

Figure 24. Mass of aluminum and copper for selected flow periods, Exposure Area 3a (site AR45.5), 1995–97.

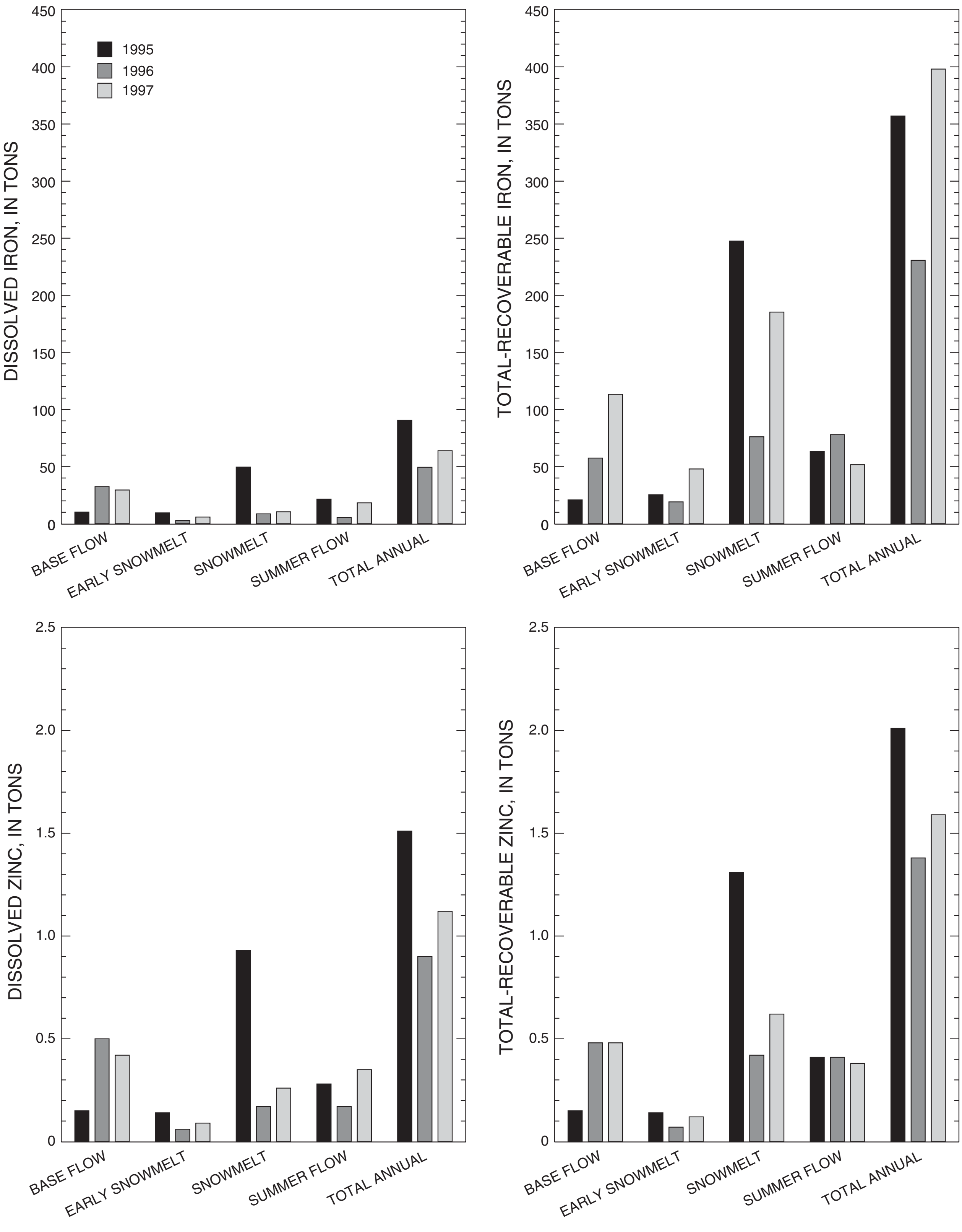

Figure 25. Mass of iron and zinc for selected flow periods, Exposure Area 3a (site AR45.5), 1995–97.

metal mass shown for 1995 in figures 26–28 were based on partial year records and included estimates only for the snowmelt and summer-flow periods.

Many tons of metals were transported past AR43.6 between 1995 and 1997. Between 185 and 415 tons of total-recoverable aluminum (fig. 27), between 7 and 40 tons of total-recoverable copper (fig. 27), between 285 and 760 tons of total-recoverable iron (fig. 28), and between 6 and 20 tons of total-recoverable zinc (fig. 28) were estimated to have been transported annually past AR43.6 from 1995 through 1997. The largest estimated annual mass for dissolved aluminum, dissolved and total-recoverable copper, dissolved iron, and dissolved and total-recoverable zinc occurred in 1995. The smallest annual mass, with the exception of dissolved aluminum, occurred in 1996. The annual total-recoverable metal mass estimated for 1995 was between 2 and 5 times larger than the annual metal mass estimated for 1996 and about the same or just slightly larger than the annual metal mass estimated for 1997. The annual mass of dissolved aluminum, copper, iron, and zinc substantially decreased after 1995.

More than 60 percent of the annual streamflow occurred during the snowmelt period (fig. 26). For 1995 and 1997, the mass of total-recoverable aluminum, copper, iron, and zinc transported during the snowmelt period constituted between about 70 and 90 percent of the annual metal mass. However during 1996, the total-recoverable metal mass transported during the snowmelt period was between about 25 and 42 percent of the annual total-recoverable metal mass. During 1996, a large percentage of the dissolved aluminum (92 percent), copper (85 percent), iron (80 percent), and zinc (59 percent) for the year was transported past AR43.6 during the base-flow period.

From 1995 through 1997, between 8 and 25 percent of the annual aluminum mass, between 60 and 75 percent of the annual copper mass, between 12 and 22 percent of the annual iron mass, and between 85 and 100 percent of the annual zinc mass was transported past AR43.6 in the dissolved fraction.

A comparison of the annual streamflow at AR43.6 to the annual streamflow at AR45.5 and WF0.0 indicated that about 75 percent of the annual streamflow at AR43.6 was attributable to streamflow upstream from AR45.5 (EA3a), and about 25 percent from Wightman Fork (EA2). A comparison of the annual metal mass at AR43.6 to the annual mass at AR45.5 and WF0.0 indicated that 45–65 percent of the annual total-recoverable aluminum mass at AR43.6 may be attributed to EA3a (AR45.5) and about 30–55 percent may be attributed to contributions from Wightman Fork. Less than 4 percent of the annual total-recoverable copper mass at AR43.6 may be attributed to EA3a (AR45.5) and more than 85 percent of the annual total-recoverable copper mass at AR43.6 may be attributed to contributions from Wightman Fork. About 50–80 percent of the annual total-recoverable iron mass at AR43.6 may be attributed to EA3a (AR45.5) and about 15–40 percent of the annual total-recoverable iron mass at AR43.6 may be attributed to contributions from Wightman Fork. About 10–25 percent of the annual total-recoverable zinc mass at AR43.6 may be attributed to EA3a (AR45.5) and about 80-90 percent of the annual total-recoverable zinc mass at AR43.6 may be attributed to contributions from Wightman Fork.

Alamosa River at AR41.2 and AR34.5 (Exposure Area 3c)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes and the annual streamflow and metal mass for 1995–97 at AR41.2 and AR34.5 are presented in figures 29–33.

