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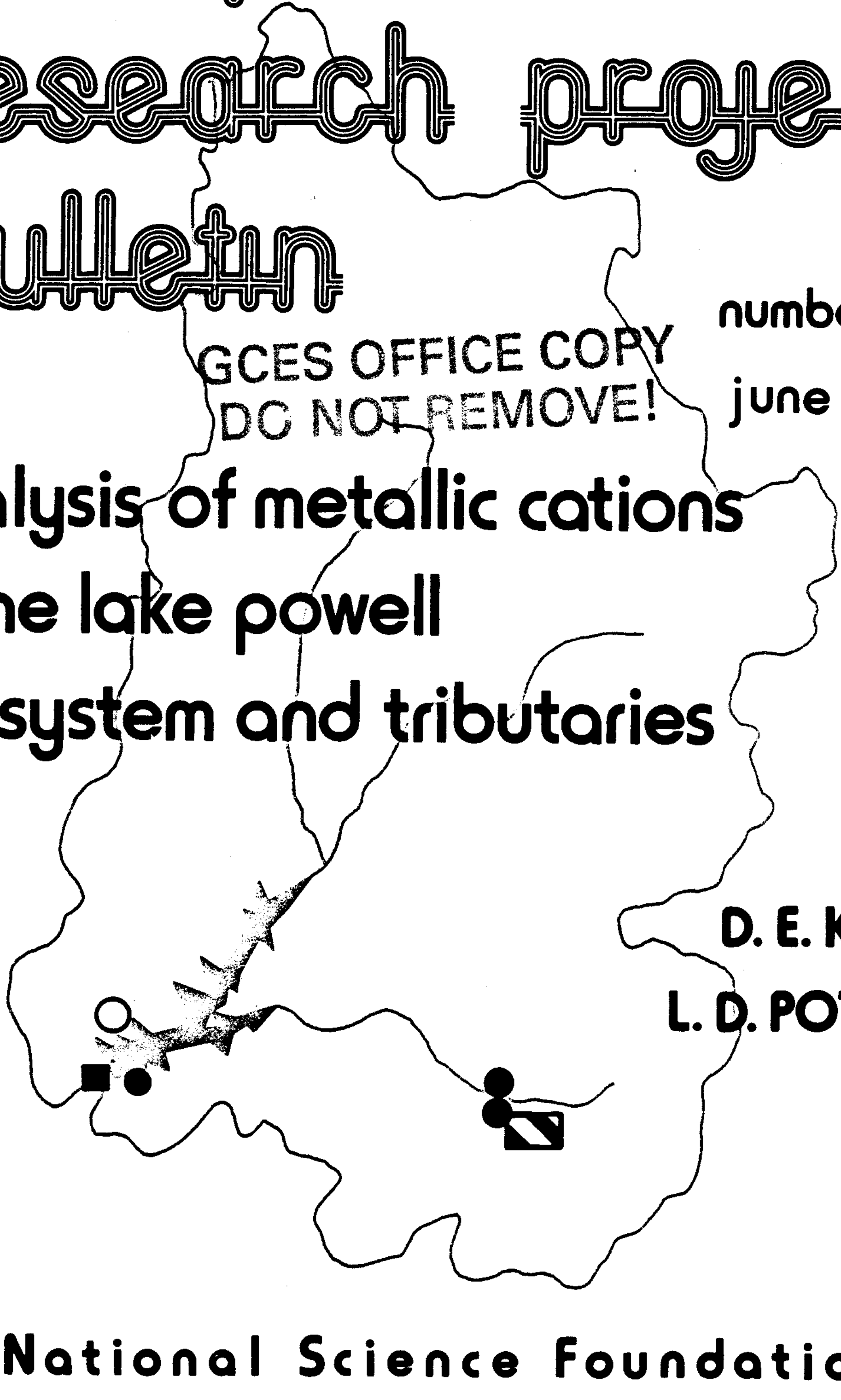

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National Science Foundation
Research Applied to National Needs

ANALYSIS OF METALLIC CATIONS IN THE LAKE POWELL ECOSYSTEM AND TRIBUTARIES

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LAKE POWELL RESEARCH PROJECT

The Lake Powell Research Project (formally known as Collaborative Research on Assessment of Man's Activities in the Lake Powell Region) is a consortium of university groups funded by the Division of Advanced Environmental Research and Technology in RANN (Research Applied to National Needs) in the National Science Foundation.

Researchers in the consortium bring a wide range of expertise in natural and social sciences to bear on the general problem of the effects and ramifications of water resource management in the Lake Powell region. The region currently is experiencing converging demands for water and energy resource development, preservation of nationally unique scenic features, expansion of recreation facilities, and economic growth and modernization in previously isolated rural areas.

The Project comprises interdisciplinary studies centered on the following topics: (1) level and distribution of income and wealth generated by resources development; (2) institutional framework for environmental assessment and planning; (3) institutional decision-making and resource allocation; (4) implications for federal Indian policies of accelerated economic development of the Navajo Indian Reservation; (5) impact of development on demographic structure; (6) consumptive water use in the Upper Colorado River Basin; (7) prediction of future significant changes in the Lake Powell ecosystem; (8) recreational carrying capacity and utilization of the Glen Canyon National Recreational Area; (9) impact of energy development around Lake Powell; and (10) consequences of variability in the lake level of Lake Powell.

One of the major missions of RANN projects is to communicate research results directly to user groups of the region, which include government agencies, Native American Tribes, legislative bodies, and interested civic groups. The Lake Powell Research Project Bulletins are intended to make timely research results readily accessible to user groups. The Bulletins supplement technical articles published by Project members in scholarly journals.

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ABSTRACT

The specific objective was to determine baseline concentrations of heavy metals laterally and vertically in water, terrestrial vegetation, soils, sediments, plankton and fish. The investigative area included Lake Powell and major tributary sites. In water samples the element in the particulate phase exceeds its concentration in the dissolved phase for chromium, copper, iron, lead and zinc at tributary sites. The hypothesis that cultural inputs of lead occur at Lake Powell is supported by the fact that more dissolved lead leaves the reservoir than is received from input waters. Analysis of surface waters within Lake Powell and at tributary sites yields values that were usually below surface water standards. Sediment concentrations are generally at the lower range for habitats that have cultural impacts. Concentrations in soils compare favorably with levels anticipated for uncontaminated areas. The Navajo Power Plant probably does not affect adversely the ecology of the Glen Canyon Region as far as the elements investigated. High concentrations of the elements investigated are found in plankton. Lead is particularly high in plankton collected in the vicinity of the Wahweap Marina. Higher lead levels occur in fish collected from the vicinity of Wahweap Bay than in a more remote area. In Wahweap Bay there is a direct relationship between boating activity and lead levels in the water. However only selenium levels in fish flesh were high enough to be of public health significance. Concentrations of cations in terrestrial plants and soils do not reflect major cultural inputs.

Recommendations include further analysis of selenium forms, control of lead emissions, analysis of water samples in two stages (dissolved and particulate), and use of data as a standard for comparison.

ANALYSIS OF METALLIC CATIONS IN THE LAKE POWELL ECOSYSTEM AND TRIBUTARIES

INTRODUCTION

The Upper Colorado River Basin, and especially the area around Lake Powell, represents an area relatively unaffected at present by industrial pollution. It is recognized that the upper watersheds arise in areas of rich deposits of heavy metal ores. Added to the natural background concentrations in water, soils, and biological material will be the release of heavy metals from the burning of large quantities of coal in power plants in the area. In addition, as boating use expands, input of lead and nickel directly into the lake by gas spillages can be expected to increase.

Our intent is to provide baseline levels for cadmium, chromium, copper, iron, lead, arsenic, selenium, zinc, and mercury in a variety of materials that can be used to evaluate these expected future impacts and to assess whether environmental degradation is presently occurring.

METHODS

Samples for analysis were collected at four-month intervals from the following sites (Figure 1):

Colorado River east of Grand Junction, Colorado
Gunnison River at Grand Junction, Colorado
Dolores River at Gateway, Colorado
Green River at Green River, Utah
San Juan River at Mexican Hat, Utah

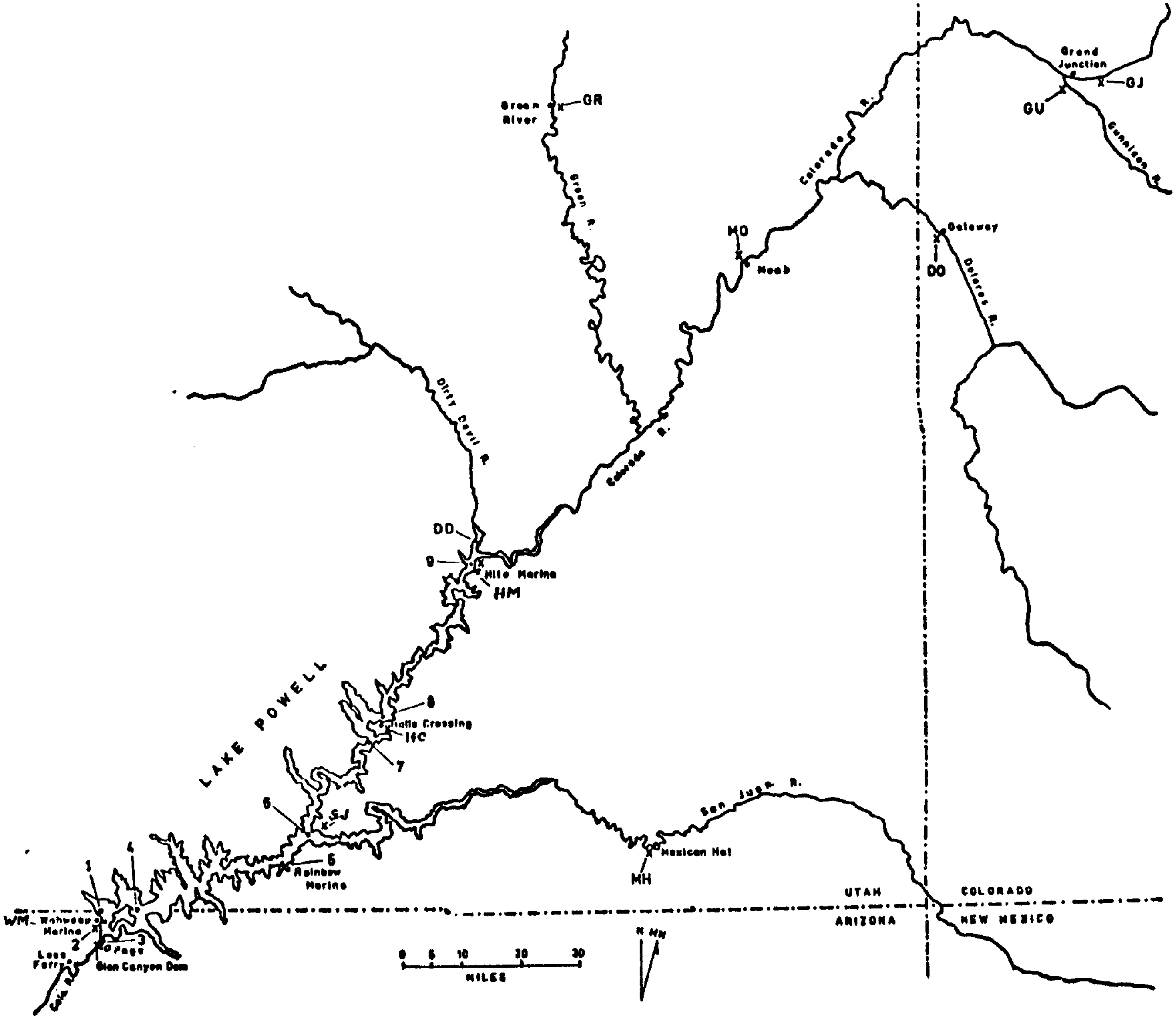

Figure 1. Collection locations. Numbered areas represent Lake Powell sites, areas with an "x" and letter code represent shoreline, Colorado River, and tributary sites.

Dirty Devil River above Hite, Utah
Lake Powell near Hite, Utah (Site 9)
Lake Powell near Moki Bar above Hall's Crossing (Site 8)
Lake Powell below Hall's Creek (Site 7)
Lake Powell below confluence of San Juan (Site 6)
Rainbow Bridge Marina (Site 5)
Limnology Site 4 not used in this investigation
Glen Canyon Dam near Page, Arizona (Site 3)
Below Wahweap Marina (Site 2)
Above Wahweap Marina (Site 1)

Sediment grabs were made with either an Eckman or Ponar Dredge. Samples were placed in plastic bags and kept at approximately 4° C in the field. These materials were returned to the laboratory, oven-dried at 60° C for 72 hours, then ground to a fine powder and returned to the drying oven. The materials were then subjected to wet digestion using nitric and perchloric acid according to procedures described by C. M. Johnson and A. Ulrich (1959).

Soil samples were processed in a similar manner. The materials were ground with mortar and pestle and poured through a fine mesh sieve. Oven-dry weights were obtained for both sediments and soils prior to analysis.

Plankton were collected with a Wisconsin Plankton Net with a number 25 mesh and frozen. Upon thawing the material was filtered using a 0.45 μ pore size millipore filter. All filters were dried and weighed before use. Plankton wet weight was determined and then the filters and material were digested in a hot one part water to one part HCl (1:1) solution and then brought up to volume for analysis.

Composited cut samples of seasonal plant growth or cut twigs with leaves, flowers, and fruits, if present, were oven-dried at 60° C. Material ground on a Wiley Mill at 20 and 40 mesh sizes was redried and then subjected to wet digestion using the nitric and perchloric acid procedure.

Water sample grabs were made at the surface and near the reservoir bottom at each site, except the tributaries, using a plastic Kemmerer bottle. Samples were filtered in the field using a 0.45 μ pore size filter. The filtrate was acidified to pH 2 and the filters were saved for particulate analysis. All filters were pre-washed and the filtrate samples were refrigerated. When samples were unusually turbid, they were pre-filtered with a 1.2 μ pore size filter. Field blanks were processed in the same manner as a check for contamination. The filters were dissolved in the hot acid mixture. This material was then washed into volumetric flasks and brought up to volume.

Sediment cores were collected by Dartmouth College personnel and kept frozen until analyzed. The material was processed according to the sediment procedures.

Table 1 summarizes the procedures used to detect each element in a particular material. A Perkin-Elmer Model 306 atomic absorption spectrophotometer was used according to specifications for sensitivity described in the Perkin-Elmer manual. When appropriate, a Perkin-Elmer Model 70 heated graphite atomizer (HGA) was used. This was later replaced with a Model 2100 HGA. The Perkin-Elmer High Sensitivity Sampling System was used in conjunction with flame analysis for arsenic and selenium.

The extraction system for water analysis involved sodium diethyldithiocarbonate and methyl iso-butyl ketone. The general procedure followed is described by Nix and Goodwin (1970).

Table 1. Summary of procedures used to detect the elements in water (W), soils (SL), plankton (PL), plants (P), and sediments (S)

Element	Generator	Extracted	Flame	Graphite Atomizer
Calcium			W SL PL P S	
Magnesium			W SL PL P S	
Cadmium		PL P		W SL PL P S
Lead		W SL PL P S	S	W SL PL P S
Copper			SL S	W PL P
Zinc			W SL PL P S	
Iron			W SL PL P S	
Arsenic	W SL PL P S		W SL PL P S	
Selenium	W SL PL P S		W SL PL P S	
Chromium				W SL P S

Table 1 indicates which elements were extracted when a particular water was analyzed for a specific element and whether it was read on the flame or the graphite atomizer. In the case of lead, both were used at various times depending upon the concentration of lead encountered.

In the analysis of lead in soils, lead was extracted using ammonium citrate buffer, potassium cyanide addition and pyrrolidine carbodithioc acid as the chelating agent and methyl isobutyl ketone (Yeager et al., 1971).

For plankton, Nix extraction procedure was followed. Plants and soils were also extracted according to the procedure for soils (Johnson and Ulrich, 1959). In March of 1974 and 1975, a gelatinous precipitate formed during the extraction procedure for plants. This necessitated use of the method of additions for cadmium at these times.

Analytical performance was evaluated using the National Bureau of Standards (NBS) orchard leaves: Percentage errors were high for copper on the heated graphite atomizer (HGA) and for chromium and cadmium. We therefore may underestimate copper and the differences for chromium and cadmium at such low levels is negligible (Table 2).

Because of the large numbers and varieties of materials tested, we did not elect to use the method of additions for each element. We therefore corrected the water, sediment, soil and plant data for percentage recoveries. Table 3 summarizes the percentage recovery data. For most of the elements, the mean percentage recovery ranged from 89 to 105. Occasional extreme values did occur as indicated by the ranges.

There was a concern that use of the Wiley Mill which could

Table 2. Analysis of National Bureau of Standards (NBS) orchard leaves by the University of New Mexico (UNM)

Element	Technique	Mean Percentage Recovery	NBS Value	UNM Value	Percentage Error
Copper	HGA	93	12 μg/g	8.50 μg/g	29
Copper	Flame	101	12 μg/g	11.49 μg/g	4
Chromium	HGA	105	2.3 μg/g	3.01 μg/g	24
Lead	HGA	107	45 μg/g	40.20 μg/g	11
Cadmium	HGA	107	0.11 μg/g	0.19 μg/g	42
Zinc	Flame	103	25 μg/g	27.09 μg/g	8
Iron	Flame	101	300 μg/g	273 μg/g	9
Calcium	Flame	94	2.09 wt. %	1.81 wt. %	13
Magnesium	Flame	100	0.62 wt. %	0.62 wt. %	0

Table 3. Summary of percentage recovery data for materials analyzed from 1972-76. The mean and range are given

Element	Water Dissolved	Water Particulate	Sediment	Soil	Ephedra	Atriplex	Oryzopsis	Tamrix
Lead	97 63-120	75 46-98	99 55-135	94 75-121	94 82-109	90 73-108	97 71-113	96 83-109
Cadmium	94 85-105	92 69-133	93 83-123	87 71-116	88* 82-92	75* 69-77	87* 86-89	101* 81-115
Chromium	103 95-110	103 80-118	92 80-121	101 80-123	?	94 55-119	104 95-121	97 51-116
Copper	98 91-116	105 89-118			89 81-92	90 81-103	94 90-112	97 87-118
Calcium	98 90-100	98 90-105			95 84-103	97 97-97	100 99-100	98 93-102
Magnesium	103 102-104	99 98.8-100			95 89-100	91 81-98	94 89-98	102 101-104
Zinc	100 94-105	98 92-101			97 94-100	101 100-104	101 101-101	100 100-101
Iron	97 96-98	99 98.8-99			101 99-103	99 98-102	98 98-98	97 93-111

*Most analyses for cadmium utilized the method of additions.

not be acid washed might be a source of contamination. Table 4 provides comparison data between analysis of material ground on the Wiley Mill and by mortar and pestle. Under the assumption that if contamination occurs, then the percentage recoveries for material ground on the Wiley Mill should be higher than the same material ground on the mortar and pestle. Since there was no unusually high value for percentage recoveries on the material processed by the Wiley Mill and no consistent pattern of higher Wiley Mill percentage recovery between the three kinds of plants, we concluded that the Wiley Mill could be used if it was carefully cleaned and rinsed with distilled water.

MASS BALANCE OF SELECTED IONS ON THE COLORADO PLATEAU

Mass balance calculations are based on six or seven sampling periods in time between March 1974 and November 1975. These included times of low and high water flow as well as different seasons. A mean of the concentrations was multiplied by the mean annual flow based on United States Geological Survey (USGS) stream records for the water years of 1973, 1974, and 1975. The upper and lower 0.90 confidence interval about the mean concentration was also multiplied by the mean annual flow. The calculation for the output was estimated by computing the mean of the cation concentration in bottom and surface water samples taken just in front of the dam and then weighting this value by the flow record at Lee's Ferry. This then represents the outlet site and represents the mean concentration of water passing through the dam. Total weighted input concentration was based on the sum of the flow weighted concentrations at the Green, San Juan, and Colorado (at Moab) rivers.

A recent review (Utah State University, 1975) does not indicate that any mass balance calculations have been made for

Table 4. Comparison of percentage recovery data used to compare processing of plant materials by Wiley Mill (WM) and Mortar and Pestle (MP)

Element	Tamarix pentandra Percent Recovery		Oryzopsis hymenoides Percent Recovery		Atriplex confertifolia Percent Recovery		Unit
	WM	MP	WM	MP	WM	MP	
Calcium	98	99	100	102	97	97	ppm
Cadmium	58	83	87	97	75	83	ppb
Chromium	104	85	78	51	97	101	ppb
Copper	95	92	91	95	91	95	ppb
Iron	93	99	98	104	99	98	ppm
Lead	87	93	103	109	95	93	ppb
Magnesium	102	101	94	95	98	93	ppm
Zinc	100	102	101	93	101	102	ppm

the Upper Colorado River Basin, so the estimates made by us represent much needed new information for cations and particularly those which have public health significance.

Dissolved Phase

The dissolved phase for each cation is defined operationally as the filtrate that passes through a 0.45 μ pore size filter. The flow weighted concentrations in kilograms are given in Table 5. The order of abundance of the ions in tributary waters from higher to lower concentrations is Ca>Mg>Fe>Zn>Cu>Pb>Cd. Five of the seven elements were highest in concentration at the Dolores River. These were calcium, magnesium, cadmium, copper, and zinc. Iron and lead were both highest in concentration at the outlet site on the Colorado River.

In Table 6 we compare the rankings for the various elements from highest to lowest concentration in order to determine qualitative similarities in heavy metal behavior. As expected, calcium and magnesium are very similar in ranking pattern. Cadmium and copper are similar in pattern, but the other elements are dissimilar in pattern.

Particulate Phase

Particulate material is defined as the matter that is retained by a 0.45 μ pore size filter. Kilograms of heavy metals in the particulate phase are given in Table 7. The order of the ions from highest to lowest concentration is Fe>Ca>Mg>Zn>Cu>Pb>Cd. The order differs from the ranking for the dissolved species in that calcium was highest in concentration of the dissolved species; otherwise, the order of the ions is similar. Calcium, magnesium, copper, and zinc were highest in concentration at the Green River Site and cadmium and lead

Table 5. Flow weighted concentration of dissolved cations in tributary waters to Lake Powell in kilograms

Sites	Calcium	Magnesium	Cadmium	Lead	Copper	Zinc	Iron
Gunnison River	$1.63x10^{8}$	$5.29x10^{7}$	$8.34x10^{2}$	$5.40x10^{3}$	$2.15x10^{4}$	$4.42x10^{4}$	$2.60x10^{5}$
Colo. R. at Gr. Junc.	$2.12x10^{8}$	$5.56x10^{7}$	$2.23x10^{3}$	$4.72x10^{3}$	$2.79x10^{4}$	$9.98x10^{4}$	$4.71x10^{5}$
Dolores River	$7.65x10^{8}$	$3.08x10^{8}$	$7.20x10^{3}$	$1.36x10^{4}$	$7.62x10^{4}$	$3.41x10^{5}$	$1.29x10^{6}$
Green River	$3.90x10^{8}$	$1.46x10^{8}$	$6.78x10^{3}$	$4.24x10^{3}$	$5.83x10^{4}$	$5.51x10^{4}$	$2.48x10^{6}$
San Juan River	$1.42x10^{8}$	$3.80x10^{7}$	$1.76x10^{3}$	$9.35x10^{2}$	$2.06x10^{4}$	$4.66x10^{4}$	$3.69x10^{5}$
Colo. R. at Moab	$4.71x10^{8}$	$1.45x10^{8}$	$3.91x10^{3}$	$4.13x10^{3}$	$5.52x10^{4}$	$6.91x10^{4}$	$1.58x10^{6}$
Colo. R. at Lee's Ferry	$7.13x10^{8}$	$2.65x10^{8}$	$3.72x10^{3}$	$4.99x10^{4}$	$3.04x10^{4}$	$7.34x10^{4}$	$6.80x10^{6}$

Table 6. Ranking of sites on the basis of highest to lowest concentrations of cations in the dissolved phase measured at the tributaries to Lake Powell

	Ranking						
Element	7	6	5	4	3	2	1
Calcium	Dolores River	Colo. R. at Lee's Ferry	Colo. R. at Moab	Green River	Colo. R. at Grand Junction	Gunnison River	San Juan River
Magnesium	Dolores River	Colo. R. at Lee's Ferry	Green River	Colo. R. at Moab	Colo. R. at Grand Junction	Gunnison River	San Juan River
Cadmium	Dolores River	Green River	Colo. R. at Moab	Colo. R. at Lee's Ferry	Colo. R. at Grand Junction	San Juan River	Gunnison River
Lead	Colo. R. at Lee's Ferry	Dolores River	Gunnison River	Colo. R. at Grand Junction	Green River	Colo. R. at Moab	San Juan River
Copper	Dolores River	Green River	Colo. R. at Moab	Colo. R. at Lee's Ferry	Colo. R. at Grand Junction	Gunnison River	San Juan River
Zinc	Dolores River	Colo. R. at Grand Junction	Colo. R. at Lee's Ferry	Colo. R. at Moab	Green River	San Juan River	Gunnison River
Iron	Colo. R. at Lee's Ferry	Green River	Colo. R. at Moab	Dolores River	Colo. R. at Grand Junction	San Juan River	Gunnison River

Table 7. Flow weighted concentrations of particulate phase cations in tributary water to Lake Powell in kilograms

Sites	Calcium	Magnesium	Cadmium	Lead	Copper	Zinc	Iron
Gunnison River	$6.51x10^6$	$1.76x10^6$	$6.36x10^2$	$1.04x10^4$	$1.44x10^4$	$2.44x10^4$	$4.17x10^6$
Colo. R. at Gr. Junc.	$4.02x10^6$	$1.79x10^6$	$8.32x10^2$	$1.99x10^4$	$1.84x10^4$	$1.33x10^5$	$5.64x10^6$
Dolores River	$1.63x10^7$	$6.64x10^6$	$7.99x10^3$	$4.61x10^4$	$6.18x10^4$	$1.90x10^5$	$1.91x10^7$
Green River	$3.03x10^7$	$1.59x10^7$	$1.65x10^3$	$2.05x10^4$	$6.87x10^4$	$1.65x10^6$	$3.59x10^7$
San Juan River	$1.19x10^7$	$6.46x10^6$	$4.08x10^2$	$1.36x10^4$	$3.08x10^4$	$7.89x10^4$	$1.09x10^7$
Colo. R. at Moab	$2.52x10^7$	$9.08x10^6$	$8.16x10^2$	$2.28x10^4$	$4.67x10^4$	$1.00x10^5$	$2.06x10^7$
Colo. R. at Lee's Ferry	$1.20x10^7$	$3.72x10^6$	$2.44x10^3$	$1.26x10^4$	$2.24x10^4$	$7.09x10^4$	$6.79x10^7$

were highest at the Dolores River, and iron was calculated to be highest at the outlet site.

The rankings of sites for the various elements from highest to lowest concentration are given in Table 8. Although the rankings for calcium and magnesium were similar for the dissolved phase, they were not similar for the particulate phase. Magnesium was more similar to copper and calcium does not match any other ranking pattern. Although the ranking patterns for dissolved copper and cadmium were alike, they were not similar in the particulate phase.

Calcium, magnesium, cadmium, and copper were higher in concentration in the dissolved phase; whereas lead, zinc, and iron were higher in the particulate phase (Tables 5 and 7). A similar finding for cadmium was made from data collected at the tributary streams to Cayuga Lake, New York (Kubota, 1974). However, Gibbs (1973) found that copper was carried predominantly in the suspended phase comprising detrital crystalline material of the Amazon River. Similarly, iron in the tributaries to Lake Powell and in the Amazon River was less abundant in the dissolved phase. Zinc was higher in the particulate phase in the tributaries to Lake Powell and in the Amazon River.

On the basis of the weighted mean annual concentrations (Tables 5 and 7) at the tributary sites, the cations calcium and magnesium in the dissolved phase exceed their concentration in the particulate phase by one or two orders of magnitude. Cadmium was an order of magnitude higher in the dissolved phase at four of seven tributary sites. Cadmium in the particulate phase was greater at only one site - the Dolores River. Lead in the particulate phase exceeded its concentration in the dissolved phase by one order of magnitude at most sites. However, the calculated amounts for the outlet indicate that the

Table 8. Ranking of sites on the basis of highest to lowest concentrations of cations in the particulate phase measured at the tributaries to Lake Powell

	Ranking						
Element	7	6	5	4	3	2	1
Calcium	Green River	Colo. R. at Moab	Colo. R. at Lee's Ferry	Dolores River	San Juan River	Gunnison River	Colo. R. at Grand Junction
Magnesium	Green River	Colo. R. at Moab	Dolores River	San Juan River	Colo. R. at Lee's Ferry	Colo. R. at Grand Junction	Gunnison River
Cadmium	Dolores River	Colo. R. at Lee's Ferry	Green River	Colo. R. at Grand Junction	Colo. R. at Moab	Gunnison River	San Juan River
Lead	Dolores River	Colo. R. at Moab	Green River	Colo. R. at Grand Junction	San Juan River	Colo. R. at Lee's Ferry	Gunnison River
Copper	Green River	Dolores River	Colo. R. at Moab	San Juan River	Colo. R. at Lee's Ferry	Colo. R. at Grand Junction	Gunnison River
Zinc	Green River	Dolores River	Colo. R. at Grand Junction	Colo. R. at Moab	Colo. R. at Lee's Ferry	San Juan River	Gunnison River

dissolved phase was about four times greater in concentration than the particulate phase. For copper, the concentration in the dissolved phase exceeded the particulate phase at five of seven tributary sites, but for zinc the particulate phase exceeded the dissolved phase at four of seven sites. Iron concentration in the particulate phase was greater than its concentration in the dissolved phase by one to two orders of magnitude at each tributary site. Selenium concentration in the particulate phase exceeds the concentration in the dissolved phase at four of seven sites (Table 9), but arsenic in the particulate phase exceeds the concentration in the dissolved phase at six of seven sites (Table 10).

In Table 11 the percentage of individual water samples in which the element in the particulate phase was greater than in the dissolved phase does indicate a few patterns. In the tributaries, chromium, copper, iron, lead, and zinc had higher concentrations in the particulate phase and ranged in percent from 60 to 100. Three elements, cadmium, arsenic, and selenium, were higher in the dissolved phase. When the percentages for the tributaries are compared with the percentages of samples in which the particulate exceeds the dissolved phase for the upper and lower Lake Powell, we note that the percentages decrease for chromium, iron, lead, and zinc. Seemingly, this decrease could be explained on the basis that lower Lake Powell has relatively little sediment in the water as compared to the tributaries; and this might account for the decrease in the abundance of a heavy metal ion in the particulate phase. However, note that cadmium increased in the particulate phase along with selenium in lower lake waters. However, the change in level in the particulate phase was not great enough for lead and zinc.

We conclude that it is not possible to generalize that a

Table 9. Weighted mean annual selenium concentration at the seven tributary sites (units are in kilograms and the calculations are based on three collection times)

Sites	Dissolved	Particulate	Total
Gunnison River	913	9,436	10,349
Colo. R. at Gr. Junc.	4,194	332	4,526
Dolores River	29,676	1,500	31,176
Green River	6,946	24,862	31,807
San Juan River	5,304	3,826	9,130
Colo. R. at Moab	14,692	5,060	19,753
Colo. R. at Lee's Ferry	3,086	20,969	24,056

Table 10. Weighted mean annual arsenic concentration at the seven tributary sites (units are in kilograms and the calculations are based on three collection times)

Sites	Dissolved	Particulate	Total
Gunnison River	2,046	4,469	6,515
Colo. R. at Gr. Junc.	2,464	2,729	5,192
Dolores River	11,640	20,256	31,896
Green River	6,174	0	6,174
San Juan River	2,006	2,737	5,746
Colo. R. at Moab	5,496	31,343	36,894
Colo. R. at Lee's Ferry	24,376	36,191	60,566

Table 11. Percentage of samples in which particulate exceeds dissolved phase for the tributaries and upper and lower Lake Powell

	Lake Powell Tributaries	Lake Powell	
		Upper	Lower
Cadmium	16	35	26
Chromium	90	82	82
Copper	60	63	64
Iron	100	94	89
Lead	88	72	37
Arsenic	41	41	25
Selenium	33	27	42
Zinc	71	43	28

heavy metal ion is to be found mostly in one phase or another since the dissolved phase could be more prevalent at any one instant in time. Thus, any analysis of a particular individual water sample should include the dissolved and particulate phase. Those analytical programs, such as that of USGS, do not provide enough pertinent information about the level of an ion in a water sample. They usually record a value for the dissolved phase of the constituent. The USGS does not make a direct measurement of the particulate phase in a water sample.

Total

The total amount of a heavy metal ion is operationally defined as the sum of the dissolved and particulate phase concentrations. Total concentrations are given in Table 12 for seven of the cations and selenium and arsenic concentrations are given in Tables 9 and 10. All concentrations in the tables represent mean annual flow weighted values. The highest and lowest concentrations respectively are as follows:

calcium, 7.82×10^8 kg (Dolores R.) & 1.54×10^8 kg (San Juan R.);
magnesium, 3.15×10^8 kg (Dolores R.) & 4.45×10^7 kg (San Juan R.);
cadmium, 1.51×10^4 kg (Dolores R.) & 1.48×10^3 kg (Gunnison R.);
lead, 6.25×10^4 kg (outlet) & 1.45×10^4 kg (San Juan R.);
copper, 1.38×10^5 kg (Dolores R.) & 3.59×10^4 kg (Gunnison R.);
zinc, 1.76×10^6 kg (Green R.) & 6.84×10^4 kg (Gunnison R.);
iron, 3.84×10^7 kg (Green R.) & 4.43×10^6 kg

Table 12. Total concentrations of flow weighted cations in kilograms for tributary sites of Lake Powell

Sites	Calcium	Magnesium	Cadmium	Lead	Copper	Zinc	Iron
Gunnison River	$1.70\mathrm{x}10^{8}$	$5.47\mathrm{x}10^{7}$	$1.48\mathrm{x}10^{3}$	$1.58\mathrm{x}10^{4}$	$3.59\mathrm{x}10^{4}$	$6.86\mathrm{x}10^{4}$	$4.43\mathrm{x}10^{6}$
Colo. R. at Gr. Junc.	$2.16\mathrm{x}10^{8}$	$5.74\mathrm{x}10^{7}$	$3.06\mathrm{x}10^{3}$	$2.46\mathrm{x}10^{4}$	$4.63\mathrm{x}10^{4}$	$2.32\mathrm{x}10^{5}$	$6.11\mathrm{x}10^{6}$
Dolores River	$7.82\mathrm{x}10^{8}$	$3.15\mathrm{x}10^{8}$	$1.51\mathrm{x}10^{4}$	$5.97\mathrm{x}10^{4}$	$1.38\mathrm{x}10^{5}$	$5.32\mathrm{x}10^{5}$	$2.04\mathrm{x}10^{7}$
Green River	$4.20\mathrm{x}10^{8}$	$1.62\mathrm{x}10^{8}$	$8.43\mathrm{x}10^{3}$	$2.48\mathrm{x}10^{4}$	$1.27\mathrm{x}10^{5}$	$1.76\mathrm{x}10^{6}$	$3.84\mathrm{x}10^{7}$
San Juan River	$1.54\mathrm{x}10^{8}$	$4.45\mathrm{x}10^{7}$	$2.17\mathrm{x}10^{3}$	$1.45\mathrm{x}10^{4}$	$5.14\mathrm{x}10^{4}$	$1.25\mathrm{x}10^{5}$	$1.13\mathrm{x}10^{7}$
Colo. R. at Moab	$4.96\mathrm{x}10^{8}$	$1.54\mathrm{x}10^{8}$	$4.73\mathrm{x}10^{3}$	$2.69\mathrm{x}10^{4}$	$1.02\mathrm{x}10^{5}$	$1.69\mathrm{x}10^{5}$	$2.22\mathrm{x}10^{7}$
Colo. R. at Lee's Ferry	$7.25\mathrm{x}10^{8}$	$2.69\mathrm{x}10^{8}$	$6.28\mathrm{x}10^{3}$	$6.25\mathrm{x}10^{4}$	$5.27\mathrm{x}10^{4}$	$1.44\mathrm{x}10^{5}$	$6.85\mathrm{x}10^{6}$

(Gunnison R.);
selenium, 31,807 kg (Green R.) & 4,526 kg (Colorado R. at Grand Junction);
arsenic, 60,566 kg (outlet) & 5,192 kg (Colorado R. at Grand Junction).

Input-Output Budget Total

The rank order of cations from highest to lowest concentration (Table 13) in the output was Ca>Mg>Fe>Zn>Cu>Pb>Cd. The rank order for all of the tributaries (Table 9) was Ca>Mg>Fe>Zn>Cu>Pb>Cd. This comparison would indicate that the overall pattern of the elements, regardless of phase, does not change under the influence of chemical and physical events within the reservoir.

On the basis of total concentrations, Lake Powell acts as a cation trap for all of the elements investigated for which enough collections were made through time (Table 13). A possible exception was lead, whose upper limit of input minus output calculation suggests that more lead left the reservoir than remained in it.

Particulate and Dissolved

Input-output calculations indicated that for every cation investigated, Lake Powell served as a trap for the particulate phase (Table 14). However, in the dissolved phase we note that more lead leaves the reservoir in the dissolved phase than is trapped within it (Table 15). Since lead differs from the patterns for the other elements, it deserves more consideration.

We noted that lead in the particulate phase exceeded the element in the dissolved phase by one order of magnitude. However, the calculated weighted lead concentrations for the

Table 13. Input-output budget for Lake Powell in kilograms (calculations are for total concentrations of the cations)

	Calcium $\times 10^7$	Magnesium $\times 10^7$	Cadmium $\times 10^3$	Lead $\times 10^4$	Copper $\times 10^5$	Zinc $\times 10^5$	Iron $\times 10^7$
Input							
Mean	107.19	36.22	15.34	6.62	2.80	20.59	7.20
Upper Limit	136.61	47.73	32.06	10.33	4.99	52.60	13.48
Lower Limit	77.78	24.72	-	2.92	0.61	-	0.92
Output							
Mean	72.59	26.91	6.28	6.25	0.52	1.44	0.68
Upper Limit	80.73	28.95	11.60	16.14	1.04	2.50	1.98
Lower Limit	64.45	24.88	0.85	-	0.01	0.38	-
Input-Output							
Mean	55.88	9.31	9.06	0.37	2.28	19.15	6.52
Upper Limit	34.60	18.78	20.46	5.81	3.95	50.10	11.50
Lower Limit	13.33	-	-	-	0.60	-	-

Table 14. Input-output budget for Lake Powell in kilograms (calculations are for particulate concentrations of the cations)

	Calcium x 10^7	Magnesium x 10^7	Cadmium x 10^3	Lead x 10^4	Copper x 10^5	Zinc x 10^5	Iron x 10^7
Input							
Mean	6.76	3.15	2.87	5.69	1.46	18.32	6.76
Upper Limit	10.48	5.19	5.94	9.22	2.47	49.12	12.35
Lower Limit	3.03	1.11	-	2.17	0.45	-	1.16
Output							
Mean	1.20	0.37	2.44	1.26	0.22	0.70	0.67
Upper Limit	3.34	1.06	5.85	3.30	0.37	1.23	1.97
Lower Limit	-	-	-	-	0.07	0.18	-
Input-Output							
Mean	5.56	2.78	0.43	4.43	1.24	17.62	6.09
Upper Limit	7.14	4.13		5.92	2.10	47.89	10.38
Lower Limit	-	-		-	0.38	-	-

Table 15. Input-output budget for Lake Powell in kilograms (calculations are for dissolved concentrations of cations)

	Calcium x 10^7	Magnesium x 10^7	Cadmium x 10^3	Lead x 10^4	Copper x 10^5	Zinc x 10^5	Iron x 10^7
Input							
Mean	100.43	33.07	12.46	0.93	1.34	1.70	0.44
Upper Limit	129.66	43.79	27.04	1.90	2.57	4.45	1.26
Lower Limit	71.21	22.35	-	-	0.10	-	-
Output							
Mean	71.39	26.54	3.72	4.99	0.30	0.73	0.006
Upper Limit	78.08	28.78	6.60	12.89	0.69	1.36	0.01
Lower Limit	63.69	24.31	0.95	-	-	0.10	0.001
Input-Output							
Mean	29.04	6.53	8.74	(4.06)	1.04	0.97	0.43
Upper Limit	63.69	15.01	20.44	(10.99)	1.88	3.09	1.25
Lower Limit	7.52	(1.96)	-		-	-	

outlet indicated that the dissolved phase exceeded the element in the particulate phase by about four times (Tables 5 and 7). Total mean annual input of lead to Lake Powell was 6.62 x 10^4 kg and the output was 6.25 x 10^4 kg and meant that 0.37 x 10^4 kg was trapped (Table 13). However, when the upper limits for the input and output are considered, then as much as 5.81 x 10^4 kg could be leaving the reservoir. Examination of the budgets for particulate (Table 14) and dissolved (Table 15) indicated that more lead leaves in the dissolved phase than is trapped by the reservoir. When we considered the percent of the element lead carried in the particulate phase (Table 9), we noted that lead behaved like the other heavy metal cations at the tributaries and in the upper reservoir, but in the lower reservoir lead behaved more like the two cations, magnesium and calcium, in that they were predominantly in the dissolved phase. On this basis we hypothesize that recreational boating and gas spills contribute to dissolved lead levels in the lower reservoir. These dissolved lead levels would be swept down to the dam and out and thus account for the calculated higher levels at the outlet.

An alternative hypothesis is that water borne sediments release lead and this demineralization process contributes to elevated dissolved lead concentrations. Data presented in this report support the first hypothesis. For example, finding of elevated lead levels in the gills of fish below Wahweap Marina (Bussey et al., 1976) supports the hypothesis of cultural inputs of lead into the lower reservoir.

SUMMARY OF MASS BALANCE INVESTIGATION

1. The order of abundance of ions in the dissolved phase in tributary waters from higher to lower concentration is Ca>Mg>Fe>Zn>Cu>Pb>Cd.

2. Five of the seven elements in the dissolved phase were highest in concentration at the Dolores River.

3. The order of ions in the particulate phase from highest to lowest concentration is Fe>Ca>Mg>Zn>Cu>Pb>Cd.

4. Calcium, magnesium, copper, and zinc were highest in weighted concentrations at the Green River and cadmium and lead were highest at the Dolores River.

5. Calcium, magnesium, cadmium, and copper were higher in concentration in the dissolved phase; whereas lead, zinc, and iron were higher in the particulate phase.

6. Lead in the particulate phase exceeded its concentration in the dissolved phase by one order of magnitude; however, at the outlet the dissolved phase was four times greater than the particulate phase.

7. Copper in the dissolved phase exceeded its weighted concentration in the particulate phase at most tributary sites.

8. On a volume basis, chromium, copper, iron, lead,and zinc were higher in the particulate phase at tributary sites. This differs for copper in the weighted phase (summary statement 7.) because the weighted values are based on the annual mean.

9. On a volume basis, cadmium, arsenic, and selenium were higher in the dissolved phase in tributary waters.

10. Only cadmium and selenium increased in amount in the particulate phase in lower reservoir waters as compared

to tributary waters.

11. We conclude that it is important for monitoring agencies to analyze a water sample for both the dissolved and particulate phase.

12. Total concentrations for each element were highest at the Dolores River for calcium, magnesium, cadmium, and copper; lead was highest at the outlet; and zinc, iron, selenium, and arsenic were highest at the Colorado River near Grand Junction.

13. The rank order of total concentration of ions was the same for the outlet as for the tributaries. Therefore, processes within the reservoir do not significantly alter the distribution of the cations.

14. On the basis of total concentration, Lake Powell serves as a cation trap. The upper confidence limit for lead indicates that lead may not be trapped - more lead leaves the reservoir than is retained.

15. On the basis of the particulate phase concentration, Lake Powell serves as a cation trap.

16. On the basis of the dissolved phase concentration, Lake Powell serves as a trap for all of the cations except lead.

17. It is suggested that cultural inputs of lead occur in the lower reservoir.

CONCENTRATIONS OF ELEMENTS ON A VOLUME BASIS IN WATERS

A summary of baseline information for surface and bottom waters is given in Tables 16 and 17. Comparison is made to potable water criteria (FWPCA, 1968). Measurements given are for total concentrations (dissolved + particulate phases).

Cadmium

Mean values for cadmium range from 0.2 to 1 µg/l. Higher values were found at the Green River and Dolores River Sites (Table 16). Tributary mean concentrations (excluding the Dirty Devil which is considered to be a reservoir site) ranged from 0.8 to 2 µg/l and in the reservoir ranged from 0.2 to 1 µg/l. All cadmium values were below the 10 µg/l standard for potable water supplies. One value of 8 µg/l, obtained at the Green River Site, did approach the threshold standard.

Mean concentrations for cadmium in the bottom waters were 0.3 to 1 µg/l which was similar to the range for mean concentrations in surface waters (Table 17).

The portion of cadmium present in either the dissolved or particulate phase and seasonal changes in concentrations at each site are given for the tributaries (Figure 2), upper Lake Powell (Figure 3) and lower Lake Powell (Figure 4). The total amount is represented by a bar and the particulate phase function is indicated by the shaded portion of each bar.