Many tons of metals were transported past AR41.2 and AR34.5 between 1995 and 1997. Between 180 and 500 tons of total-recoverable aluminum (fig. 30) were estimated to have been transported annually past AR41.2, and between 170 and 670 tons of total-recoverable aluminum (fig. 30) were estimated to have been transported annually past AR34.5. Between 7 and 36 tons of total-recoverable copper (fig. 31) were estimated to have been transported annually past AR41.2, and between 7 and 32 tons of total-recoverable copper (fig. 31) were estimated to have been transported annually past AR34.5. Between 320 and 880 tons of total-recoverable iron (fig. 32) were estimated to have been transported annually past AR41.2, and between 280 and 1,140 tons of total-recoverable iron (fig. 32) were estimated to have been transported annually past AR34.5. Between 6 and 20 tons of total-recoverable zinc (fig. 33) were estimated to have been transported annually past AR41.2, and 5 and 18 tons of total-recoverable zinc (fig. 33)

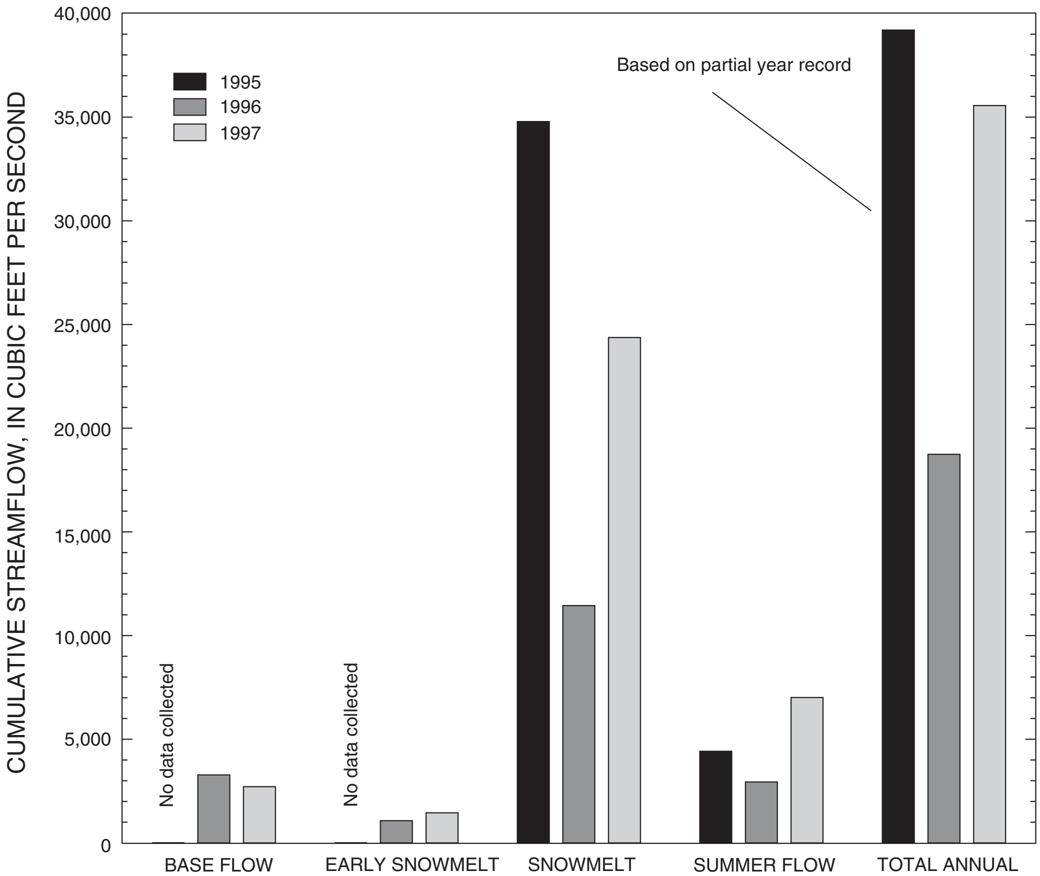

Figure 26. Cumulative streamflow for selected flow periods, Exposure Area 3b (site AR43.6), 1995–97.

were estimated to have been transported annually past AR34.5.

The largest estimated annual mass for dissolved aluminum, copper, iron, and zinc and total-recoverable copper and zinc was measured in 1995. The smallest annual mass for all dissolved and total-recoverable constituents was measured in 1996. The annual total-recoverable metal mass estimated for 1995 was between 2 and 5 times larger than the annual total-recoverable metal mass estimated for 1996 and just slightly larger than the annual total-recoverable metal mass estimated for 1997; total-recoverable aluminum and iron were larger in 1997. The annual mass of dissolved aluminum, copper, iron, and zinc at AR41.2 substantially decreased after 1995. The annual mass of dissolved aluminum, copper, and iron at AR34.5 substantially decreased after 1995.

More than 58 percent of the annual streamflow occurred during the snowmelt period (fig. 29). The mass of total-recoverable aluminum, copper, iron, and zinc transported during the snowmelt period in 1995 and 1997 constituted between about 70 and 85 percent of the annual metal mass at AR41.2 and AR34.5. During 1996, the total-recoverable metal mass transported during the snowmelt period was between about 30 and 45 percent of the annual total-recoverable metal mass at AR41.2 and between about 45 and 60 percent of the annual total-recoverable metal mass at AR34.5.

From 1995 through 1997, between 6 and 16 percent of the annual aluminum mass, between about 55 and 61 percent of the annual copper mass, between about 12 and 26 percent of the annual iron mass, and between about 88 and 94 percent of the annual zinc mass was transported past AR41.2 in the dissolved