At the tributaries, the particulate phase exceeds the dissolved phase in 16 percent of the samples. There does not seem to be any consistent pattern of seasonal changes in

Table 16. Annual mean and range of cation concentrations in surface waters of Lake Powell and major tributary sites. Reference is made to FWPCA water criteria

	Cd µg/l	Cr µg/l	Pb µg/l	Zn µg/l	Fe mg/l	Ca mg/l	As µg/l	Se µg/l	Mg mg/l	Cu µg/l
Site 1	0.4 0-0.9	0.5 0-0.9	2 0-9	17 4-49	0.02 0.004-0.05	62 53-68	0.7 0-1	5 2-8	23 20-26	2 0-4
Site 2	0.2 0-0.9	0.9 0-3	0.6 0.1-1	9 0-25	0.02 0.02-0.03	62 55-68	1 0-2	2 1-3	22 20-24	2 0-5
Site 3	0.3 0-0.8	0.2 0-0.5	2 0.5-9	13 2-47	0.04 0-0.08	60 46-68	9 5-12	3 0-7	23 20-25	1 0.3-3
Site 5	0.2 0.1-0.5	0.04 0-0.2	0.7 0-2	13 2-32	0.03 0.02-0.014	58 48-63	4 0-8	16 5-36	21 18-24	1 0-4
Site 6	0.6 0.2-2	0.9 0-4	3 0.8-10	17 2-37	0.03 0.005-0.08	59 47-74	3 0.7-8	2 0.1-4	19 16-22	3 0-9
Site 7	0.9 0.1-2	0.1 0-0.4	1 0.2-3	12 1-27	0.03 0-0.04	55 48-63	4 2-6	2 0.2-3	19 16-24	3 0-6
Site 8	0.6 0-2	0.5 0-2	2 0.6-5	8 0-19	0.06 0.004-0.2	54 46-63	3 0-5	0.9 0.5-2	19 14-23	2 0-5
Site 9	1 0.1-5	0.4 0-2	3 0.4-9	10 2-21	0.2 0.02-0.6	60 43-76	0.9 0.2-1	6 0-13	22 13-29	0.8 0-3
Dirty Devil	0.3 0-1	0.2 0-0.6	2 0.8-4	11 0-33	0.1 0.001-0.2	64 45-80	10 7-15	5 3-8	23 14-31	5 0.1-14
Colo. River at Moab	0.9 0-2	9 0-13	5 2-8	31 0-91	4 1-9	91 52-138	7 2-15	4 3-6	28 13-45	19 6-54
Colo. R. at Gr. Junction	0.9 0.1-3	5 0-20	7 0-27	70 2-178	2 0.2-3	65 36-89	2 0.5-3	1 0.5-2	17 7-26	14 2-44
San Juan R. at Mex. Hat	1 0.1-3	12 0-51	9 3-23	74 2-223	7 0.5-24	9 42-129	3 0-4	5 0-9	26 8-49	30 4-92
Gunnison River	0.8 0-3	5 0-14	8 0-16	35 2-99	2 0.5-5	86 55-129	3 1-5	5 1-9	28 19-39	18 4-52
Green River	2 0-8	12 0.4-45	5 0-10	320 0-1971	7 0.2-29	76 42-133	1 0.2-2	6 1-14	30 13-38	23 6-77
Dolores River	2 0-4	3 0-10	8 0.6-18	67 5-156	3 0.5-9	99 37-137	4 0-9	4 1-6	40 8-68	17 4-54
Criteria	10	50	50	500	30 (filterable)	-	50	10	-	1000

Table 17. Annual mean and range of cations in bottom waters

	Cd µg/l	Cr µg/l	Pb µg/l	Zn µg/l	Fe mg/l	Ca mg/l	As µg/l	Se µg/l	Mg mg/l	Cu µg/l
Site 1	0.3	0.2	1	13	33	61	3	0.5	23	3
	0-0.7	0-0.7	0.4-3	1-27	16-50	52-68	0.8-4	0-0.9	20-25	0-5
Site 2	0.6	0.2	4	15	50	72	2	5	26	3
	0.01-2	0-0.6	0-19	2-27	20-90	65-81	0-5	3-7	23-29	0.3-6
Site 3	0.9	6	9	15	1252	76	2	1	28	6
	0-2	0-36	0-49	2-47	21-7,322	55-89	0-4	0.1-2	24-32	0.1-14
Site 5	1	0.2	3	16	73	71	4	7	26	3
	0-5	0-1	0.8-13	2-25	20-194	61-81	3-4	2-11	23-32	0-6
Site 6	0.9	5	5	15	1409	71	2	4	27	8
	0.3-2	0-31	2-15	2-42	20-5257	56-82	0-4	3-6	24-29	0-16
Site 7	1	1	1	12	86	71	0.5	7	26	4
	0.1-3	0-1	0.4-6	2-22	31-116	65-79	0-2	4-12	24-29	0-16
Site 8	1	9	4	17	2,941	74	8	1	27	8
	0.2-3	0-44	0-14	4-33	16-15,022	62-92	2-20	0.9-2	18-32	0.1-25
Site 9	0.7	6	4	13	2,094	71	2	2	28	9
	0.1-1	0-35	0.8-10	0-28	110-10,891	56-78	0.4-6	0-7	18-30	0-36

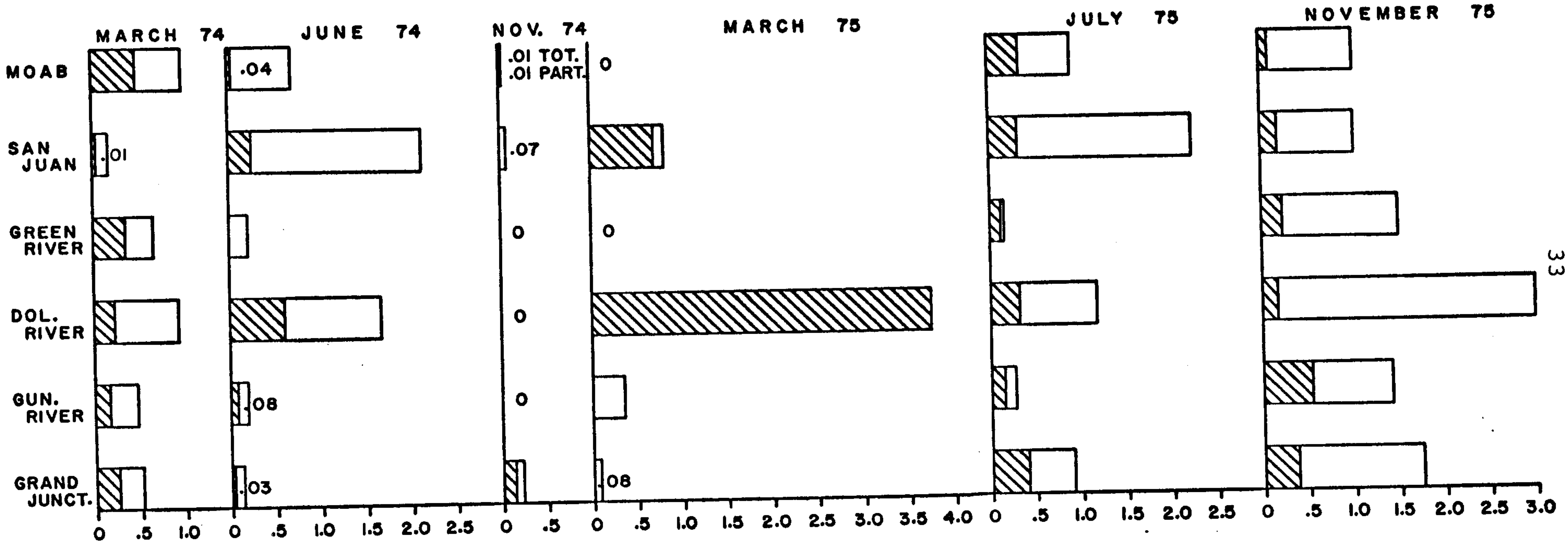

Figure 2. Bar graph of cadmium concentrations in surface waters at tributary sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

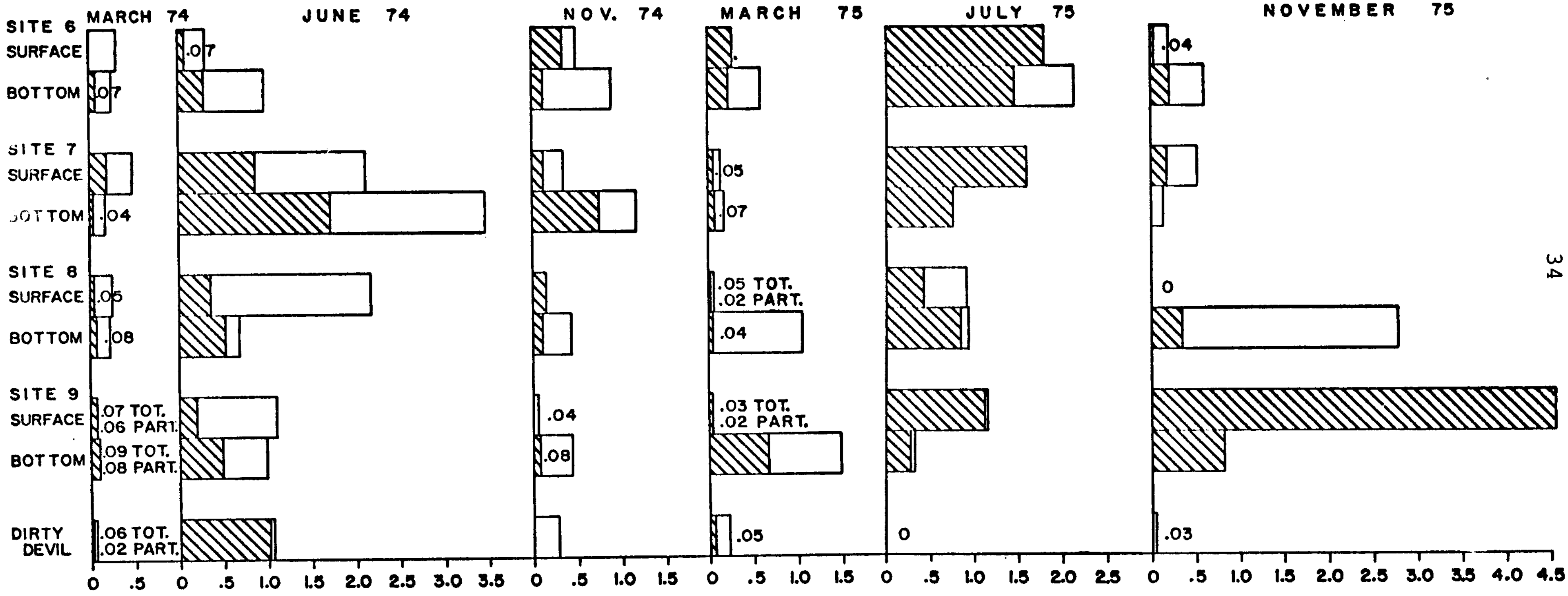

Figure 3. Bar graph of cadmium concentrations in surface and bottom waters at upper reservoir sites in μg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

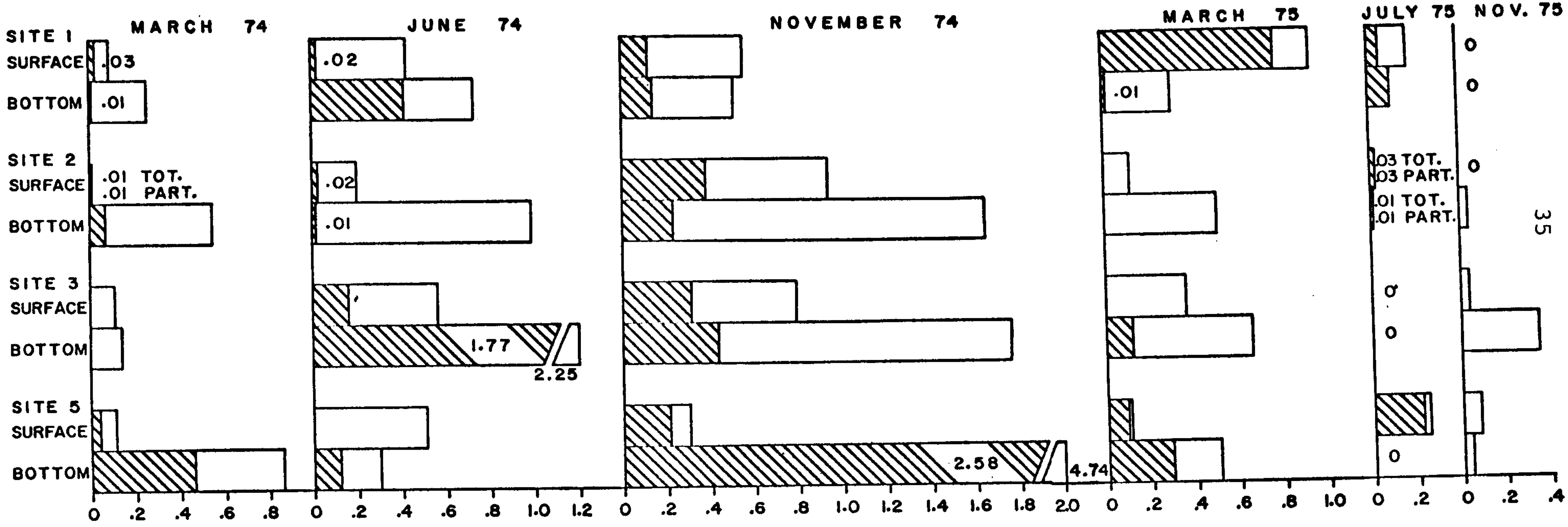

Figure 4. Bar graph of cadmium concentrations in surface and bottom waters at lower reservoir sites in µg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

concentrations among the sites.

For upper Lake Powell, 35 percent of the samples displayed higher concentrations in the particulate phase. There was evidence of a seasonal pattern among surface water sites. All upper reservoir sites were lower in concentration at the March 1974 date, higher in June 1974 at four of five sites, and lower in November 1975 at four of five sites. Bottom water samples do not display a seasonal pattern.

Twenty-six percent of the samples were higher in the particulate phase at the lower reservoir sites. The general seasonal trend of concentrations at the surface was lower (March 1974), higher (June 1974), higher at three of four sites (November 1974), lower at three of four sites (March 1975), lower at three of four sites (July 1975), and lower at three of four sites (November 1975). This seasonal trend did not follow the same pattern found at the upper reservoir sites. The bottom samples displayed a trend of concentrations which was lower, higher, higher, lower, and no correspondence between sites in November 1975.

Chromium

Mean chromium concentrations in surface waters of the reservoir ranged from 0.04 to 0.9 μg/l. At the tributary sites concentrations were higher and ranged from 3 to 12 μg/l (Table 16). All of the concentrations are below the standard of 50 μg/l for potable waters. Mean bottom water concentrations ranged from 0.2 to 9 μg/l. These levels were more similar to concentrations at the tributary sites than at the lower reservoir sites (Table 17). Ninety percent of the tributary samples had higher concentrations in the particulate phase (Figure 5). The presence of chromium in the particulate phase occurred to the

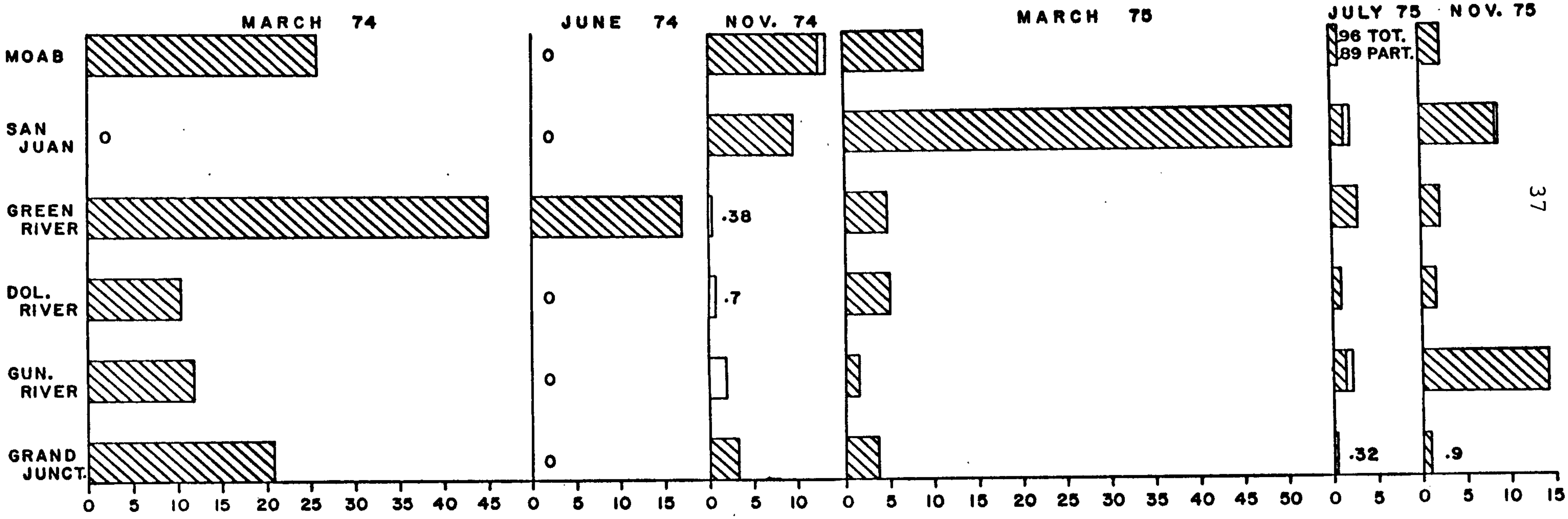

Figure 5. Bar graph of chromium concentrations in surface waters at tributary sites in μg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

exclusion of the dissolved phase at most dates. Chromium, more than any of the other elements investigated, occurred at concentrations below detectable limits (indicated by zero in the figures). Summer levels, June 1974 and July 1975, were lower than March and November levels.

At Sites 6-9 and the Dirty Devil (Figure 6) the particulate phase was dominant in 82 percent of the samples. No clear-cut seasonal patterns existed between sites. The great variability between sites is well illustrated by examining the data for March and June 1974. Certain sites were very high, while other sites were below detectable limits.

Sites 1-5 in the lower reservoir (Figure 7) also displayed higher chromium concentrations in the particulate phase (82 percent). Little correspondence in seasonal patterns existed between sites. A major difference between the lower reservoir and the upper and tributary regions was the relatively higher concentrations in July 1975 at Sites 1-3.

Kharkar et al. (1968) report average dissolved chromium concentrations of 1.37 (Mississippi River), 0.71 (Susquehanna River), 0.72 (Klamath River), and 0.10 (Brazos River). All units were in µg/l and approximate the concentrations found for dissolved chromium in tributary waters to Lake Powell.

Turekian and Scott (1967) report levels of particulate (suspended) chromium in rivers of the central and eastern U. S. which are on the order of 37 to 460 ppm, whereas our highest concentration detected in tributary waters was about 50 ppb (Figure 6). They note that these higher eastern levels may be due to greater amounts of trace-element rich soils and cultural inputs.

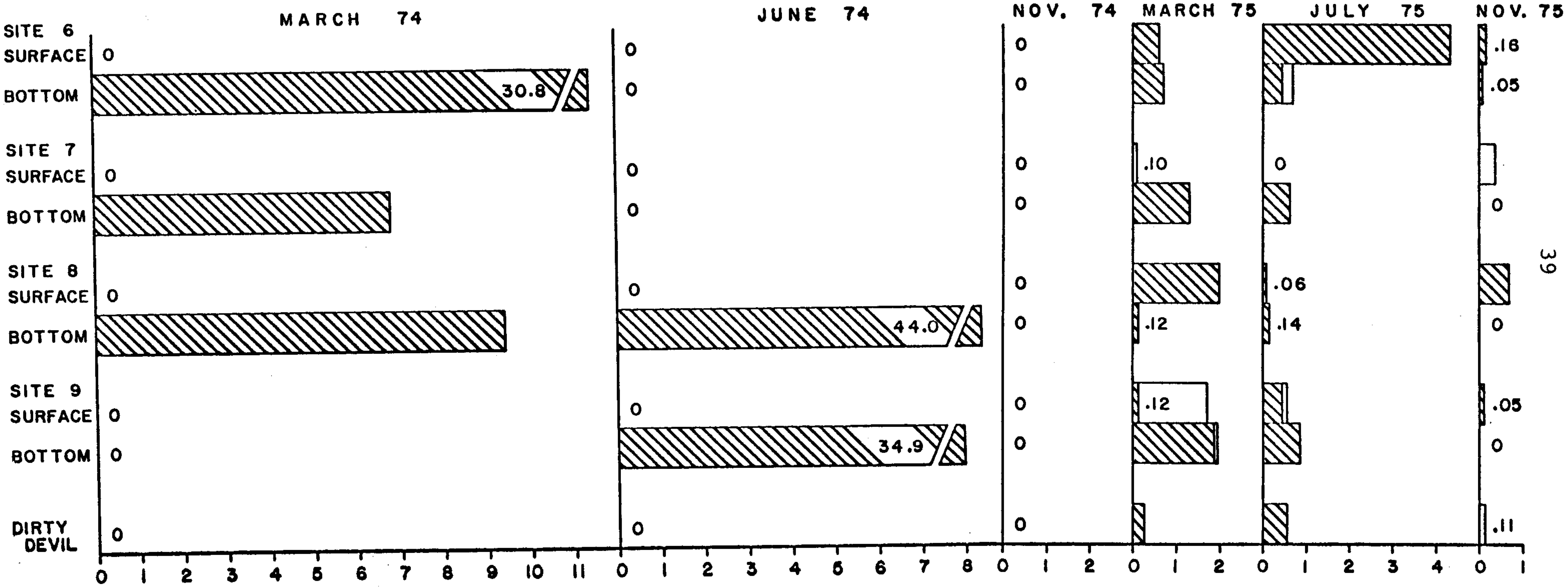

Figure 6. Bar graph of chromium concentrations in surface and bottom waters at upper reservoir sites in μg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

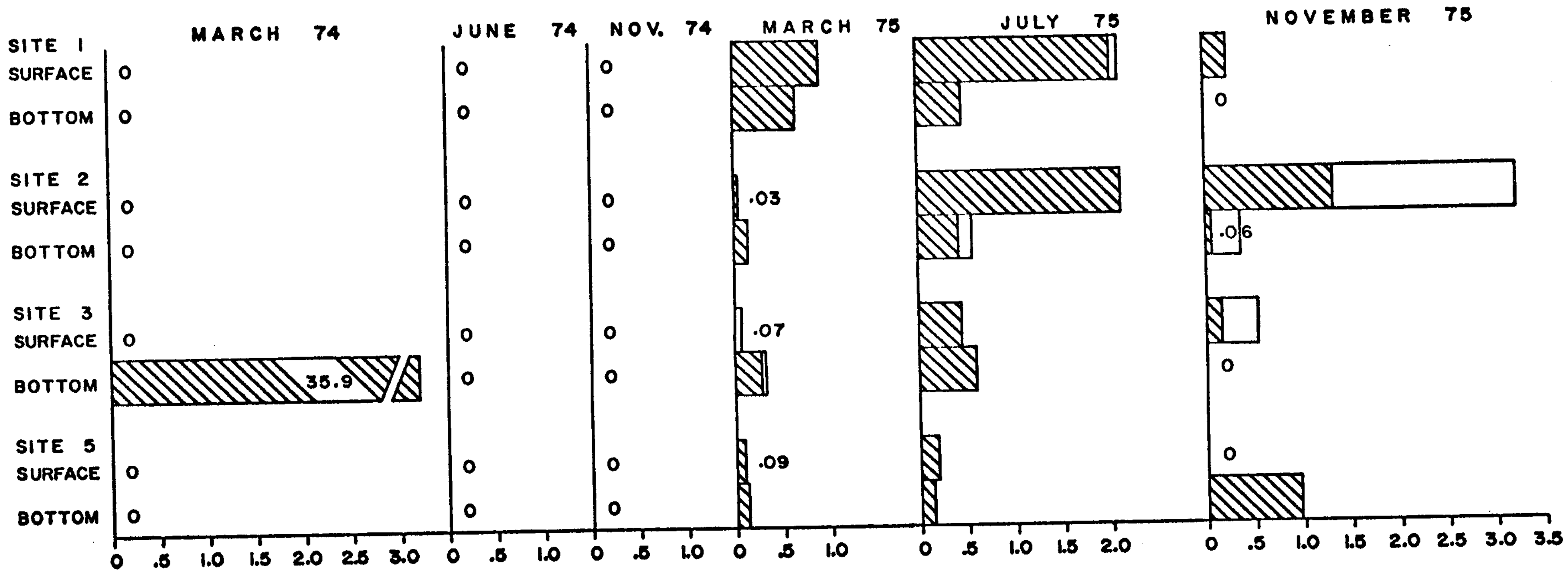

Figure 7. Bar graph of chromium concentrations in surface and bottom waters at lower reservoir sites in μg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

Lead

Lead values are relatively low at the lake sites (Table 16) and range in mean concentrations from <1 to 3 μg/l. However, certain tributary sites were approximately twice the lake values. These sites were the Colorado River at Grand Junction (7 μg/l), the San Juan River at Mexican Hat (9 μg/l), the Gunnison River near Grand Junction (8 μg/l), and the Dolores River near Gateway (8 μg/l). All of the upper range concentrations were below the 50 μg/l standard.

Angino et al. (1974) report higher dissolved lead values for Kansas rivers than we found for the tributaries to Lake Powell. Their lowest mean concentration was 20 μg/l which far exceeds our highest mean of 3 μg/l. Our highest range value was 10 μg/l which would fall within the lower portion of the range of concentrations reported for the Kansas rivers.

For bottom water samples (Table 17) the mean concentrations for lead were 1 to 9 μg/l which was closer to the range for tributary sites, 5 to 9 μg/l, than to the range in surface waters.

Lead in the particulate phase exceeded its concentration in the dissolved phase in 88 percent of the tributary water samples. Similar seasonal behavior between tributary sites was present (Figure 8). The pattern at most sites was one of lower concentrations in March 1974, higher in June 1974, no consistent high or low values between sites in November 1974, lower in March 1975, higher in July 1975, and then lower in November 1975. The San Juan River was a notable exception to this pattern.

Similarly, at Sites 6-9 and the Dirty Devil, the particulate

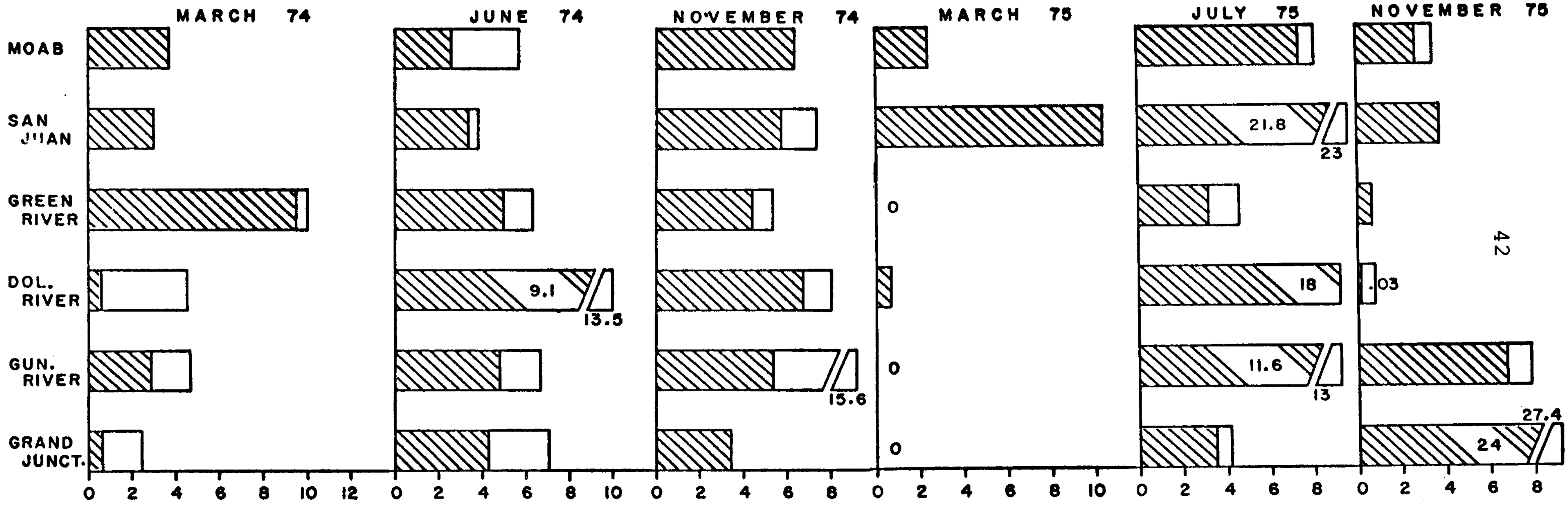

Figure 8. Bar graph of lead concentrations in surface waters at tributary sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

phase was dominant (72 percent). However, no consistent seasonal pattern of concentrations existed between sites. This was true for both bottom and surface water samples (Figure 9).

At the lower reservoir Sites 1-5 the particulate phase was predominant over the dissolved in only 37 percent of the samples. A strong seasonal pattern between surface water sites existed. The general pattern of concentrations was higher, lower, lower, lower, higher, and then lower in concentration. Bottom samples displayed a similar pattern (Figure 10).

Zinc

Mean zinc concentrations at the reservoir sites ranged from 8 to 17 μg/l. This was considerably lower than at the tributary sites where the mean concentrations ranged from 31 to 320 μg/l in surface waters (Table 16).

Zinc mean concentrations in bottom waters ranged from 12 to 17 μg/l which is closer to the range for surface waters, 8 to 17 μg/l, than for the tributary sites, 31 to 320 μg/l (Table 17). The standard of 500 μg/l was exceeded at the Green River Site where concentrations ranged up to 1,971 μg/l. However, if the waters are used for irrigation, then they are below the irrigation water plant tolerance level of 5000 μg/l (FWPCA, 1968).

In comparison of dissolved concentrations in the tributaries to Kansas rivers (Angino et al., 1974) we find that our highest mean dissolved concentration was 30 μg/l and the lowest mean concentration reported for the Kansas rivers was 82 μg/l. Our highest range value was 140 μg/l which would fall approximately in the middle of the ranges for the Kansas rivers.

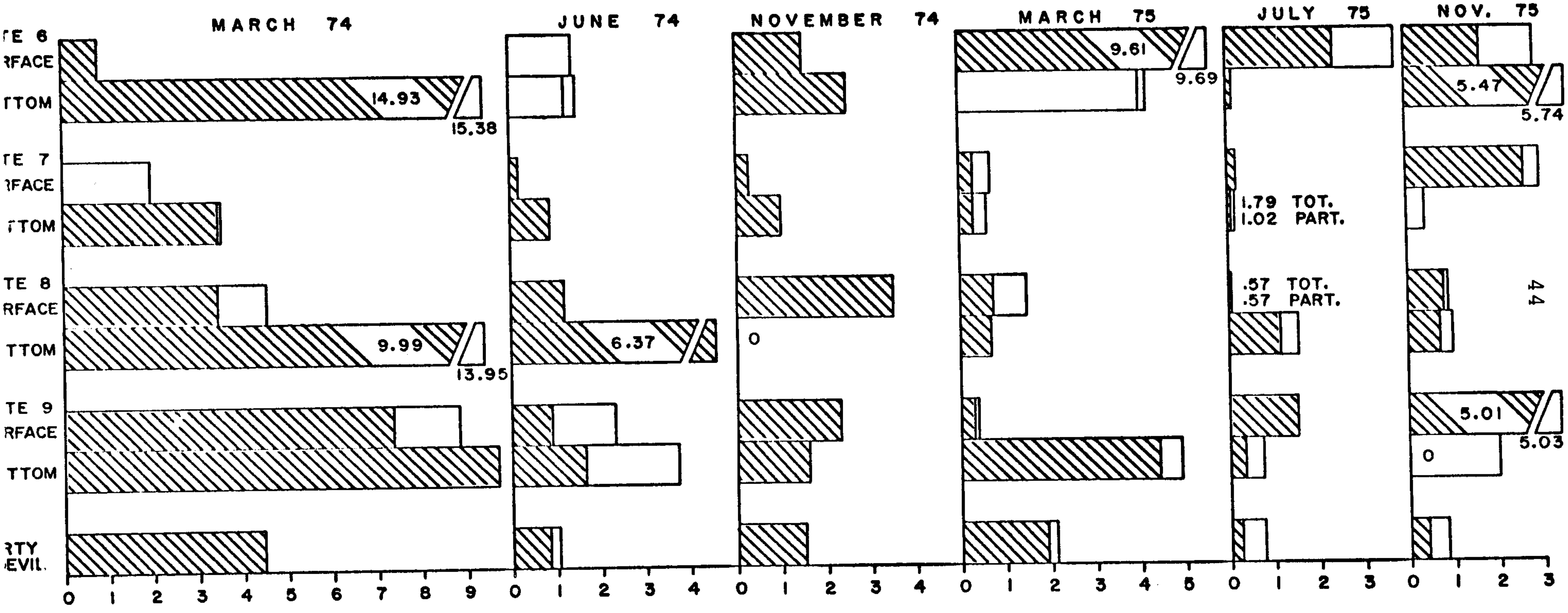

Figure 9. Bar graph of lead concentrations in surface and bottom waters at upper reservoir sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

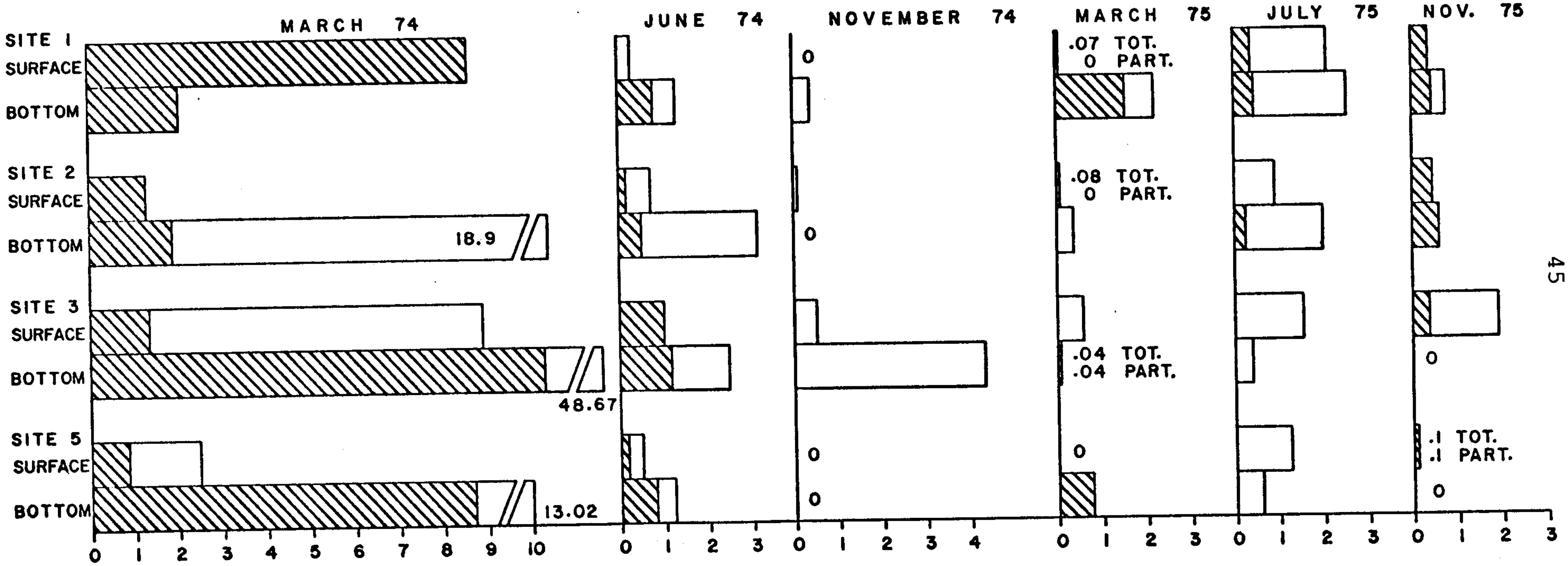

Figure 10. Bar graph of lead concentrations in surface and bottom waters at lower reservoir sites in µg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

In 71 percent of the cases, the particulate phase was greater in concentration than the dissolved phase at tributary sites. Similar seasonal trends between sites were not evident (Figure 11).

At the upper reservoir Sites 6-9 and the Dirty Devil (Figure 12) 43 percent of the samples had higher concentrations in the particulate phase. A general seasonal pattern existed between sites. Concentrations were initially higher, then lower, lower, higher, higher, and then no pattern between sites in November 1975. The bottom sample seasonal pattern was similar to the surface samples.

The particulate phase was greater than the dissolved phase in 28 percent of the samples at Sites 1-5 (Figure 13). The seasonal trends of concentrations between sites was higher, lower, higher, higher, lower, and lower. The pattern was not similar to the trends at upper reservoir sites. The bottom samples were similar in trend except in November 1975.

Calcium and Magnesium

Calcium and magnesium mean surface water concentrations ranged from 54 to 62 mg/l for calcium and from 19 to 23 mg/l for magnesium. The range of concentrations at tributary sites was 65 to 99 and 17 to 40 mg/l respectively for calcium and magnesium. Tributary sites were generally higher than lake sites (Table 16).

Calcium and magnesium mean concentrations in bottom waters ranged from 61 to 76 and 23 to 28 mg/l respectively. These ranges were more like the tributary values than the surface water values (Table 17).

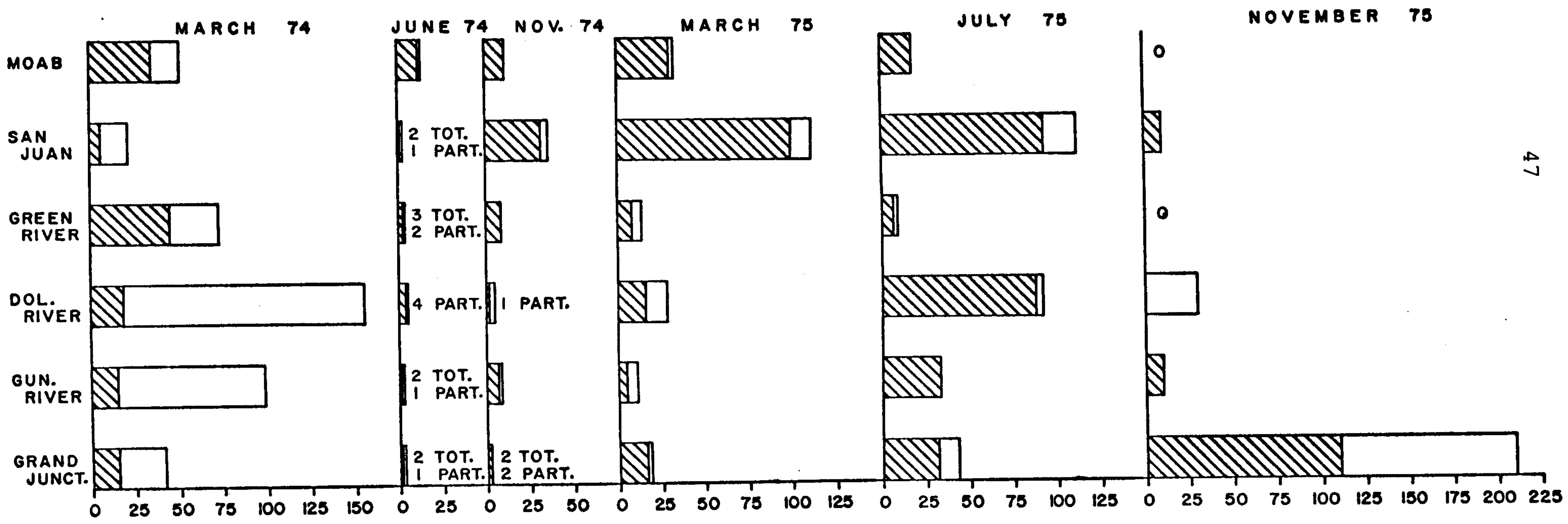

Figure 11. Bar graph of zinc concentrations in surface waters at tributary sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

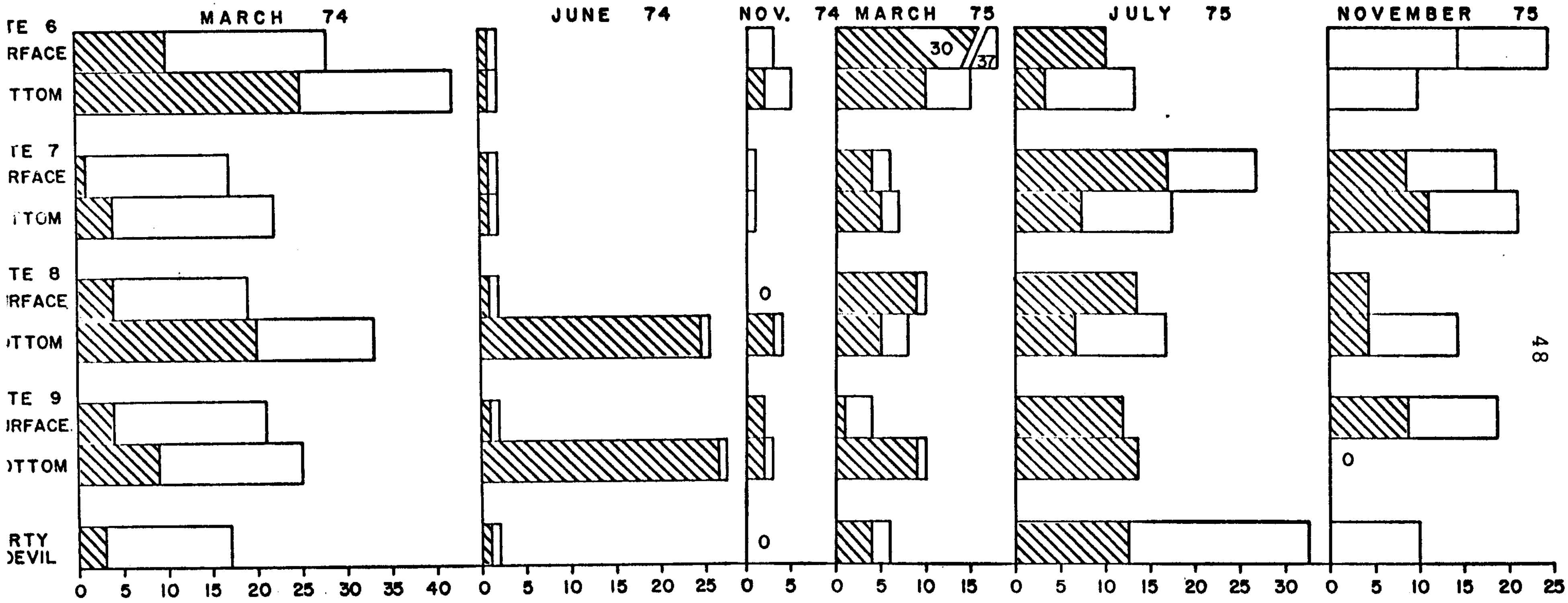

Figure 12. Bar graph of zinc concentrations in surface and bottom waters at upper reservoir sites in μg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

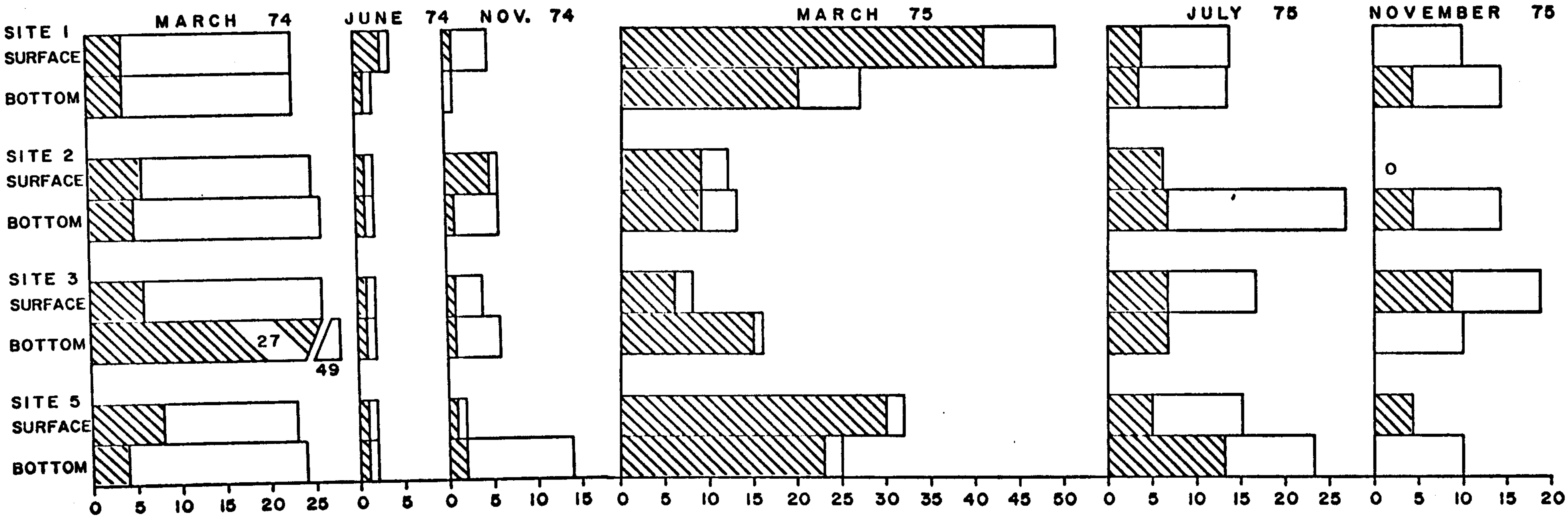

Figure 13. Bar graph of zinc concentrations in surface and bottom waters at lower reservoir sites in µg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

Iron

Mean concentrations of iron were quite uniform at the lake sites and did not exceed 0.06 mg/l in surface waters. At Site 9 the mean concentration was 0.2 mg/l. Tributary sites were considerably higher and ranged in mean concentration from 2 to 7 mg/l (Table 16). Angino et al. (1974) report a range in mean dissolved iron of 0.100 to 0.457 mg/l. The range of mean concentrations for the tributaries to Lake Powell was 0.131 - 8.451 mg/l. The highest value for the Kansas rivers was 1.750 mg/l and the highest value for the Lake Powell tributaries was 3.060 mg/l. In general, the two regions of the country are similar in regard to dissolved iron levels. The concentrations of iron in bottom waters were much higher than in surface waters and ranged in mean concentration from 33 to 2,941 mg/l. Concentrations ranged as high as 15,022 mg/l (Table 17).

At the tributary sites (Figure 14) all samples displayed a higher concentration of the element in the particulate phase. The seasonal pattern of changing concentrations for most sites was higher, lower, higher, no pattern (March 1975), higher, and then lower.

For Sites 6-9 and the Dirty Devil, the particulate phase was also dominant (Figure 15). The seasonal pattern of changing concentrations did not show very similar trends between sites.

The particulate phase was also dominant at Sites 1-5 in 89 percent of the samples (Figure 16). No consistent seasonal trends in concentration levels existed between sites.