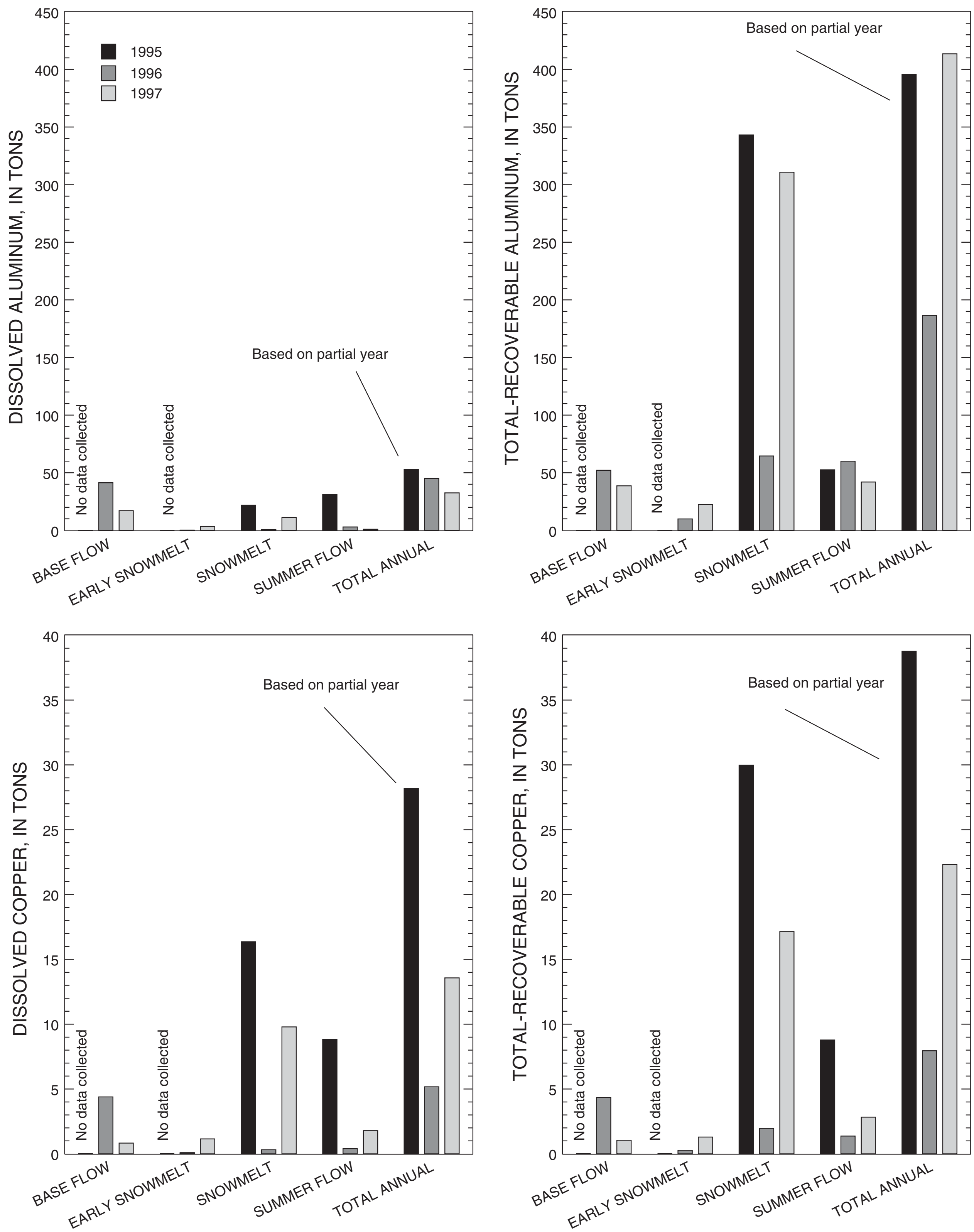

Figure 27. Mass of aluminum and copper for selected flow periods, Exposure Area 3b (site AR43.6), 1995–97.

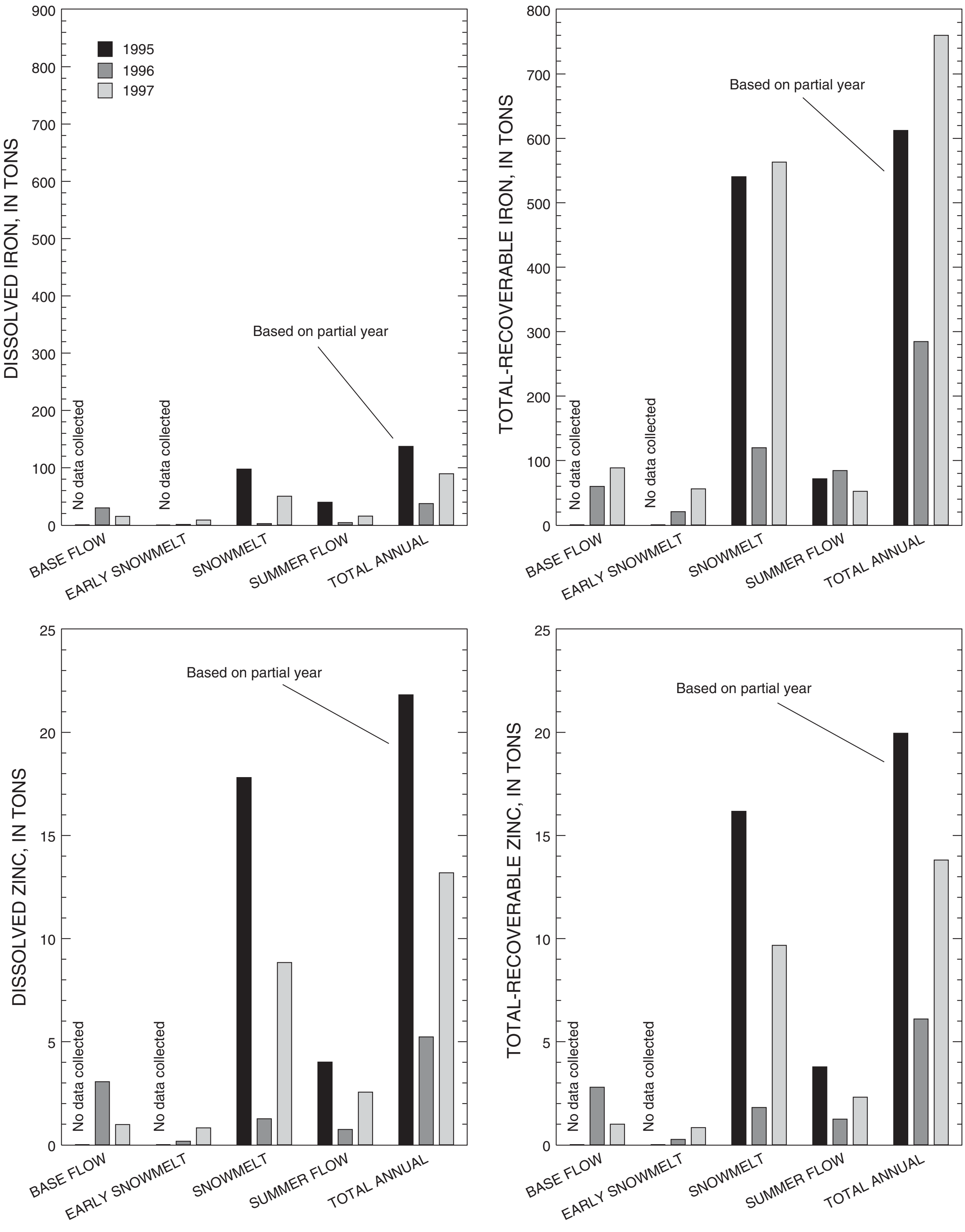

Figure 28. Mass of iron and zinc for selected flow periods, Exposure Area 3b (site AR43.6), 1995–97.

fraction. From 1995 through 1997, less than 2 percent of the annual aluminum mass, between about 14 and 32 percent of the annual copper mass, between about 3 and 8 percent of the annual iron mass, and between 55 and 80 percent of the annual zinc mass were transported past AR34.5 in the dissolved fraction. The smaller dissolved-metal mass fraction at AR34.5 relative to AR41.2, which is located in the upper part of EA3c (fig. 1), indicates that a large portion of the dissolved aluminum, copper, iron and, to a lesser extent, zinc mass (figs. 30, 31, 32, and 33) is partitioned to the particulate or suspended fraction in the stream reach.

A comparison of the annual streamflow at AR41.2 to the annual streamflow at AR43.6 (EA3b) indicated that about 80 to 90 percent of the annual streamflow at AR41.2 was attributable to streamflow upstream from AR43.6. A comparison of the annual metal mass at AR41.2 to the mass at AR43.6 indicated that the total-recoverable metal mass at AR41.2 was approximately equivalent to the total-recoverable metal mass at AR43.6. The only exceptions were for the total-recoverable aluminum mass in 1997 and the total-recoverable iron mass in 1995, 1996, and 1997. This comparison indicates that there were no appreciable sources of total-recoverable metals entering the intervening drainage area between AR43.6 and AR41.2.

A comparison of the annual streamflow at AR34.5 and AR41.2 indicated that between 88 and 100 percent of the annual streamflow at AR34.5 was attributable to streamflow upstream from AR41.2 (fig. 29). A comparison of the annual metal masses at AR34.5 and AR41.2 indicated that the annual total-recoverable copper and zinc mass at AR34.5 was similar to the annual mass at AR41.2. This comparison indicated there were no appreciable sources of total-recoverable copper and zinc entering the intervening drainage area between AR41.2 and AR34.5. In 1995 and 1997, however, the annual total-recoverable aluminum and iron mass at AR34.5 was about 30 percent greater than the annual total-recoverable aluminum and iron mass at AR41.2. A plausible explanation for these increases is that aluminum and iron deposited in the streambed were resuspended and contributed to the increases in estimated aluminum and iron mass estimated at AR34.5.

Alamosa River at AR31.0 (Exposure Area 5)

The cumulative streamflow and estimates of the mass of dissolved and total-recoverable aluminum, copper, iron, and zinc for each of the four seasonal flow regimes and the annual streamflow and metal mass for 1995–97 at AR31.0 are presented in figures 34–36. Estimates of metal mass presented in this section of the report represent: (1) the mass of metals being transported past AR31.0 and the mass of metals available for risk exposure in EA5, and (2) the mass of metals being transported out of Terrace Reservoir that were available for risk exposure in EA4.