Copper

Mean concentrations of copper display a pattern of lower

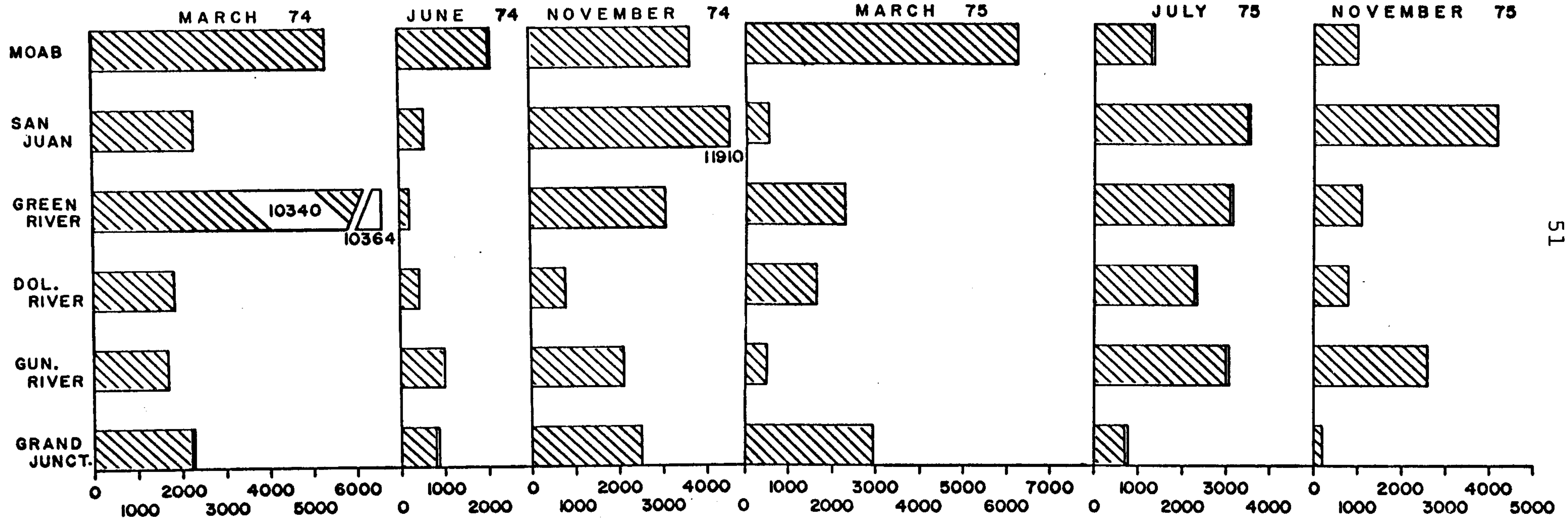

Figure 14. Bar graph of iron concentrations in surface waters at tributary sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

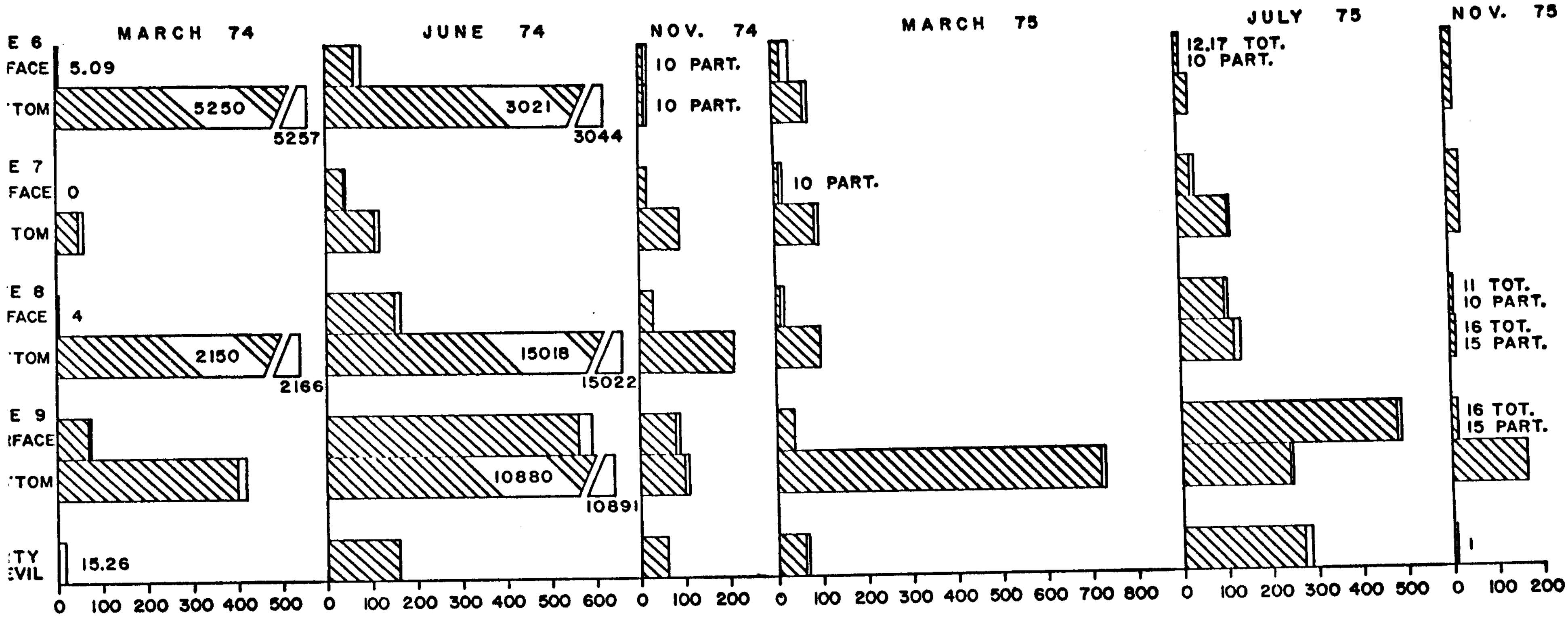

Figure 15. Bar graph of iron concentrations in surface and bottom waters at upper reservoir sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

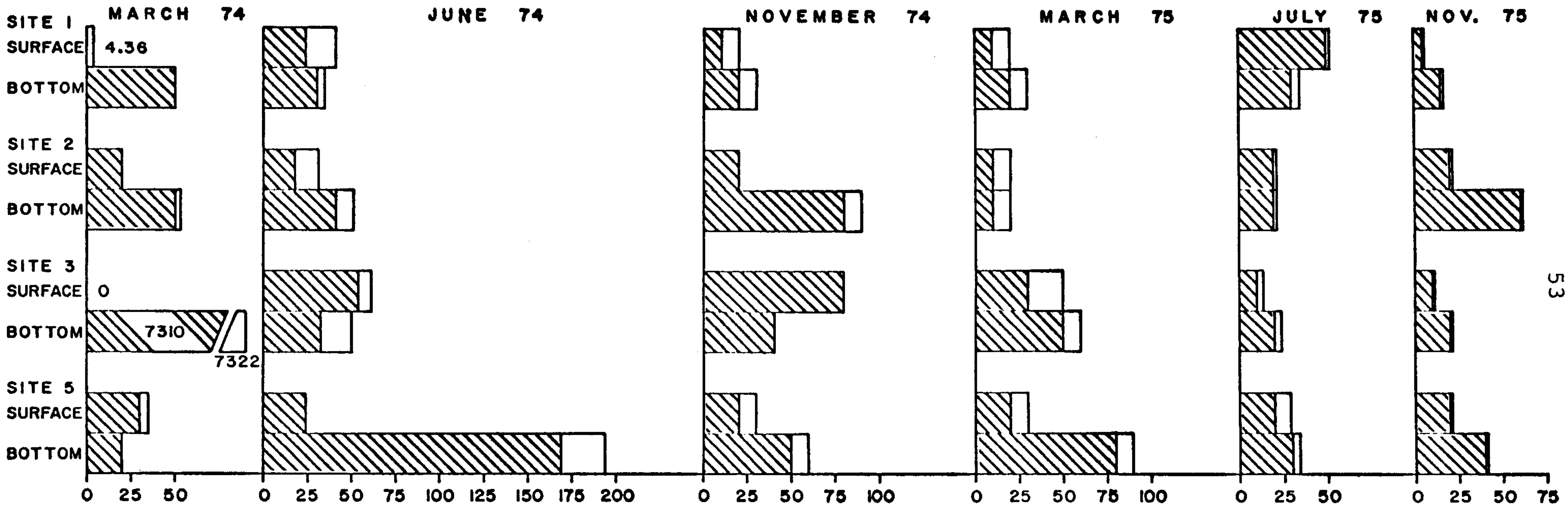

Figure 16. Bar graph of iron concentrations in surface and bottom waters at lower reservoir sites in µg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

concentrations in the reservoir and higher concentrations at the tributary sites. Reservoir concentrations ranged from 0.8 to 3 μg/l and ranged from 14 to 30 μg/l at the tributary sites (Table 16).

Copper mean concentrations in bottom waters ranged from 3 to 9 μg/l and from 0.8 to 3 μg/l in surface waters. Concentrations in bottom waters were generally intermediate between levels in surface waters and at tributary sites (Table 17). All concentrations were below the threshold level. Dissolved copper concentrations had a range in mean concentrations of 8 to 12 μg/l. The range of mean concentrations for Kansas rivers was 16 to 44 μg/l (Angino et al., 1974). Our values were at the lower range of the concentrations reported for Kansas rivers.

At the tributary sites (Figure 17) 60 percent of the samples had higher concentrations in the particulate phase. Total concentrations at each site displayed a similar pattern of increasing and decreasing concentration in most instances. The pattern at the surface was higher in March 1974, lower, lower, lower, higher, and lower in November 1975.

The particulate phase was higher than the dissolved phase in 63 percent of the samples collected at Sites 6-9 and the Dirty Devil (Figure 18). A seasonal pattern did exist at three of four sites and the pattern was higher, lower, lower, higher, lower, and then higher in concentrations. This pattern was not similar to the seasonal trend at the tributary sites.

At the lower reservoir Sites 1-5 (Figure 19) concentrations in the particulate phase were greater than in the dissolved phase in 64 percent of the samples. The general seasonal pattern of increasing and decreasing concentrations was higher, lower,

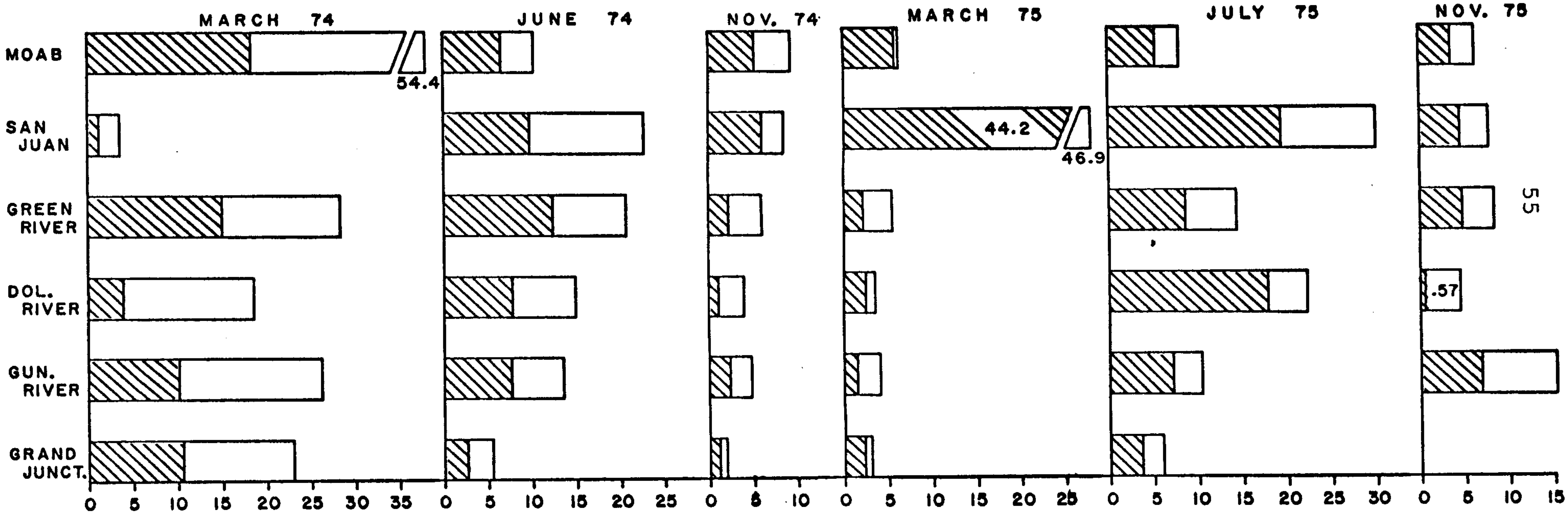

Figure 17. Bar graph of copper concentrations in surface waters at tributary sites in µg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

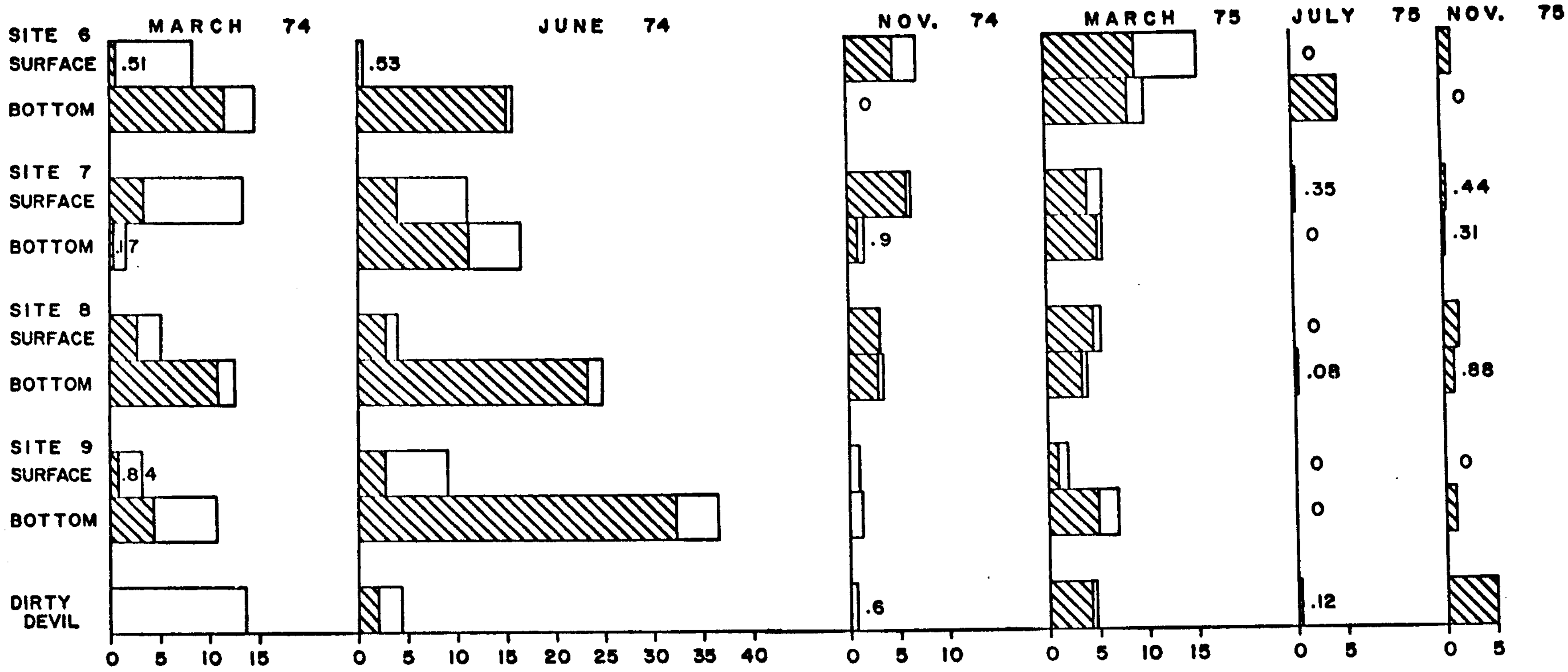

Figure 18. Bar graph of copper concentrations in surface and bottom waters at upper reservoir sites in μg/l. The shaded portion of a bar represents the particulate fraction of the total concentration.

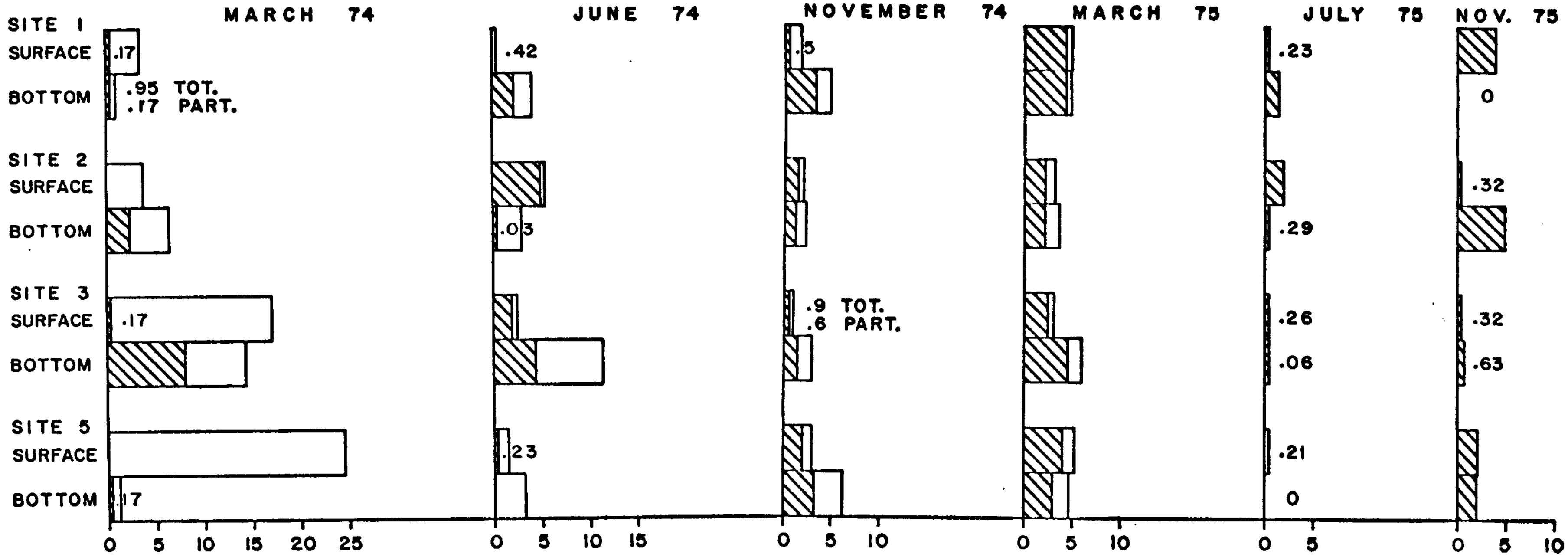

Figure 19. Bar graph of copper concentrations in surface and bottom waters at lower reservoir sites in μg/l. The shaded portion of each bar represents the particulate fraction of the total concentration.

no pattern between sites (November 1974), higher, lower, and then higher. This pattern was not similar to the trend of changing concentrations found in the tributary sites. No seasonal trend exists in the bottom samples. The conclusion that copper is more prevalent in the particulate phase is consistent with the findings for various rivers investigated by M. J. Stiff (1971).

Arsenic

Mean concentrations of arsenic were uniform throughout all of the surface water sites sampled and ranged from 0.7 to 10 μg/l. Tributary sites were not higher than lake sites (Table 16).

In bottom waters, mean concentrations for arsenic ranged from 0.5 to 8 μg/l and were similar to the range of 0.7 to 10 μg/l for both reservoir and tributary sites (Table 17).

Concentrations in the particulate phase were greater than in the dissolved phase in 41 percent of the tributary samples (Table 18). At the upper reservoir sites (Tables 19 and 20) the particulate phase was greater than the dissolved phase in 41 percent of the samples and in only 25 percent of the samples at the lower reservoir sites (Tables 21 and 22). All arsenic concentrations were below the 50 μg/l standard.

Selenium

Selenium values were also uniform and do not differ greatly between lake and tributary sites. Average concentrations ranged from 0.9 to 16 μg/l (Table 16). Mean concentrations in bottom waters ranged from 0.5 to 7 μg/l (Table 17).

Table 18. Concentration of arsenic in surface waters at the tributary sites. The ratio represents dissolved/total concentration

	Colorado River at Moab	San Juan River at Mex. Hat	Green River	Dolores River	Colorado River at Gr. Junc.	Gunnison River
March, 1975	2.21/2.21	1.15/4.36	2.35/2.35	1.22/8.75	0/0.48	0.65/1.18
July, 1975	0.15/14.55	2.39/2.39	0.15/0.15	3.20/3.35	2.22/3.44	2.44/4.33
November, 1975	0.68/3.57	0/--	0.87/0.87	0/0	0/0.75	0/5.00

Table 19. Concentration of arsenic in surface waters at the upper reservoir sites. The ratio represents dissolved/total concentration

	Site 6	Site 7	Site 8	Site 9	Dirty Devil
March, 1975	0/0.94	1.63/3.85	0/2.27	0/1.16	0/15.40
July, 1975	0/8.13	4.63/5.67	5.19/5.46	0/0.22	0/6.87
November, 1975	0.41/0.68	0/2.20	0/0	0.82/1.30	9.06/9.06

Table 20. Concentration of arsenic in bottom waters at the upper reservoir sites. The ratio represents dissolved/total concentration

	Site 6	Site 7	Site 8	Site 9
March, 1975	0.25/4.20	1.26/1.36	1.24/2.94	2.95/5.74
July, 1975	0.46/0.46	1.66/2.38	15.28/19.92	0.67/0.67
November, 1975	0/0	0/0	1.98/1.98	0.39/0.39

Table 21. Concentration of arsenic in surface waters at the lower reservoir sites. The ratio represents dissolved/total concentration

	Site 1	Site 2	Site 3	Site 5
March, 1975	0.79/0.79	0.86/0.86	0.08/12.19	0/0
July, 1975	3.86/4.34	2.16/2.16	0/5.17	7.62/7.62
November, 1975	0/0	0/0	10.66/0	3.57/4.55

Table 22. Concentration of arsenic in bottom waters at the lower reservoir sites. The ratio represents dissolved/total concentration

	Site 1	Site 2	Site 3	Site 5
March, 1975	0.77/0.77	0/0	0/0	0.20/3.60
July, 1975	4.26/4.26	1.10/1.72	2.30/2.30	3.44/3.44
November, 1975	3.64/3.64	0.43/4.95	0.70/3.82	4.32/4.32

Concentrations in the particulate phase were greater than in the dissolved phase for 33 percent of the samples at the tributary sites (Table 23), in 27 percent of samples for the upper reservoir (Tables 24 and 25), in 42 percent of the samples for the lower reservoir (Tables 26 and 27).

Kharkar et al. (1968) report average levels for soluble selenium in µg/l of 0.114 (Mississippi River), 0.325 (Susquehanna River), 0.122 (Klamath River), and 0.177 (Brazos River). These concentrations are much lower than most of the levels found in the tributary waters to Lake Powell (Table 23). Although Kharkar notes a relatively narrow range of concentrations between rivers which they have investigated, inclusion of our tributary data would modify their conclusion.

Some selenium water concentrations did exceed the 10 µg/l drinking water standard at Lake Powell Sites 5, 9, and in the Dirty Devil. At times, the standard was exceeded at the Green River Site and at two other tributary sites 9 µg/l was measured. All forms of selenium are considered to be toxic above 10 µg/l to animals (Lambert, 1972). If the waters are used for irrigation, the concentrations are below the 500 µg/l selenium tolerance level for plants (FWPCA, 1968).