Terrace Reservoir has a capacity of about 17,000 acre-ft (Watts, 1996) and is primarily used as storage for irrigation water. Streamflow at AR31.0 is lowest between November and about mid-April. when the outlet works are closed. During this time, storage is gradually increased in the reservoir. From May through June, reservoir releases for downstream irrigation users generally match reservoir inflow. From July through October, reservoir releases are generally greater than the reservoir inflow (as measured at AR34.5) thus reducing the reservoir storage substantially.

Many tons of metals were transported past AR31.0 between 1995 and 1997. Between 25 and 85 tons of total-recoverable aluminum (fig. 35), between about 2 and 25 tons of total-recoverable copper (fig. 35), between about 80 and 170 tons of total-recoverable iron (fig. 36), and between about 3 and 20 tons of total-recoverable zinc (fig. 36) were estimated to have been transported annually past AR31.0 from 1995 through 1997.

The largest estimated annual mass for dissolved and total-recoverable aluminum, copper, iron, and zinc was in 1995, and the smallest annual mass was in 1996. The annual total-recoverable metal mass estimated for 1995 was between about 2 and 12 times larger than the annual metal mass estimated for 1996 and was less than 4 times the annual metal mass estimated for 1997. The annual mass of dissolved aluminum, copper, iron, and zinc substantially decreased after 1995.

Between 70 and 85 percent of the annual streamflow at AR31.0 occurred during the snowmelt period (fig. 34). From 1995 through 1997, between 87 and 94 percent of the total-recoverable aluminum mass, between 55 and 70 percent of the total-

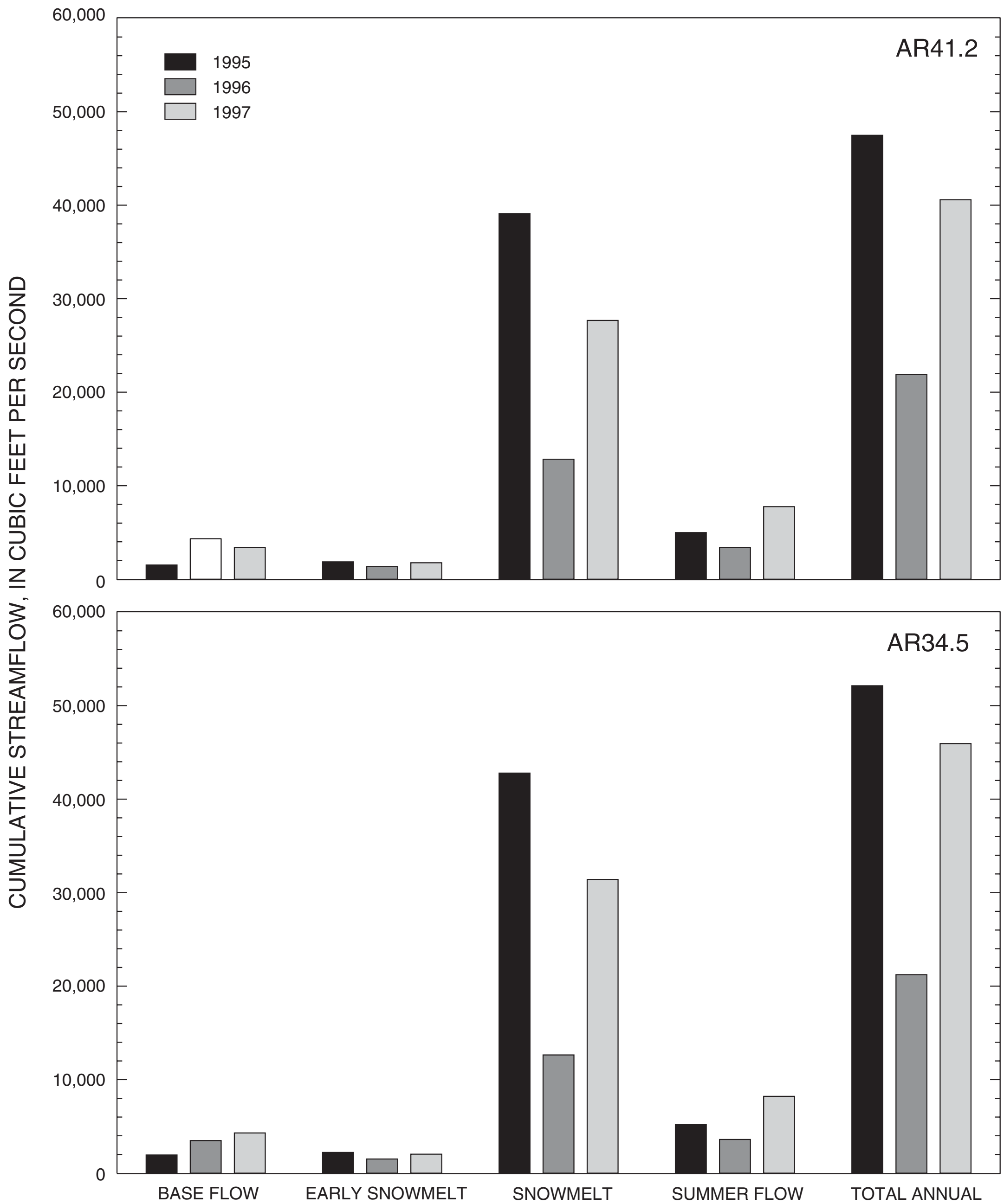

Figure 29. Cumulative streamflow for selected flow periods, Exposure Area 3c (sites AR41.2 and AR34.5), 1995–97.

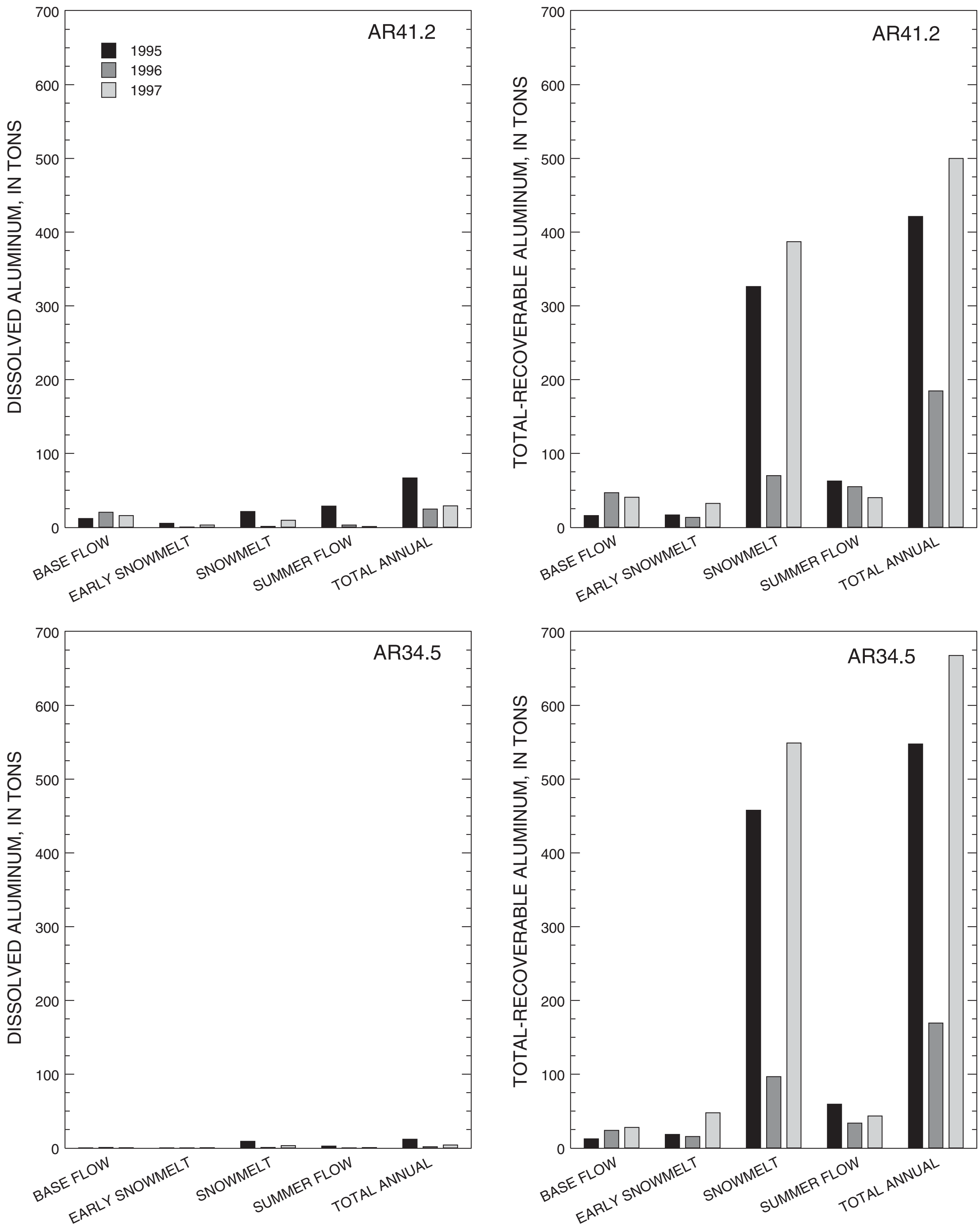

Figure 30. Mass of aluminum for selected flow periods, Exposure Area 3c (sites AR41.2 and AR34.5), 1995–97.

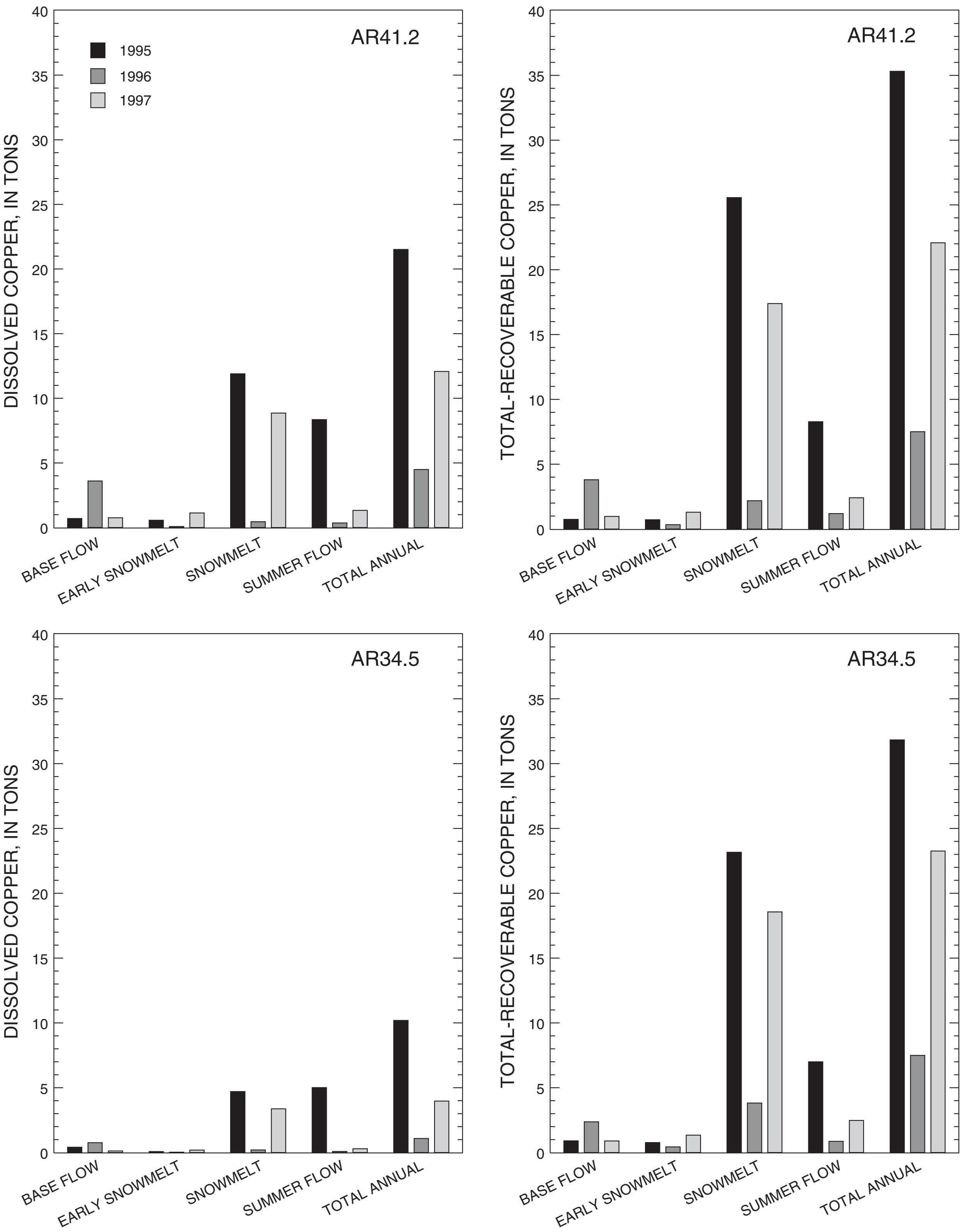

Figure 31. Mass of copper for selected flow periods, Exposure Area 3c (sites AR41.2 and AR34.5), 1995–97.