SUMMARY OF CONCENTRATIONS OF ELEMENTS ON A VOLUME BASIS IN WATERS

1. Cadmium concentrations were generally higher for tributary sites than for Lake Powell.

2. All cadmium concentrations were below the potable water standard of 10 µg/l.

3. The range of cadmium concentrations in bottom waters was

Table 23. Selenium concentrations in tributary waters. The ratio represents dissolved/total concentration

	Colorado River at Moab	San Juan River at Mex. Hat	Green River	Dolores River	Colorado River at Gr. Junc.	Gunnison River
March, 1975	2.59/2.59	2.22/8.96	1.88/1.88	5.92/6.49	0.18/0.48	0.32/5.63
July, 1975	4.28/5.79	7.14/7.14	1.07/1.07	1.25/1.25	2.36/2.36	0/8.90
November, 1975	1.24/2.51	0/0	0.83/14.35	4.09/4.09	1.24/1.24	1.05/1.10

Table 24. Selenium concentrations at upper reservoir surface waters. The ratio represents dissolved/total concentration

	Site 6	Site 7	Site 8	Site 9	Dirty Devil
March, 1975	0.75/0.75	1.82/1.82	0.56/0.56	2.83/4.11	7.58/7.58
July, 1975	0.09/0.09	0.20/0.20	1.55/1.55	0/0	2.84/2.84
November, 1975	0/4.02	2.98/2.98	0/0.48	12.69/12.69	1.04/4.75

Table 25. Selenium concentrations at upper reservoir bottom waters. The ratio represents dissolved/total concentration

	Site 6	Site 7	Site 8	Site 9	Dirty Devil
March, 1975	3.09/3.80	2.59/4.12	0/1.20	7.20/7.20	7.58/7.58
July, 1975	3.12/6.10	3.58/3.58	1.87/1.87	0/0	2.84/2.84
November, 1975	0/3.30	0/11.80	0/0.85	0/0	1.04/4.75

Table 26. Selenium concentrations in lower reservoir surface waters. The ratio represents dissolved/total concentration

	Site 1	Site 2	Site 3	Site 5
March, 1975	3.59/3.59	1.91/2.06	1.72/2.64	1.11/8.65
July, 1975	1.68/1.68	1.48/1.48	0/0	4.53/4.53
November, 1975	8.28/8.28	3.47/3.47	0/7.02	6.63/35.90

Table 27. Selenium concentrations in lower reservoir bottom waters. The ratio represents dissolved/total concentration

	Site 1	Site 2	Site 3	Site 5
March, 1975	0.73/0.73	3.03/7.49	0/0.08	2.27/2.27
July, 1975	0/0	4.91/4.91	0/2.11	6.91/6.91
November, 1975	0/0.87	0.96/3.05	0/1.69	0/11.44

more similar to the range in surface waters than the range for tributary sites.

4. Cadmium concentration in the dissolved phase exceeds its concentration in the particulate phase.

5. The seasonal pattern of cadmium concentrations between sites in the lower reservoir did not correspond to the pattern at upper reservoir sites. A seasonal pattern was not found between tributary sites.

6. Chromium concentrations were higher for tributary sites than for reservoir sites.

7. All chromium concentrations were below the standard of 50 μg/l.

8. The range of mean concentrations in bottom waters of the upper reservoir was more similar to tributary water concentrations than to bottom water concentrations in the lower reservoir.

9. Chromium concentrations were higher in the particulate phase than in the dissolved phase.

10. Chromium concentrations vary seasonally at each site as well as between sites at the same date. There were no consistent seasonal patterns between sites.

11. Dissolved chromium concentrations reported for Kansas rivers are higher than those reported in this investigation.

12. Particulate chromium concentrations are lower than levels reported for some eastern rivers.

13. Lead concentrations at tributary sites are higher than at reservoir sites.

14. All lead concentrations were below the 50 µg/l standard.

15. The range of reservoir mean concentration for lead in bottom waters was more like the concentration at tributary sites than at reservoir surface water sites.

16. Lead concentration in the particulate phase exceeded its concentration in the dissolved phase at the tributaries and upper reservoir sites, but not at the lower reservoir sites.

17. Lead displayed no consistent seasonal patterns among sites and was quite variable in concentration between dates at any one site of the tributaries and upper reservoir locations. A strong seasonal pattern at surface water sites in the lower reservoir did exist.

18. Dissolved lead concentrations were lower than those reported for Kansas rivers.

19. Total zinc concentrations within the reservoir were lower than in tributary waters.

20. The zinc standard was exceeded at the Green River Site.

21. Dissolved zinc concentrations were generally at the lower range of concentrations reported for Kansas rivers.

22. Zinc in the particulate phase exceeded its concentration in the dissolved phase in tributary waters. However, with Lake Powell the dissolved phase exceeded the particulate

phase.

23. No similar seasonal zinc pattern between sites existed at tributary sites but did exist within the reservoir. However, the between-site seasonal pattern in the upper reservoir differed from the lower reservoir pattern.

24. Iron concentrations in bottom waters of Lake Powell were higher than in surface waters. Tributary concentrations were also high.

25. Dissolved iron concentrations in tributary waters were similar to concentrations reported for Kansas rivers.

26. Iron in the particulate phase exceeded the element's concentration in the dissolved phase at tributary sites and at reservoir sites.

27. There was a between-site seasonal pattern only at the tributary sites.

28. Total copper concentrations were higher at tributary sites than at reservoir sites.

29. Reservoir bottom waters had concentrations of total copper which were intermediate between levels found in surface waters of the reservoir and at tributary sites.

30. Dissolved copper concentrations at the tributary sites were lower than those reported for Kansas rivers.

31. Copper concentrations in the particulate phase were greater than in the dissolved phase.

32. Some between-site seasonal patterns were found.

33. All copper concentrations were below the drinking water standard.

34. Arsenic in the dissolved phase exceeded its concentration in the particulate phase.

35. All arsenic concentrations were below the drinking water standard.

36. Selenium in the dissolved phase exceeded its concentration in the particulate phase.

37. Some selenium concentrations exceeded the drinking water standard of 10 μg/l.

38. Dissolved selenium concentrations in eastern rivers are lower than those found in the tributaries to Lake Powell.

INPUTS FROM THE NAVAJO POWER PLANT AND WATER STANDARDS

Although the major problem presented by western coal-fired power plants is visibility, there is also the question of whether or not deposition on water supplies in the region represents a threat to water quality. At the south end of Lake Powell is the Navajo Power Plant and we can judge that for various elements, there will be no significant increase in these elements within Lake Powell as the result of fallout from the power plant. Selenium deposition would however increase by a very small amount those selenium levels which are already above the water standard. The amount added by the power plant is insignificant in regard to the ambient water levels for selenium (Table 28).

CONCENTRATIONS OF CATIONS IN BOTTOM SEDIMENTS

Introduction

Sediment concentrations of elements can serve as baseline information regarding concentration of cations in a system, and may provide information regarding cultural impacts. Since some heavy metal elements may be released from the sediments, there is the potential for biomagnification through food chains.

Results and Discussion

Calcium

Calcium levels in sediments obtained from Lake Powell and the tributary sites do indicate some differences (Figure 20). The tributary sites were generally lower than in the reservoir. The exception was the San Juan River at Mexican Hat, which was significantly different in terms of mean annual concentration ($p = 0.05$) from the other tributary sites and all reservoir sites.

Site 2 in Wahweap Bay, near the marina, was significantly higher in mean annual concentration ($p = 0.05$) than any other reservoir site except the Dirty Devil Arm of upper Lake Powell. Reservoir sites ranged in mean annual concentration from 10,425 ppm (Site 1) to 70,895 ppm (Site 2). Tributary concentrations on a mean annual basis ranged from 4,897 ppm (San Juan River at Mexican Hat) to 25,898 ppm (Dolores River). The mean and range of all tributary and Lake Powell sediments are given in Table 29.

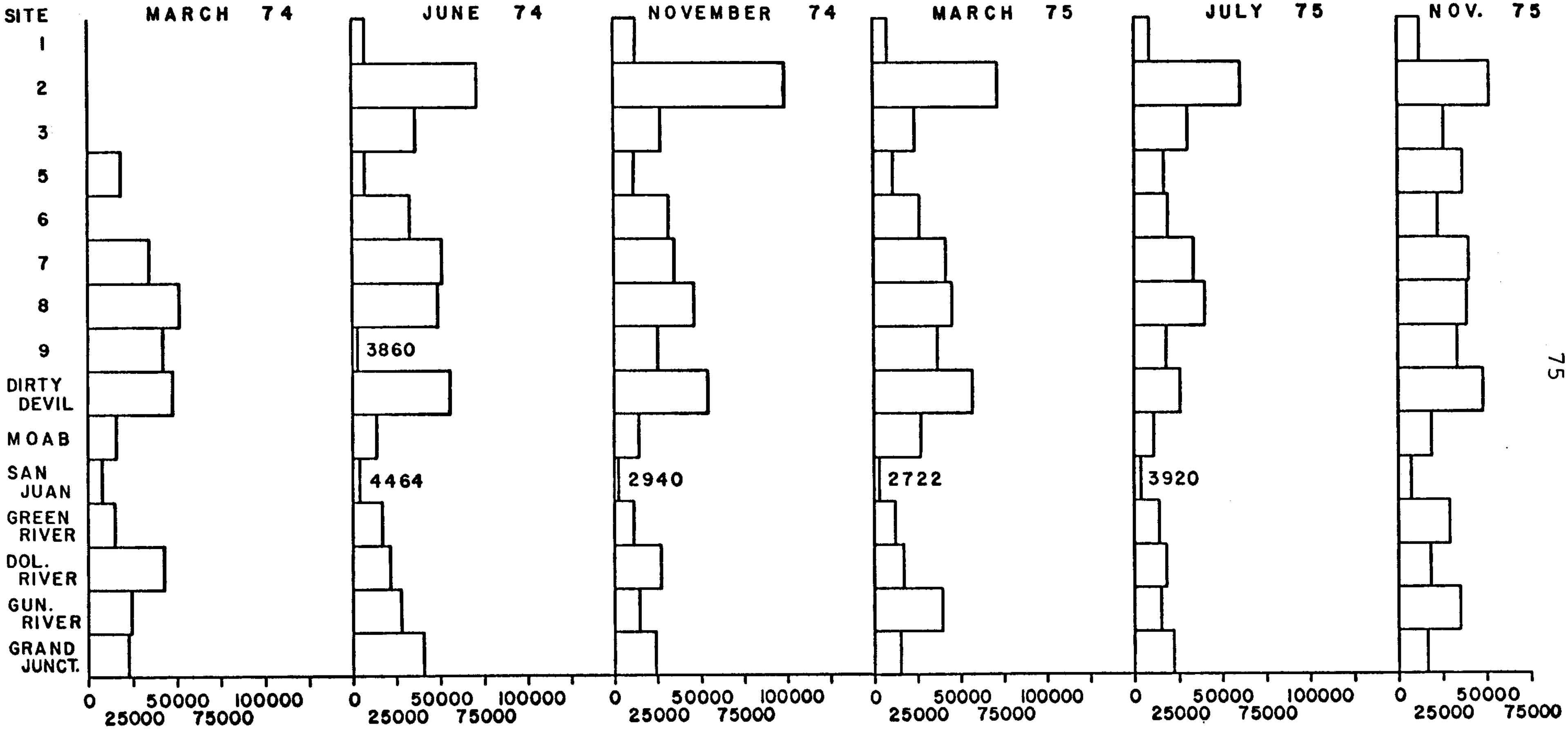

Figure 20. Mean concentration of calcium in ppm of bottom sediments.

Table 28. Expected concentrations in Lake Powell surface waters as the result of deposition from the Navajo Power Plant. Calculations for column B from Walther, 1976

	A	B	C	D
Element	Present Concentration in Lake (ppb)	Concentration Added to Lake (ppb)	Upper Limit Total (P+B) (ppb)	Potable Water Standard (ppb)
Fe_2O_3	0-60	0.4	60.4	0.3
Cr	0-4	0.0005-0.01	4.01	(Dissolved) 50
Cd	0-5	$6\text{-}33 \times 10^{-6}$	≥ 5	10
Hg	0.01	0.000-0.0003	≥ 0.01	0.1-17
Se	0-36	0.002-0.005	36.005	10
As	0-15	10^{-6}-0.0008	15.0008	50
Zn	0-49	0.0005-0.015	49.015	500
Pb	0-10	0.0011-0.0038	10.0038	50
Cu	0-9	0.0009-0.0028	9.0028	1000

Table 29. Concentrations of metallic cations in sediments obtained from the tributaries and Lake Powell. Units are ppm

	Tributaries		Lake Powell	
	Mean	Range	Mean	Range
Calcium	18,695	2,722-42,907	35,141	7,839-98,330
Magnesium	4,135	<D.L.-11,128	11,580	<D.L.-27,177
Cadmium	0.19	<D.L.-0.63	0.32	<D.L.-1.54
Chromium	9.44	<D.L.-56	31.44	2.70-135
Lead	12.24	2.43-25	17.58	1.87-56.67
Copper	9.62	1.19-33.83	19.62	1.02-50.06
Zinc	46.01	<D.L.-145	67.47	9.36-151
Iron	8,096	156-22,872	16,878	1,698-32,651
Arsenic	3.26	<D.L.-7.38	3.75 D	<D.L.-39.77
Selenium	0.28	<D.L.-1.52	0.85	<D.L.-3.502

Magnesium

Mean concentrations of magnesium ranged from 2,480 ppm at Site 1 to 17,185 ppm in the Dirty Devil. The range of mean concentrations in bottom sediments at the tributary sites was 3,377 ppm to 6,099 ppm (Figure 21). Means and ranges are given in Table 29.

Cadmium

Sediment concentrations of cadmium within the reservoir and tributaries are shown in the space-time diagram (Figure 22).

The tributary sites, Colorado River at Moab, Dolores River, Colorado River at Grand Junction, and the Gunnison River, were lower in concentration than the upper reservoir Sites 6, 7, 8, 9, and the Dirty Devil on a mean annual basis. The difference is not significant. However, the two tributary sites, San Juan River at Mexican Hat and the Green River, are significantly lower than the Dolores River, the Colorado River, reservoir Sites 7, 8, 9, and the Dirty Devil in upper Lake Powell. Site 2 (Wahweap Marina) is significantly higher than Site 1 above the marina.

The lowest mean annual concentration was 0.054 ppm (Site 1) and the highest mean annual concentration was 0.500 ppm (Site 7) for the reservoir sites. The range of mean annual concentrations at tributary sites was 0.031 ppm at the San Juan River to 0.327 ppm at the Dolores River. The highest individual concentration was 1.543 ppm at Site 5 (March 1975). The mean and range of all Lake Powell and tributary sediments are given in Table 29.

In order to make some decision as to whether the values obtained in this investigation are relatively high or low, we

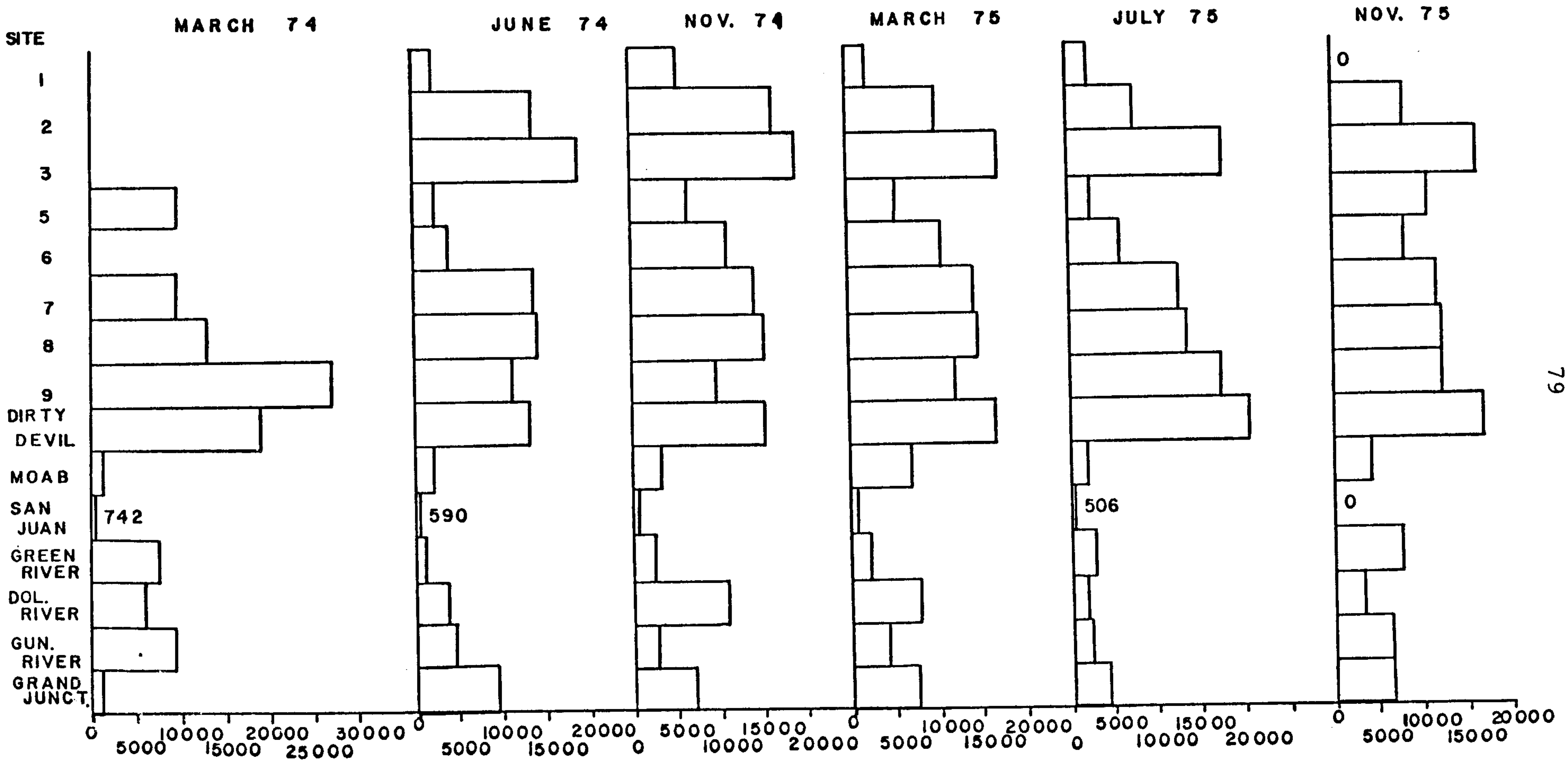

Figure 21. Mean concentrations of magnesium in ppm of bottom sediments.

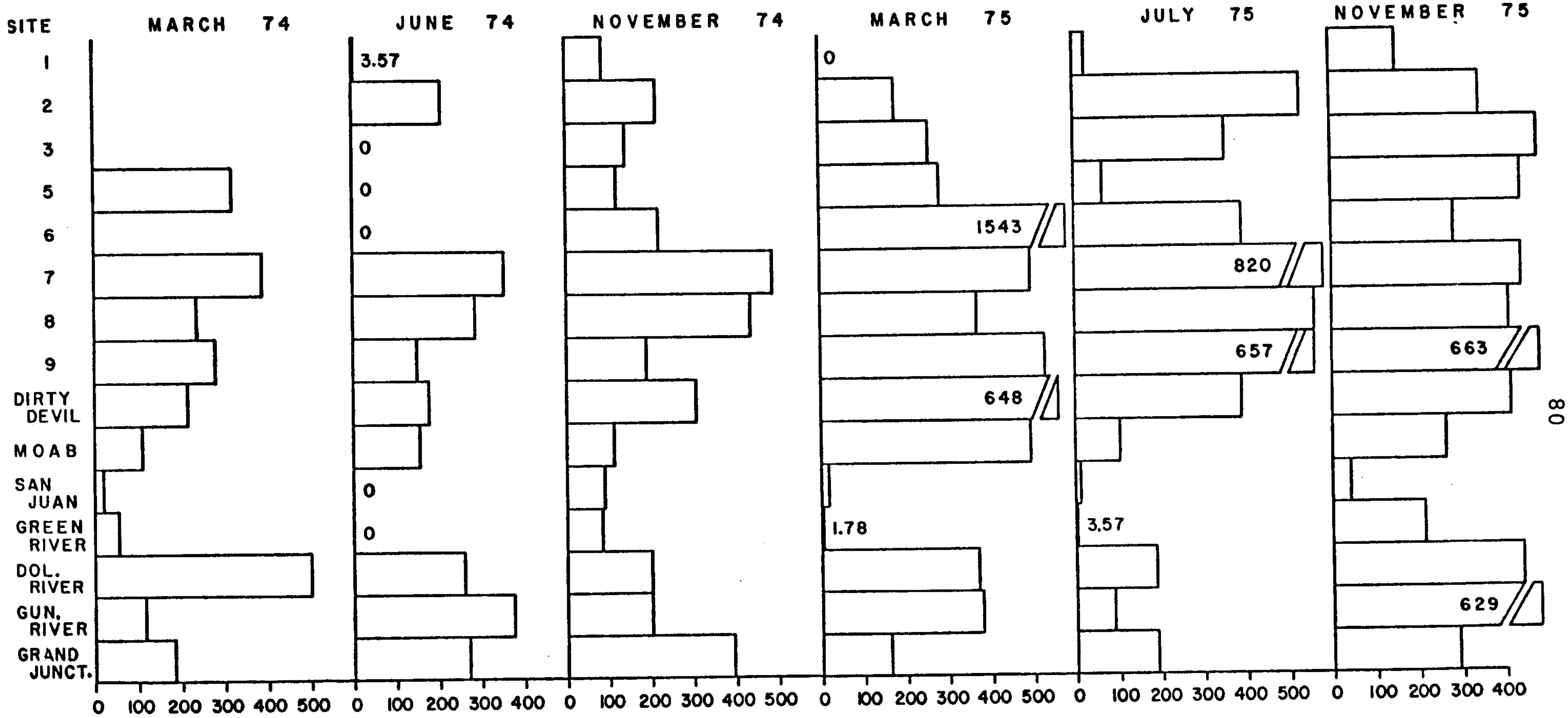

Figure 22. Mean concentrations of cadmium in ppb of bottom sediments.

compared our data to data obtained for Southern California (Chen et al., 1976) and a few midwestern and eastern lakes. Cadmium levels ranged from trace amounts to 1.54 ppm. The Southern California values ranged from 0.66 to 2.2 ppm. Our values are comparable to this range.

An investigation of cadmium concentration in estuarine sediments of Corpus Christi Bay (Holmes et al., 1974) indicated that cadmium ranged from 0.1 to 1.9 ppm. The Lake Powell sediment concentrations are close to this range. Values obtained for harbor sediments at Corpus Christi ranged from 2 to 130 ppm. Since industrial effluent enters the harbor, these higher levels probably reflect cultural impacts. On this basis then we conclude that the concentrations of cadmium in the sediments probably reflect background levels.

The range of cadmium concentrations in the top sediment layers of cores obtained from five Wisconsin lakes (Iskander et al., 1974) was 0.2 to 3.0 ppm. This range is comparable to the Lake Powell range but does exceed our upper range of 1.54. The Wisconsin lakes have been subjected to cultural impacts in the past. However, the highest Lake Powell sediment concentration of 1.54 ppm was obtained at the confluence of the San Juan Arm with the main channel and may reflect a peculiarity in sedimentation rather than a cultural influence.