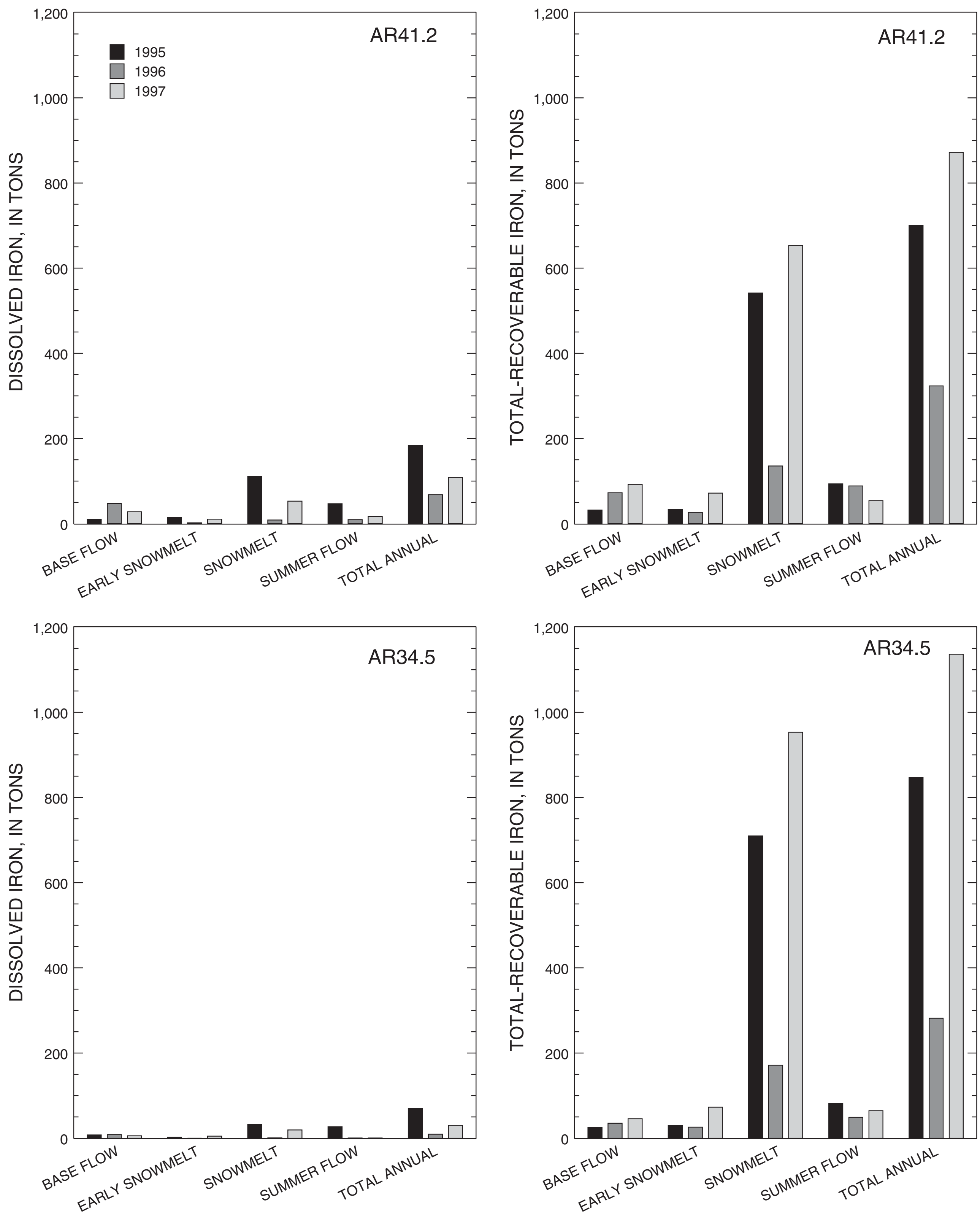

Figure 32. Mass of iron for selected flow periods, Exposure Area 3c (sites AR41.2 and AR34.5), 1995–97

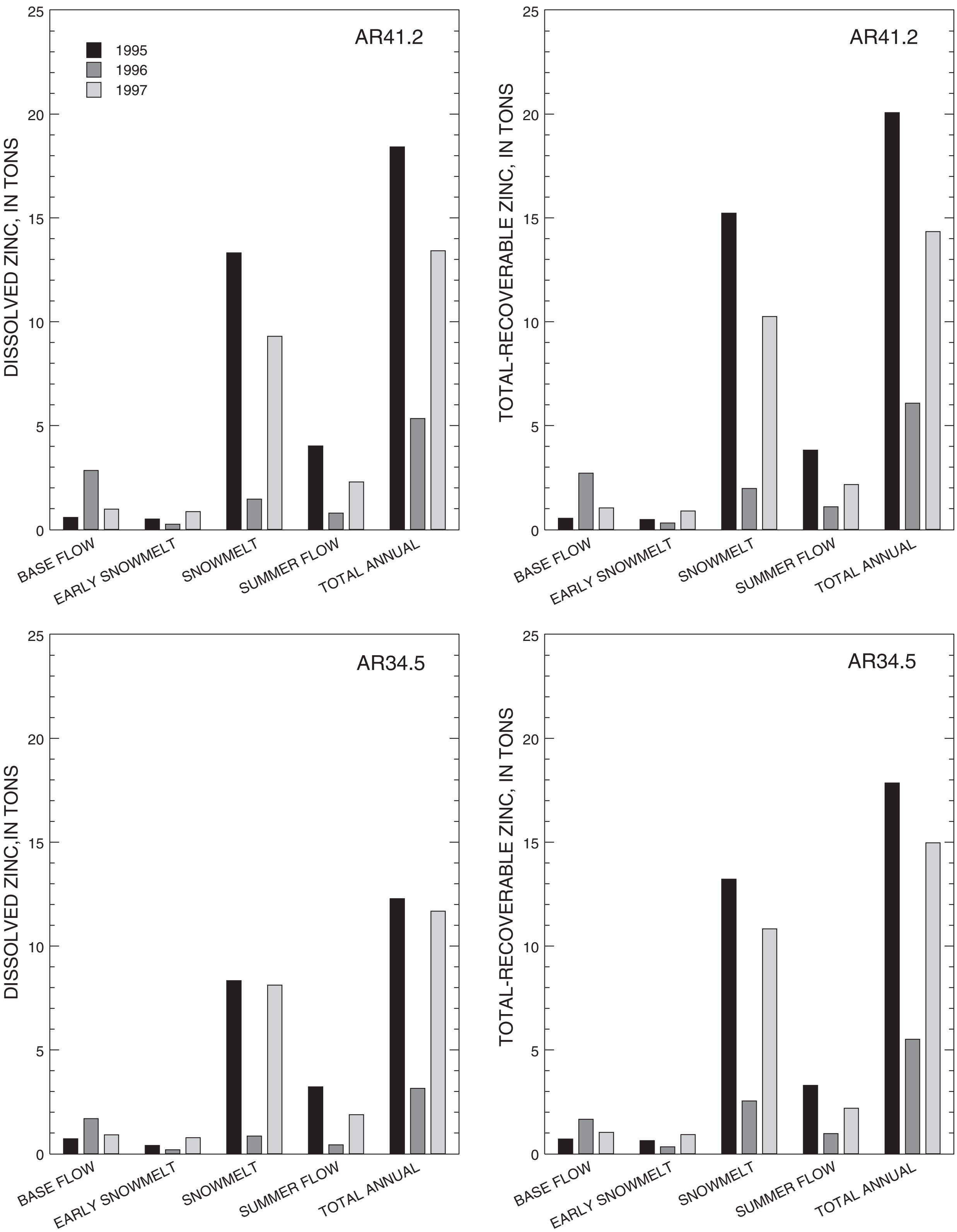

Figure 33. Mass of zinc for selected flow periods, Exposure Area 3c (sites AR41.2 and AR34.5), 1995–97.

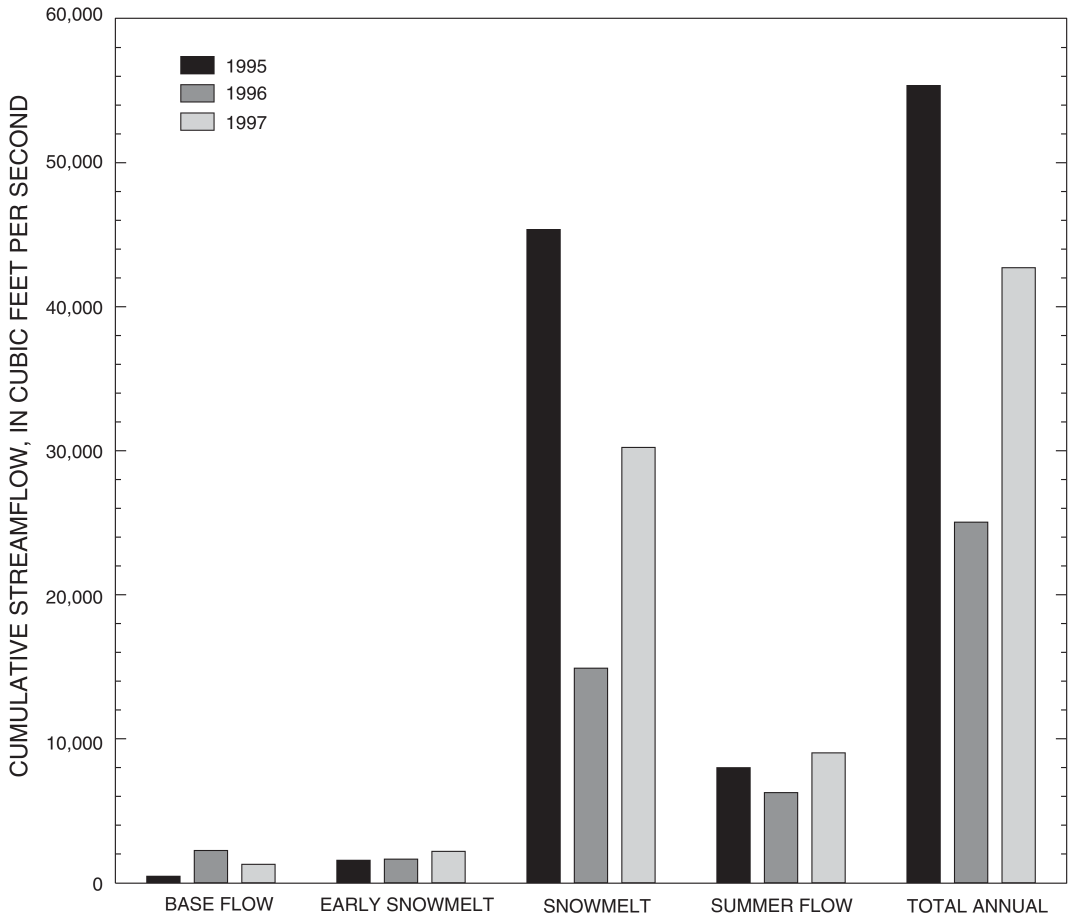

Figure 34. Cumulative streamflow for selected flow periods, Exposure Area 5 (site AR31.0), 1995–97.

recoverable copper mass, between 63 and 91 percent of the total-recoverable iron mass, and between 48 and 71 percent of the total-recoverable zinc mass were transported during the snowmelt period.

From 1995 through 1997, between 5 and 23 percent of the annual aluminum mass, between about 40 and 66 percent of the annual copper mass, between about 3 and 16 percent of the annual iron mass, and between 78 and 95 percent of the annual zinc mass were transported past AR31.0 in the dissolved fraction.

A comparison of the annual streamflow at AR31.0 to the annual streamflow at AR34.5 (EA3c) indicated that about 85 to more than 100 percent of the annual streamflow at AR31.0 was attributable from streamflow upstream from Terrace Reservoir. Downstream irrigation needs and storage limitations in Terrace Reservoir drive the operation of the reservoir. A comparison of the annual metal mass at AR31.0 to the annual metal mass at AR34.5 indicated that between 1995 and 1997, the annual total-recoverable aluminum mass at AR31.0 was about 15 percent of annual total-recoverable aluminum mass at AR34.5, the annual total-recoverable copper mass at AR31.0 was between about 25 and 75 percent of annual total-recoverable copper mass at AR34.5, the annual total-recoverable iron mass at AR31.0 was between 13 and 28 percent of annual total-recoverable iron mass at AR34.5, and the annual total-recoverable zinc mass at AR31.0 was between about 50 and 100 percent of annual total-recoverable zinc mass at AR34.5. These data indicate that Terrace Reservoir serves as a sink for metals. This conclusion is consistent with a previous report by Ferguson and Edelmann (1996).

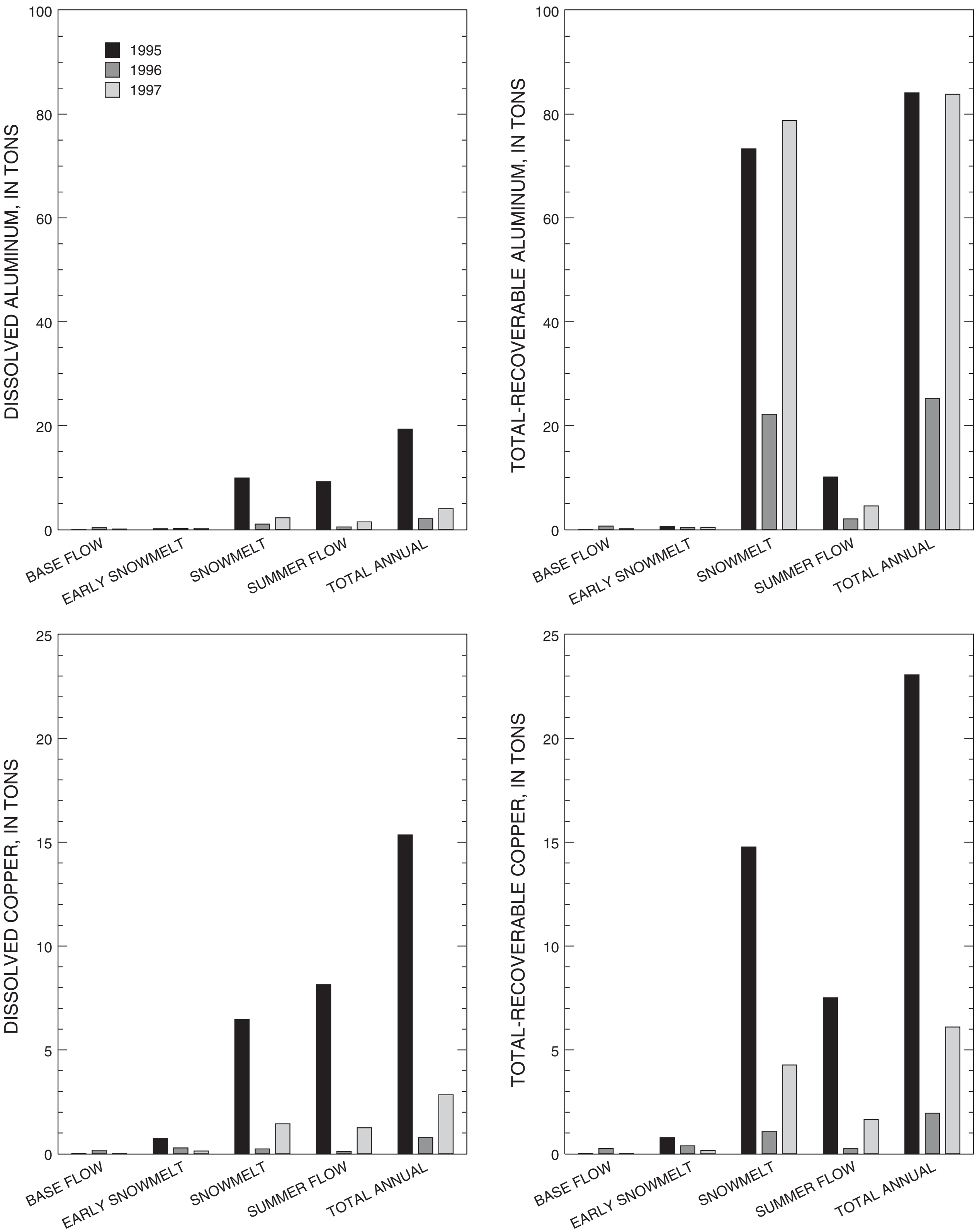

Figure 35. Mass of aluminum and copper for selected flow periods, Exposure Area 5 (site AR31.0), 1995–97.