Chromium

Examination of the space-time diagram (Figure 23) for chromium does indicate some definite patterns. The tributary sites, with the exception of the Dolores River, were generally lower in chromium concentration than the reservoir Sites 6, 7, 8, 9, and Dirty Devil. On the basis of the mean annual concentration and considering the 0.95 confidence intervals, five of

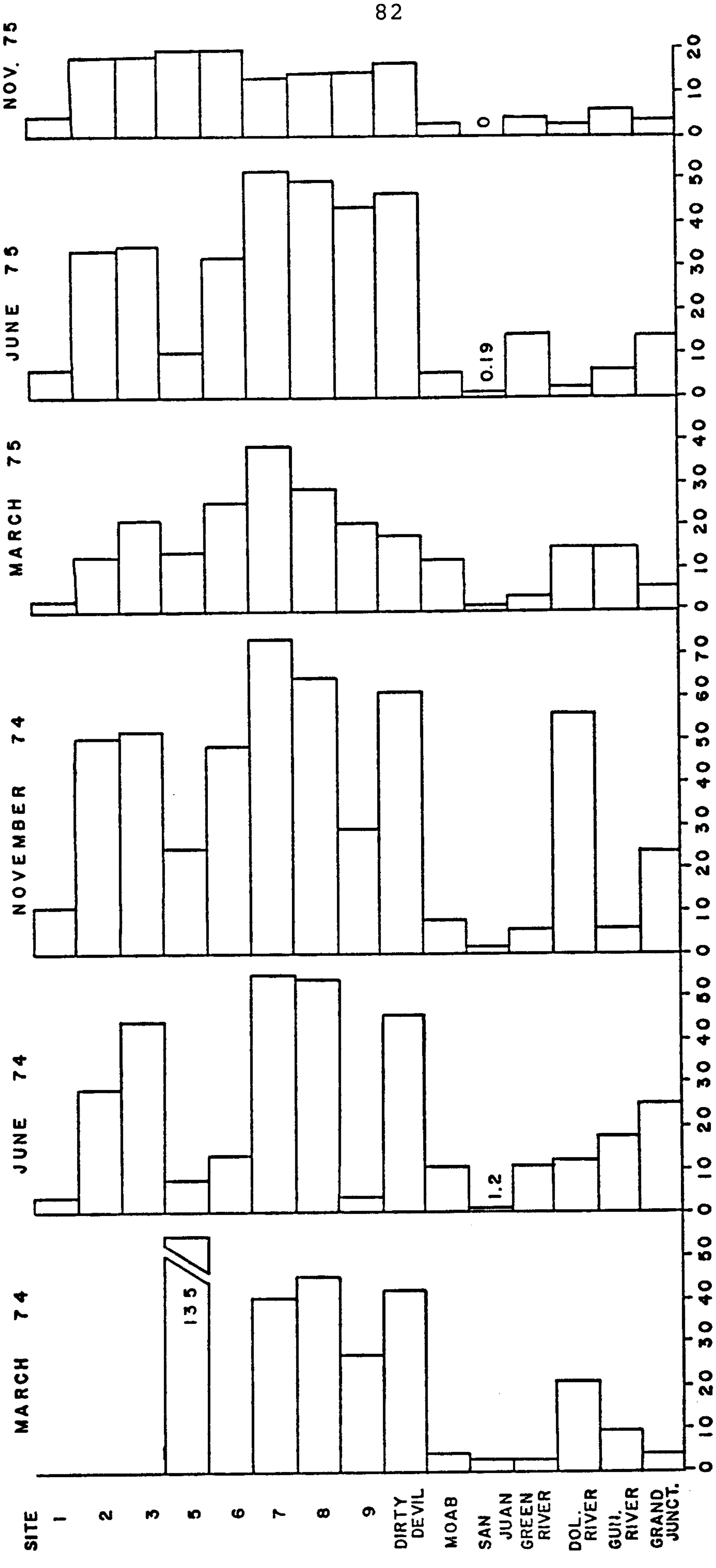

Figure 23. Mean concentrations of chromium in ppm of bottom sediments.

the six tributary sites had upper confidence limits which wer either below or just overlapped Sites 7, 8, and the Dirty Dev The San Juan River at Mexican Hat had a mean annual value of 1.30 ppm which was considerably below any other mean. The ne lowest mean annual concentration was 5.64 ppm at reservoir Site 1.

Sites 2 and 3 within the lower reservoir were usually hi in concentration than the other two lower reservoir location Sites 1 and 4.

The range of mean annual concentrations within the reser voir was 5.64 ppm (Site 1) and 46 ppm (Site 7), and the rang at the tributary sites was 1.30 ppm (San Juan River) and 18 (Dolores River).

The highest individual concentration within the reservo was 135 ppm at Site 5 in March 1974 while the highest indiv concentration at the tributaries was 56 ppm at the Dolores in November 1974. The means and ranges of all tributary an reservoir concentrations are given in Table 29.

Chromium measurements ranged from trace levels to 1.30 within the reservoir. The Southern California measurements (Chen et al., 1976) ranged from 67 to 178 ppm. Our levels very much below this and probably reflect natural backgrour concentrations.

Copper

Examination of Figure 24 reveals that sediment concent of copper are lower at the tributary sites than at the res sites. Levels of copper are very low at the San Juan Rive Green River Sites. Reservoir sites are uniformly high in

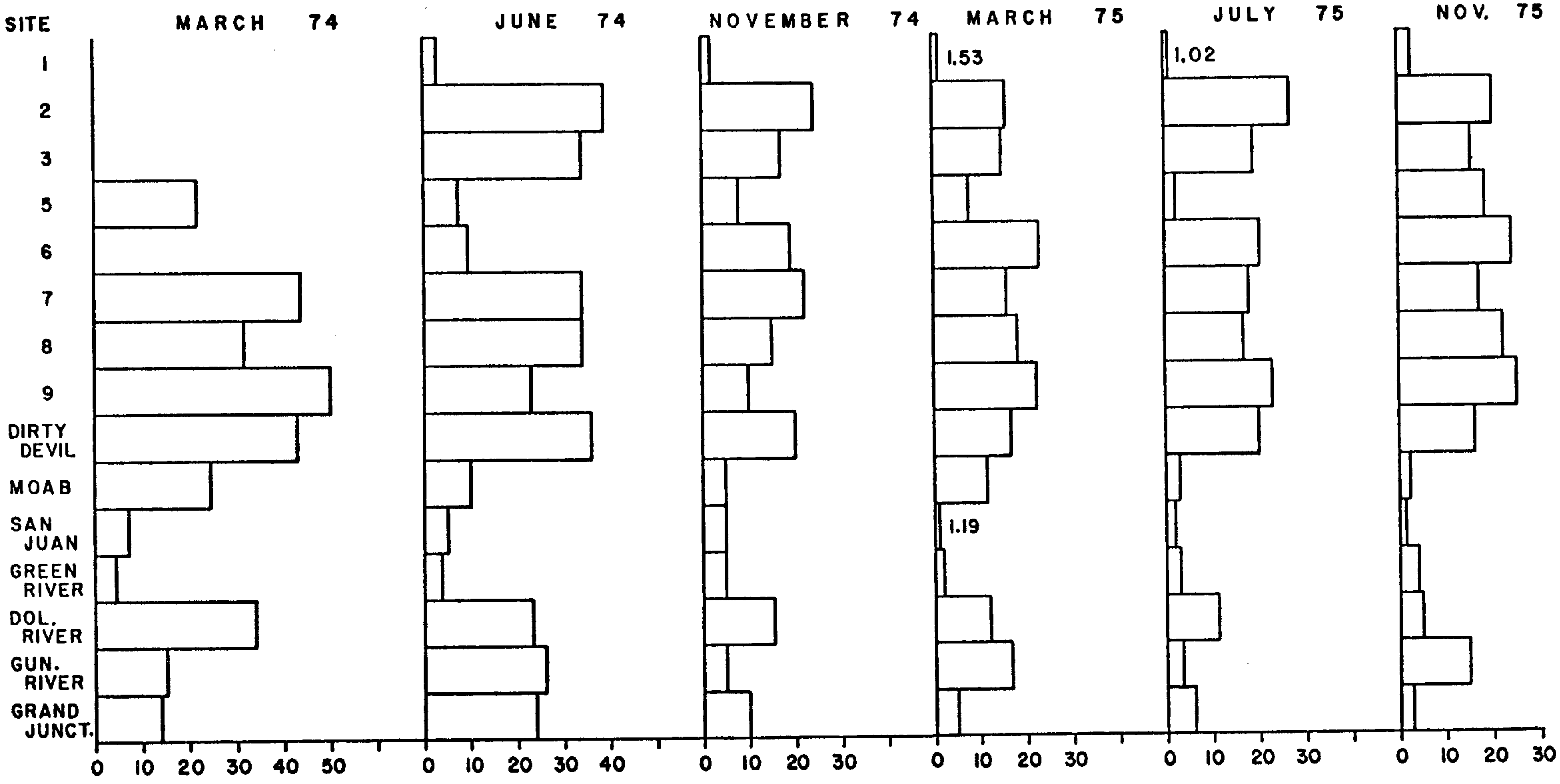

Figure 24. Mean concentrations of copper in ppm of bottom sediments.

concentration of copper, but Sites 1 and 5 are relatively low when compared to the other reservoir sites.

On the basis of comparing the mean annual concentrations, Site 1 is significantly lower than Sites 2 and 3. There is little difference between the levels of copper at the main channel Sites 3, 6, 7, 8, and 9.

In the reservoir, mean annual copper concentrations ranged from 3.84 ppm at Site 1 to 26 ppm at Site 9. At the tributary sites the range was 3.91 ppm (Green River) to 17 ppm (Dolores River).

The highest individual copper value within the reservoir was 50 ppm at Site 9 in March 1974 and the highest value at the tributary sites was 34 ppm at the Dolores River in March 1974. The means and ranges for all tributary and reservoir data are given in Table 29.

Our copper levels ranged from 1.02 to 50 ppm and the Southern California range was 35 to 568 ppm. Copper is apparently relatively low in bottom sediments of the Upper Colorado River Basin. Similarly, copper levels in the five Wisconsin lake sediments (Iskander et al., 1974) ranged from 24 to 30 ppm, which was comparable to our higher concentrations.

Zinc

Concentrations of zinc at the three tributary sites, Dolores River, Colorado River at Grand Junction, and the Gunnison River, were generally as high in zinc levels as the reservoir sites. However, Site 1 was consistently lower than these three tributary locations and the reservoir sites. Thus the tributary sites, Colorado River at Moab, San Juan River at Mexican Hat, and the Green River, were generally lower in concentration. On the basis of the annual means, Site 1 is significantly lower in concentration than any other reservoir site. Reservoir Sites 2-9 and the Dirty Devil are not significantly different on the basis of comparing annual means. However, Site 5 (Rainbow Marina) was generally lower (Figure 25).

The highest tributary concentration was 145 ppm at Grand Junction in June 1974 and the lowest value was below the detection limit at the Green River in July 1975. Mean annual concentrations for the tributaries ranged from 11 ppm (Green River) to 76 ppm (Colorado River at Grand Junction).

Within the reservoir, the highest concentration obtained was 151 ppm at Site 9 in March 1975 and lowest value was 9 ppm on two dates at Site 1. The range of annual means was 13 ppm at Site 1 to 96 ppm at Site 9. The means and ranges for all tributary and reservoir concentrations are given in Table 29.

The total zinc concentration of the Southern California sediments (Chen et al., 1976) ranged from 94 to 612 ppm. Our highest reservoir value is at the lower part of this range. Corpus Christi Bay sediment concentrations ranged from 6 to 235 ppm and in the harbor the range was 235 to 11,000 ppm (Holmes et al., 1974). Therefore, our zinc sediment levels probably do not reflect cultural influences.

Lead

The three tributary sites, Dolores River, Colorado River at Grand Junction, and the Gunnison River, had similar concentrations of lead as the reservoir sites, except for Site 1. Concentrations of lead at the San Juan River and Green River were lower than the other tributary sites and in considering

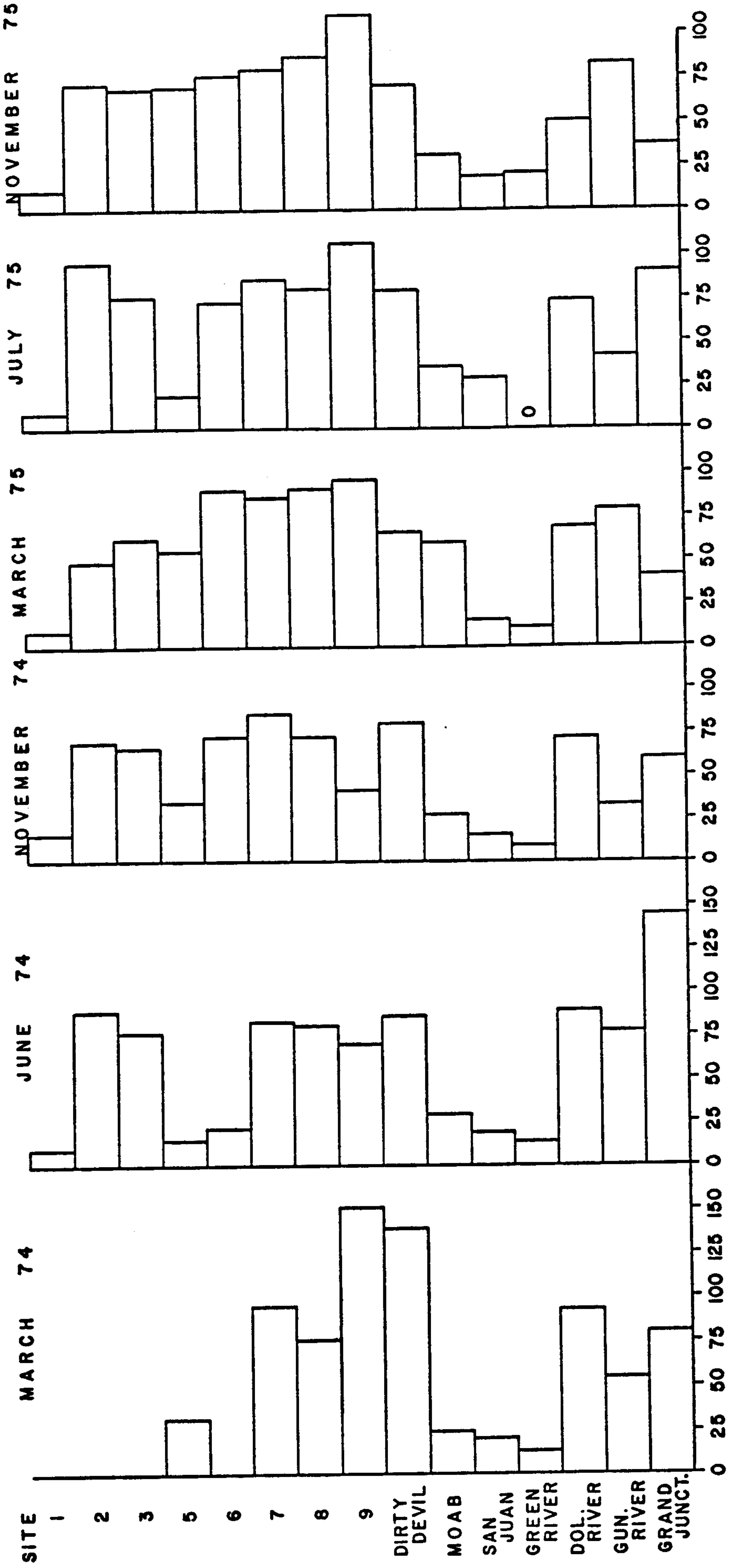

Figure 25. Mean concentrations of zinc in ppm of bottom sediments.

the annual means and confidence intervals, these two sites just overlap the upper confidence limits and indicate no significant difference from the Colorado River at Moab, but are different in that their upper limits just overlap the Gunnison River, but do not overlap the Dolores River and Grand Junction lower limits.

The reservoir sites are quite uniform except that Site 1 is very much lower in concentration (Figure 26). Highest lead concentration in the tributaries was 25 ppm at the Gunnison River in November 1975 and the lowest concentration was 2 ppm at the Green River in November 1974. In the reservoir, the highest concentration was at Site 5, 57 ppm, in November 1975 and the lowest was at Site 1, 2 ppm, in November 1974. The means and ranges of all tributary and reservoir sediments are given in Table 29.

The range of lead concentrations in the Southern California sediments was 32 to 332 ppm. Since the California values are for Los Angeles harbor, they may reflect cultural influences. Only 16 percent of our reservoirs were equal to or exceeded the 32 ppm lower limit of the California data.

Lead concentrations in the upper sediment horizons and of the five Wisconsin lakes (Iskander et al., 1974) ranged from 3 to 33 ppm. Comparable to the Lake Powell levels, these represent northern Wisconsin lakes, but in five southern lakes the range was 62 to 183 ppm. The authors tentatively attribute the high southern lake sediment concentrations to auto traffic and boating. Lead concentrations in the upper horizons of cores from Lake Washington and Lake Michigan were 400 and 200 ppm respectively (Crecelius and Piper, 1973). Certainly the Lake Powell higher concentrations do not reflect heavy inputs of lead from cultural sources.

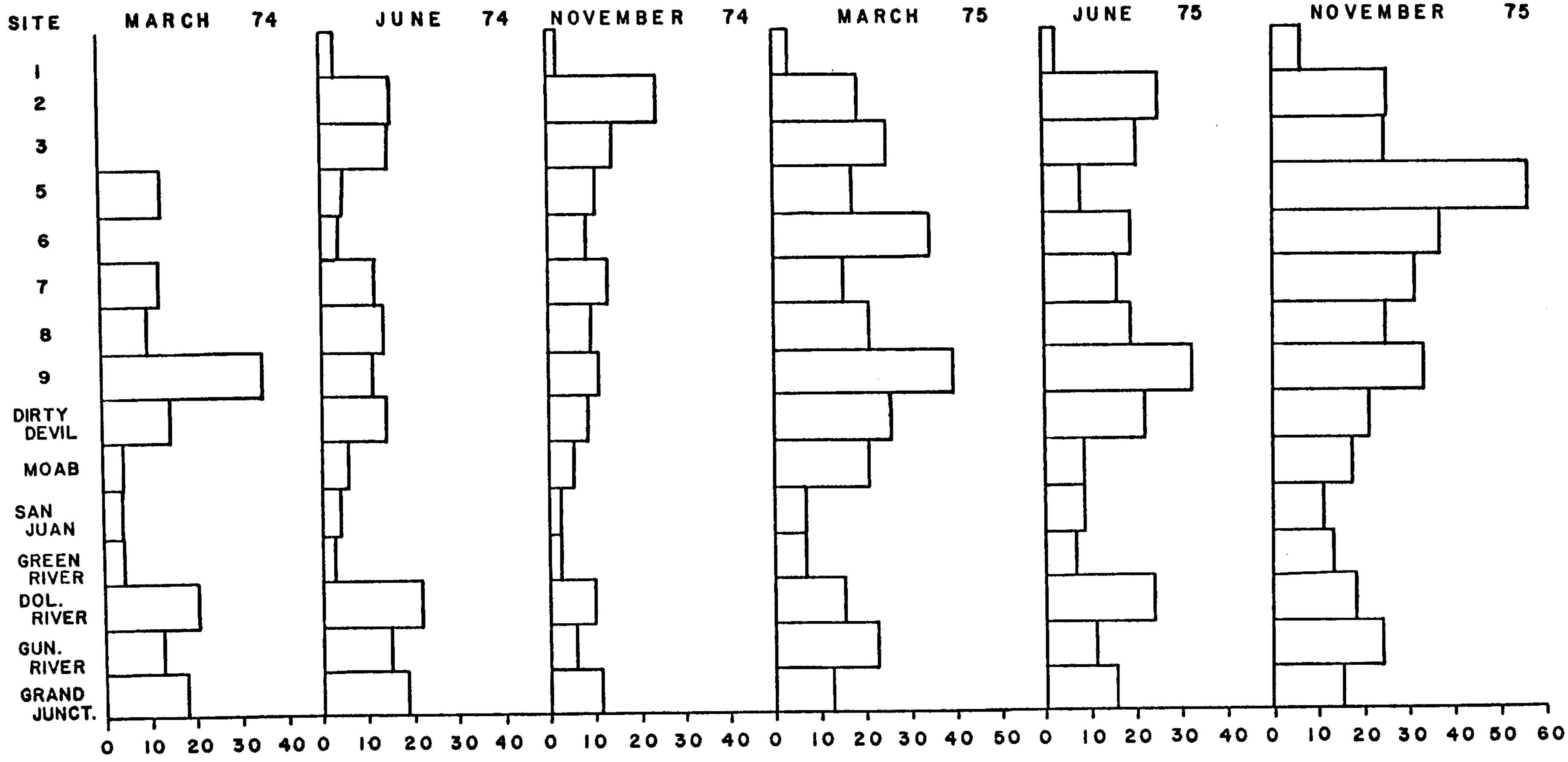

Figure 26. Mean concentrations of lead in ppm of bottom sediments.

Iron

Tributary concentrations of iron are generally lower than most reservoir sites with the exception of Sites 1, 2, and 5 (Figure 27). The lowest tributary mean annual concentration occurred at the San Juan. Within the upper reservoir, Sites 6-9, and the Dirty Devil, concentrations are uniform, but in the lower reservoir, Site 3 is higher.

At the tributary sites, the highest concentration was 16,640 ppm at the Dolores River in November 1974 and the lowest concentration of 191 ppm was also found at the Dolores River in November 1975.

Within the reservoir the highest concentration was at Site 9, 32,651 ppm, and the lowest level was 1,975 ppm at Site 5.

The range of annual means at the tributary sites was 3,486 ppm at the San Juan River to 11,341 ppm at the Dolores River. Within the reservoir, the range was 3,385 ppm (Site 1) to 23,452 ppm (Site 9).

Selenium and Arsenic

Selenium concentrations (Table 29) indicate that the highest concentration at the tributary sites was 1.523 ppm at the Gunnison River and below detectable limits at most sites at various times. The highest concentration within the reservoir was 3.502 ppm at Site 7 and below detectable limits at various sites. Tributary annual means ranged from zero to 0.559 ppm and within the reservoir from 1.392 ppm to 0.073 ppm.

Arsenic concentrations (Table 29) ranged from 7.381 ppm

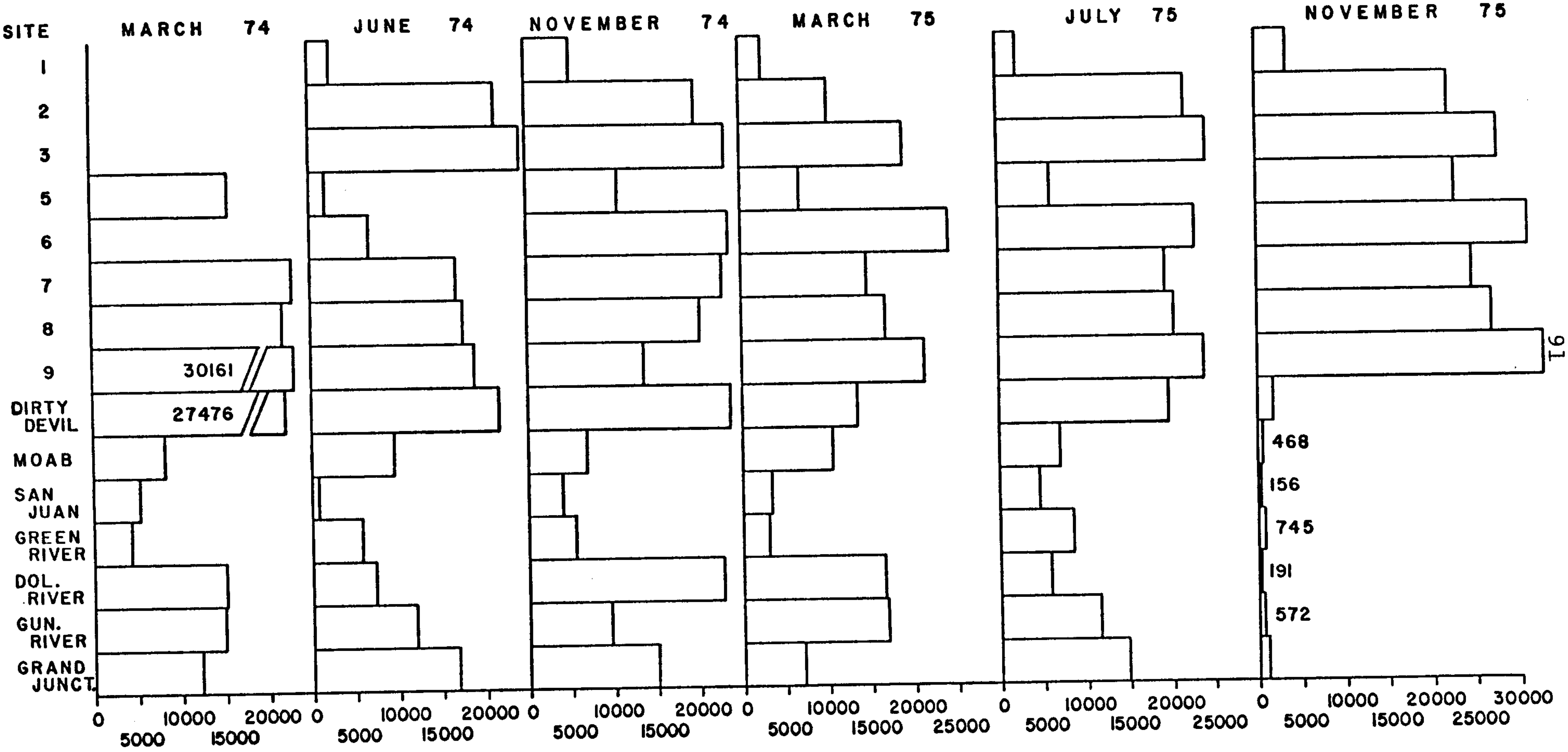

Figure 27. Mean concentration of iron in ppm of bottom sediments.