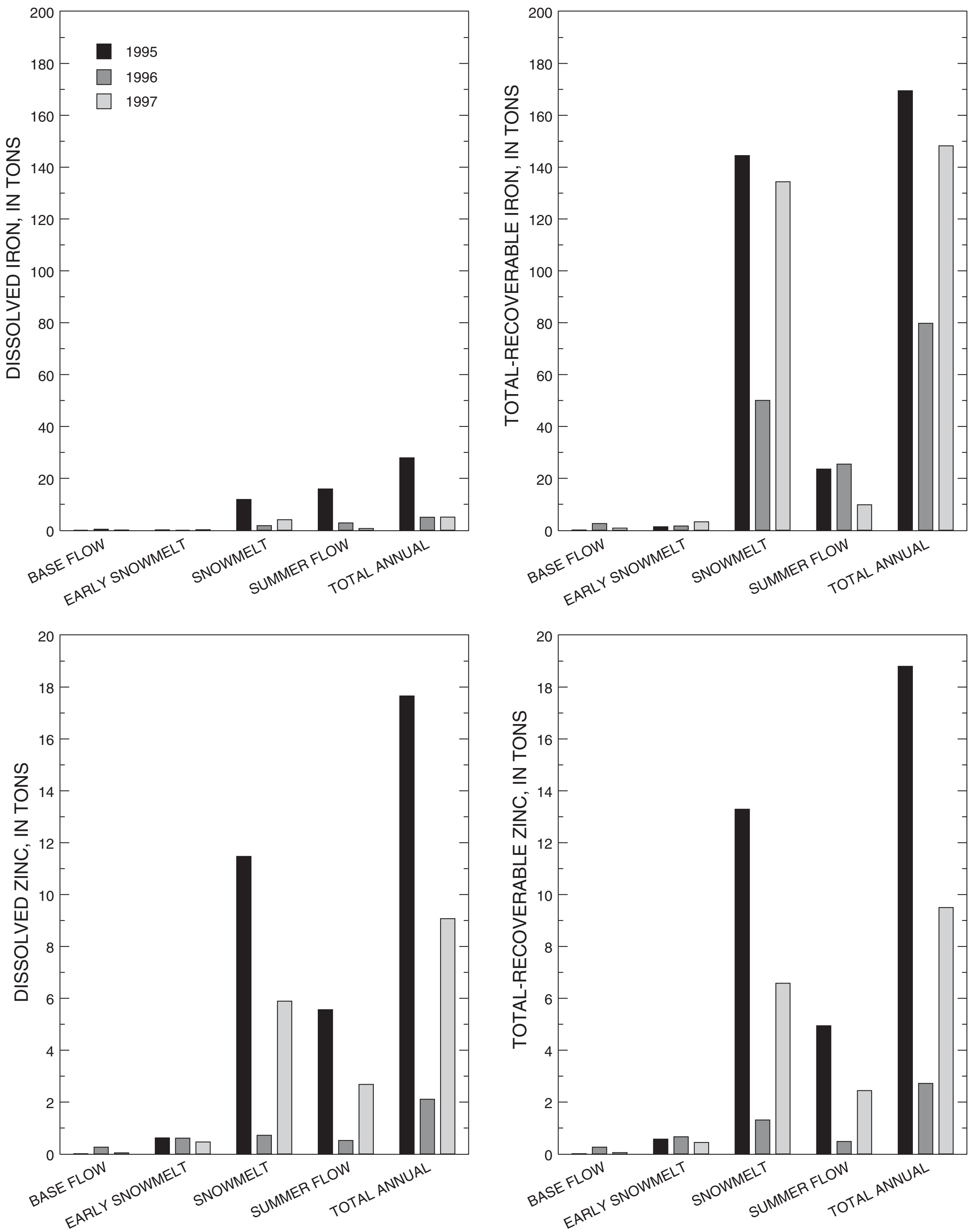

Figure 36. Mass of iron and zinc for selected flow periods, Exposure Area 5 (site AR31.0), 1995–97.

SUMMARY

The upper Alamosa River Basin is a heavily mineralized area located in the San Juan Mountains of southwestern Colorado. Metal contamination has occurred for decades from the Summitville Mine site, from other smaller mines, and from natural, metal-enriched acidic drainage in the basin. In 1995, multiple gaps in data needed for an ecological risk assessment of the Summitville Superfund site were identified. Specifically, the need to quantify contamination from various source areas in the basin and the need to quantify the spatial, seasonal, and annual metal loads in the basin was identified. As a result, the USGS developed a comprehensive data-collection plan for the basin to address these data gaps.

To meet the objectives of this study, instantaneous streamflow data and periodic water-quality data were collected from 1995 through 1997 at 6 sites on the Alamosa River, 2 sites on Wightman Fork, and 11 other tributary sites. Concentrations of metals and values of streamflow measurements were used to determine metal loads for each sampling date. Percentages of metal load contributions from tributaries were determined for each sample collected. A modified time-interval method was used to estimate seasonal and annual metal loads in the Alamosa River and Wightman Fork.

Sources of dissolved and total-recoverable aluminum, copper, iron, and zinc loads were determined for three risk exposure areas. EA3a extends upstream from Wightman Fork along the Alamosa River. EA3b extends along the Alamosa River from Wightman Fork to Fern Creek. EA3c extends along the Alamosa River from Fern Creek to Terrace Reservoir. Alum Creek is the predominant contributor of aluminum, copper, iron, and zinc loads to EA3a. The percentage of contribution of metal loads from Alum Creek was often greater than the combined metal load contribution from Iron and Bitter Creeks. In general, Wightman Fork was the predominant source of metals to EA3b particularly during the snowmelt and summer flow periods. During the base-flow period, however, aluminum and iron loads from EA3a were the dominant source of these metals to EA3b. Jasper and Burnt Creeks generally contributed less than 10 percent of the metal loads to EA3b. On a few occasions, however, Burnt Creek contributed a substantial percentage of the dissolved aluminum load, and Jasper and Burnt Creeks contributed a substantial percentage of the iron loads to the Alamosa River in EA3b. The metal loads observed in EA3c result from upstream sources; the primary upstream sources are Wightman Fork in EA1 and Alum and Iron Creeks in EA3a. Tributaries in EA3c did not contribute substantially to the metal load in the Alamosa River.

In many instances, the percentage of dissolved and/or total-recoverable metal load contribution from a tributary or the combined percentage of metal load contribution was greater than 100 percent of the metal load at the nearest downstream site on the Alamosa River. These data indicate that metal partitioning and metal deposition from the water column to the streambed may be occurring in Exposure Areas 3a, 3b, and 3c. Metals that are deposited to the streambed probably are resuspended and transported downstream during high-streamflow periods such as during snowmelt runoff and rainfall runoff.

Seasonal and annual dissolved and total-recoverable aluminum, copper, iron, and zinc loads for 1995–97 were estimated for Exposure Areas 1, 2, 3a, 3b, and 3c. EA1 incorporates the Summitville Mine site, and EA2 extends along Wightman Fork. During 1995–97, many tons of metals were transported annually through each exposure area. Generally, the largest estimated annual total-recoverable metal mass for most metals was in 1995. The smallest estimated annual total-recoverable metal mass was in 1996, which also coincided with the smallest annual streamflow. In 1995 and 1997, more than 60 percent of the annual total-recoverable metal loads generally was transported through each exposure area during the snowmelt period; however, in 1996, generally less than 40 percent of the annual total-recoverable metal loads was transported through the exposure areas during the snowmelt period. A comparison of the estimated storm load at each site to the corresponding annual load indicated that storms contribute less than 2 percent of the annual load at any site and about 5 to 20 percent of the load during the summer-flow period. The highest percentage of contribution was observed for total-recoverable aluminum and iron.

A comparison of the annual metal mass at WF5.5 (EA1) to annual metal mass estimated at WF0.0 (EA2) indicated that estimates of total-recoverable metal mass for the two exposure areas were approximately equivalent in 1995 and 1997. The annual dissolved aluminum and iron mass was larger

at WF5.5 (EA1) than at WF0.0 (EA2), indicating these metals partitioned to the solid phase. Between 1995 and 1997, many tons of total-recoverable aluminum and iron were transported past AR45.5, whereas only a relatively small mass of total-recoverable copper and zinc was transported past AR45.5. Most of the dissolved metals transported past AR45.5 occurred during base flow even though only 14 percent of the annual streamflow occurred during this period. A comparison of the annual metal mass at AR43.6 to the annual mass at AR45.5 and WF0.0 indicated that most of the annual total-recoverable aluminum and iron mass may be attributed to EA3a (AR45.5) and most of the annual total-recoverable copper and zinc mass may be attributed to contributions from Wightman Fork. A comparison of the annual metal masses at AR34.5 and AR41.2 indicated that the annual total-recoverable copper and zinc mass was similar, which indicated that there were no appreciable sources of total-recoverable copper and zinc entering the intervening drainage area. A comparison of the annual metal mass at AR31.0 to the annual metal mass at AR34.5 indicated that the annual total-recoverable aluminum and iron mass at AR31.0 was about 15–30 percent of annual total-recoverable mass at AR34.5, which indicated that Terrace Reservoir served as a sink for most contaminants of concern.

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