(Dolores River) to below detectable limits at the Colorado River at Grand Junction, at the tributary sites. The range of annual means at the tributary locations was 1.924 ppm to 5.724 ppm. Within the reservoir the highest value was 39.765 ppm (Site 2) and the lowest was below detectable limits. The range of annual means was 14.226 to 0.406 ppm.

SUMMARY OF CATIONS IN BOTTOM SEDIMENTS

1. Calcium and magnesium levels at tributary sites were generally lower than in reservoir sediments.

2. Concentrations of cadmium in sediments from the San Juan and the Green Rivers were significantly lower than at other tributary sites.

3. Cadmium concentrations at Site 1 (above Wahweap Marina) were significantly lower than at Site 2 (near the Wahweap Marina).

4. Cadmium concentrations within the reservoir probably do not reflect any cultural influences.

5. Most chromium concentrations in tributary sediments were lower than those collected within the reservoir.

6. Chromium concentrations at Sites 2 and 3 were usually higher than at other locations within the reservoir.

7. Chromium levels probably reflect background concentrations.

8. Copper concentrations in tributary sediments were lower than in reservoir sediments.

9. Site 1 concentrations are significantly lower than most other reservoir sites.

10. Copper concentrations probably reflect background levels.

11. Zinc concentrations in tributary sediments were comparable to levels in reservoir sediments.

12. Site 1 zinc concentrations were significantly lower than at other reservoir sites.

13. Zinc levels probably reflect background concentrations rather than cultural influences.

14. Tributary sediment concentrations of lead were either comparable to or lower than in the reservoir.

15. Site 1 was much lower in lead concentration than at other sites.

16. Lead concentrations do not represent heavy cultural inputs, but some concentrations were comparable to lead impacted southern Wisconsin lakes.

17. Iron concentrations in tributary sediments were generally lower than in the reservoir.

18. Generally, lower selenium values were found at the tributary sites than at reservoir sites. Arsenic was similar in pattern.

HEAVY METALS IN SEDIMENT CORES

Seasonality

Kirkland and Anderson (1969) reported a seasonality of pollen composition within lake varves which corresponded to the time sequence of mass pollen rains of the dominants of the flora. This led to the development of a submerged sediment trap to accumulate suspended fractions and amplify them in a collecting tube. The timing of the accumulation was accomplished by a pre-set mechanism which periodically inserted a marker of inert material. The accumulated material settling out of aquatic systems such as Lake Powell consists of both abiotic and biotic materials. The former includes allocthonous sand, silt, and clay; precipitated calcium carbonate; and various chemical elements attached to particulate material. The latter consist of pollen, spores, cysts, and zooplankton or phytoplankton. A preservative is added in the collecting tube to prevent activity of the microorganisms.

Two samplers were installed by Roger Anderson near the bottom of Wahweap Bay in January 1972 and retrieved in December 1972 and June 1973. Because of mutual interest, we provided cooperation in retrieval and in testing the heavy metals of the sediment core. By coincidence, the collecting period of October and November 1972 was one of exceptionally high rainfall, with several major storms. This followed the driest January-July period in 60 years. The proximity of a rainfall recording station at Wahweap allowed for good correlations of storms, run-off, and siltation rate.

Anderson (1975) reported the following correlations: The silt influx was closely correlated to rainfall pattern (1972), reflecting storms of more than 0.2 inches precipitation with a lag of only a few days. The absolute quantity of silt correlated to storm patterns better than the percentage of silt. The data from this site and from a sampler in the main channel above the dam reflected a sedimentation rate which was highest in the summer and early fall, during which seasons there were also high percentages of silt and calcium carbonate (Figure 28).

The organic matter fraction rose sharply in June-July, then tapered to "background" levels by November. The June rise in organic matter was coincident with the initial pulse of *Fragillaria*.

Calcium carbonate had a background level of 12-13 percent by weight but from July to October it was at a level of about 20 percent. This same period was identified by high concentrations of *Fragillaria* which had an initial pulse and a later one in September-October. Calcium carbonate was principally associated with intermediate particle sizes, 4 μ to 16 μ fractions. The relationships of calcium to silt and organic matter are shown in Figure 28.

Cadmium showed greater fluctuations than the above elements and apparently was in response to at least two different factors. The highest concentrations occurred during the months of coldest water temperature. However, secondary peaks occurred in July and October coincident with the pulses of *Fragillaria* concentrations (Figure 28). The July to November curves were also similar for cadmium and percentage organic matter (Figure 28).

The best relationship existed between the increases and decreases of absolute silt and the corresponding changes in concentrations of magnesium, iron, and zinc. Figure 28 indicates this relationship. Anderson suggested that the first element was from clays and weathered limestone, the latter two adsorbed

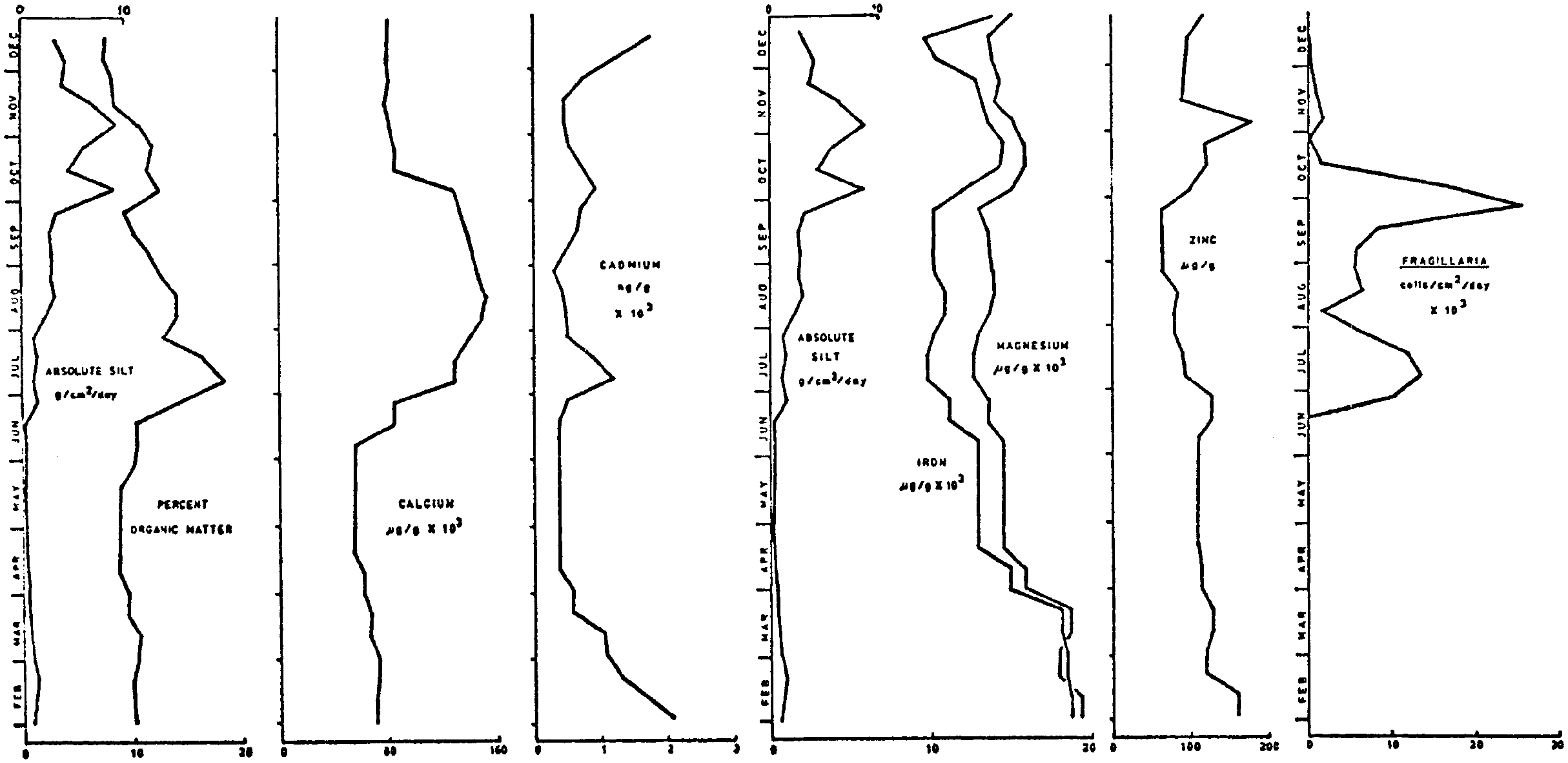

Figure 28. Seasonal amounts of silt; percentage organic matter; concentrations of calcium, cadmium, iron, magnesium, and zinc; and numbers of _Fragillaria_ from sediment collecting device, Wahweap Bay, 1972.

to the silt fraction.

For chromium and copper there was a gradual seasonal decline in both elements from January until September, then an increasing trend. No correlations were suggested.

The data for lead indicated a consistent level of 100 µg/g as background but there were two large pulses in April and June to 7,500 µg/g. An explanation for these anomalous results was not given. A reasonable assumption would be a correlation to boating activity and discharges into the reservoir from gasoline combustion and spillage at the marina. If that were the principal source, then lead may not correspond to the seasonal concentrations of other elements.

Halls Crossing Sediment Cores

As part of the Dartmouth College program in sedimentation of Lake Powell, two sediment cores were obtained for heavy metal analysis through the courtesy of Charles Drake and William Condit. Both cores were obtained from near mid-channel of the Colorado Riverbed between the mouth of Halls Creek and Halls Crossing Marina at river mile 119. The first sample of November 13, 1974 resulted from a depth of penetration of the sampler to 3 meters (m) and a recovered core of 268 centimeters (cm) length. It did not penetrate into the sand of the riverbed. The second sample of November 21, 1976 had a recovered length of 237 cm which, in spite of being shorter, reached coarse sand and gravel of the Colorado Riverbed. Both cores were frozen until the time of examination.

In the examination of previous cores from the Castle Butte area William Condit (personal communication) had been able to discern couplets of gray clay or silt (with or without organic matter) and a zone of pale brown clay. In that core representing 11 years of deposition in the reservoir there were 11 such couplets representing cyclical deposition and thus interpreted to be seasonal or varve in nature. The 1974 core did not reach the riverbed, and therefore is incomplete and has fewer couplets.

The 1974 sediment core was analyzed for several physical and biological characteristics by Roger Anderson, Geology Department, University of New Mexico. The silt percentages, color indices, and Bosmina concentrations are given in Figure 29. The silt is expressed as a percentage of particles 8-64 microns to the total dry weight. Indices of color contrast were obtained by dilution in water of a portion of the sample at 4 cm intervals and filtering; the filter papers were then dried and arranged along a scale of lightest gray to darkest red and given a corresponding number from 0 to the uppermost number sampled. The numbers of fragments of Bosmina, which was the only recognizable zooplankton left on the 200 mesh screen, were expressed as units per gram of sample. Other attributes determined but not shown were $CaCO_3$ and organic matter. Organic matter, such as plant fragments, had higher frequency during times of increased silt deposition and was more abundant in the lower 60 cm of the core.

Anderson's interpretation of the data of Figure 29 (personal communication) follows. The lower half of the core represents a period of adjustment from river to reservoir with several seasons of high sedimentation rates and local influences. The upper half of the core, representing seven or eight years of sedimentation, shows a repetitive cycle of events. There is an increase and peak of Bosmina during decreasing and low levels of silt frequency, followed by a silt pulse associated with a low color (gray) index, in turn followed by a high color (red) index and average silt frequency. A comparison of the core

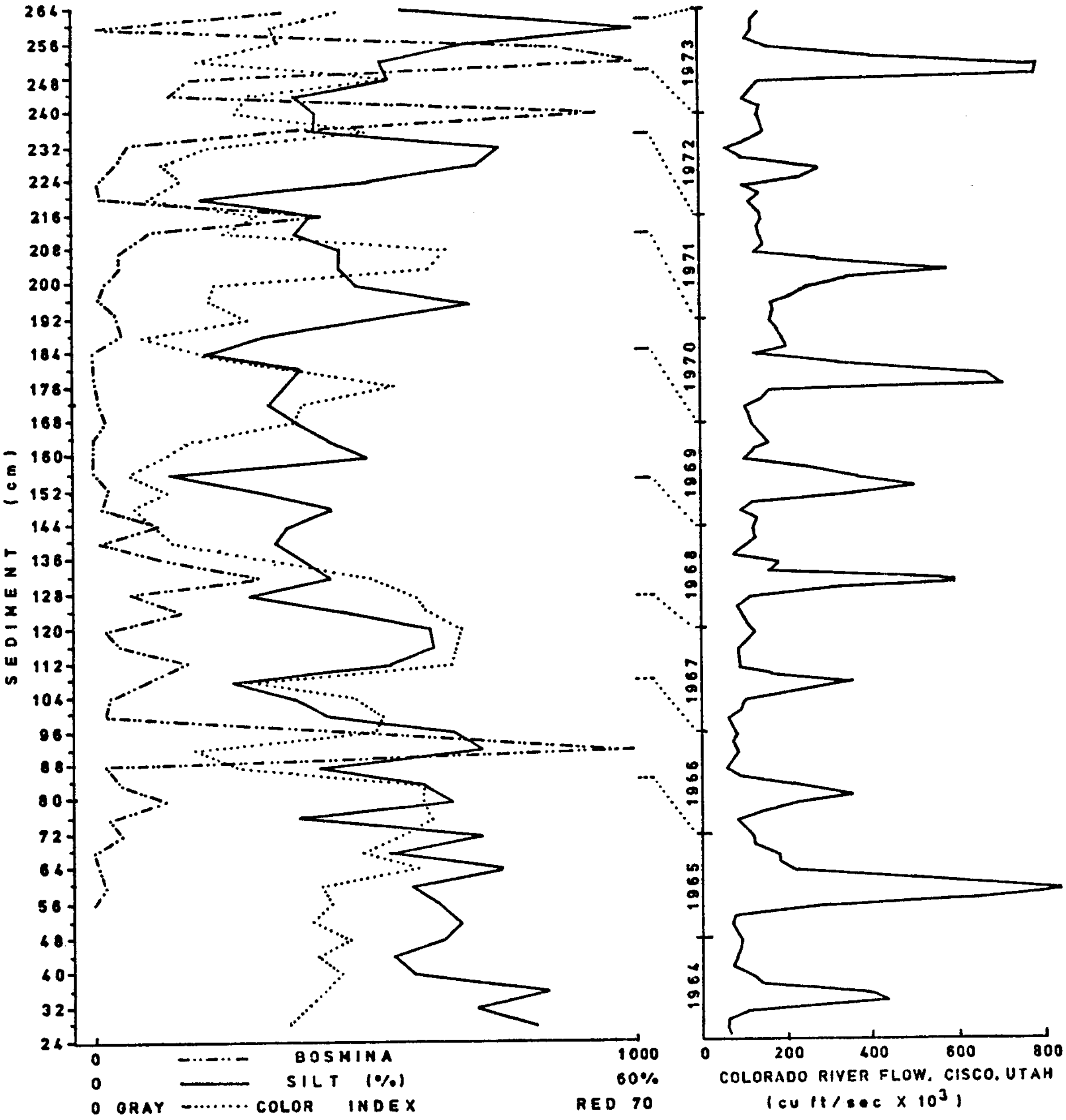

Figure 29. Curves for concentration of Bosmina, percentage silt, and color index (grey to red) from 1974 Halls Crossing sediment core as determined by Roger Anderson with tentative yearly markers and the flow of the mainstream of the Colorado River at Cisco, Utah for the corresponding time of sedimentation.

with material collected in an automated sampling device in North Wash at Hite, Utah during the 1975 season reveals the probable timing of depositional events in the cored material (Anderson, 1977). The Bosmina pulse in the automated collector occurred as a single sharp peak in May just prior to the late spring discharge and sediment increase in the Colorado River. In August, following the peak discharge period, the automated tube contained a sharply defined band of red sediment. Other tubes collected nearby in the main channel also contained red sediments at this time of the season. These observations indicate that the combined silt and high color (red) index peaks represent the late spring and summer period of high sedimentation rate. The following Bosmina peak represents a later slow period of sedimentation through the winter and early spring, with Bosmina being emplaced in mid to late spring. Hence, deposition in the upper part of the core is clearly a seasonal process and an attempt can be made to correlate the seasonal sediment pulses with the river discharge record.

Based on the above sequence, tentative yearly markers have been indicated for the upper part of the core in Figure 29. The flow of the mainstream of the Colorado River at Cisco, Utah has been included in Figure 29 as a comparison to the silt percentages. For the analysis of heavy metal concentration, increments were selected along the 1974 core at eight principal peaks of high frequency of silt and six points of low frequency of silt. These samples included the time period represented from 24 cm above the bottom of the core to the 260 cm level which was assumed to be deposited in early 1974. The uppermost few centimeters of the core were not intact enough to sample. High silt samples were taken at 24-28, 60-64, 88-92, 112-116, 156-160, 192-196, 228-232, and 256-260 cm; low silt samples were from 104-108, 124-128, 152-156, 180-184, 216-220, and 240-244 cm as indicated in the figures for heavy metal analyses.

The 1976 sediment core was not examined for silt content and Bosmina. The core was cut and examined for visual features. The lowermost part of the core (0-20 cm) consisted of coarse sand and gravel, representing the Colorado River channel. One-half the core was used for color index analysis, the second half was kept frozen for later analysis of heavy metals. Because of the correspondence of peaks of color indices and silt percentages in the 1974 core, seven peaks of the yellow-gray color (60-64, 88-92, 112-116, 172-174, 188-190, and 216-220 cm) and six alternating peaks of the red color (44-48, 100-104, 120-124, 152-156, 176-180, and 196-200 cm) were analyzed as indicated on the figures for heavy metal analyses of the 1976 core.

For the 1974 drill core the concentrations of calcium, iron, and magnesium; for chromium, copper, lead, and zinc; and for arsenic, cadmium, and selenium are given in Figure 30. In each case the corresponding curve for relative concentration of silt is given. Following the pattern previously discussed, low levels of silt might be expected to occur in mid-winter and high peaks in June-July. Elements such as calcium appear to be related to silt concentrations. Others, such as zinc, seem to be negatively related. Curves for arsenic and selenium fluctuate widely.

Analyses for the 1976 core are correlated to color index, with a high peak (red) frequently following the silt peak. Therefore, timewise the 1976 levels should be slightly later than the levels in the 1974 core. Concentrations for calcium, iron, and magnesium; for chromium, lead, and zinc; and for arsenic, cadmium, and selenium are given in Figure 31. For each, the corresponding curve for the color indices is given.

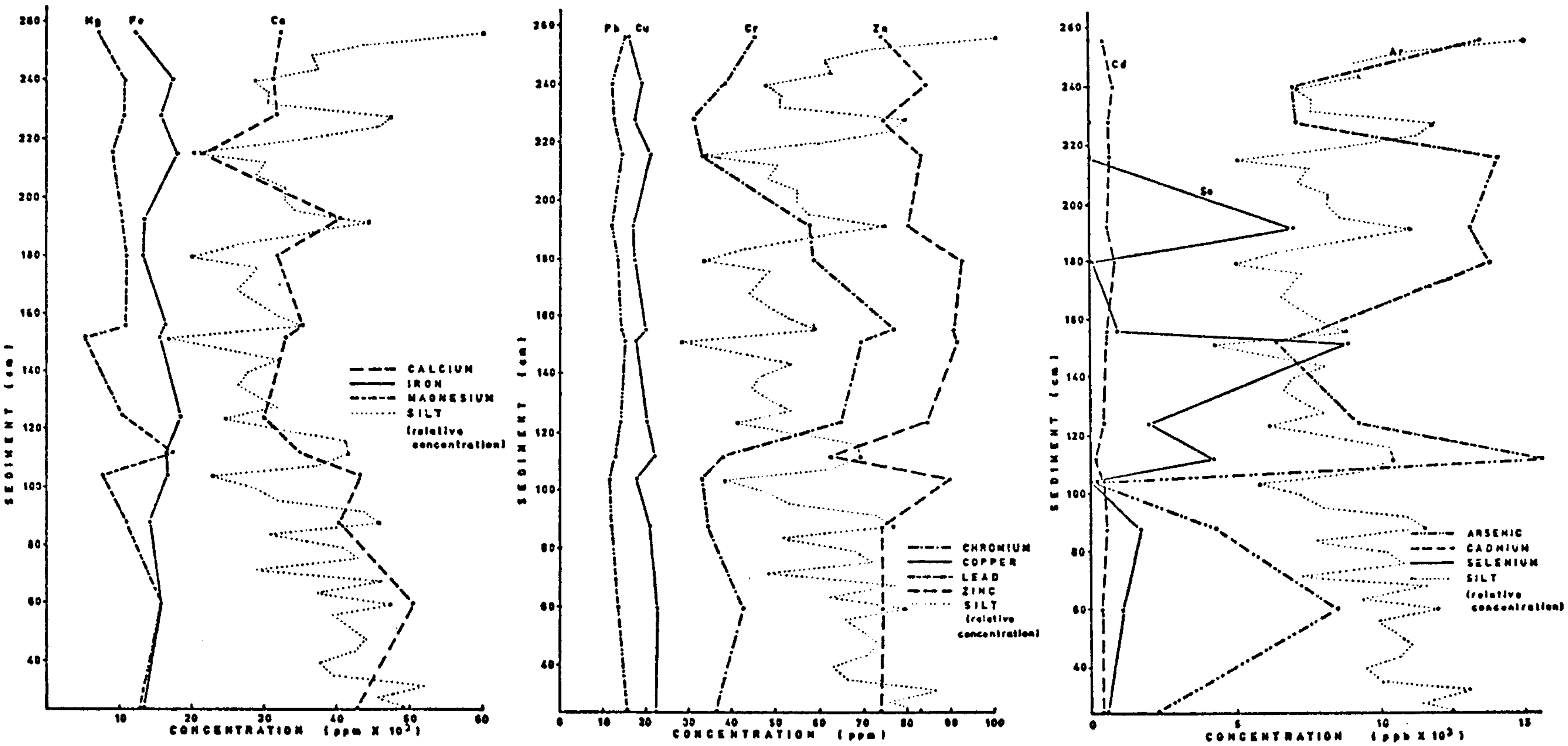

Figure 30. Analyses of 1974 sediment core from Halls Crossing for concentrations of calcium, iron, magnesium, chromium, copper, lead, zinc, arsenic, cadmium, selenium, and relative concentrations of silt.

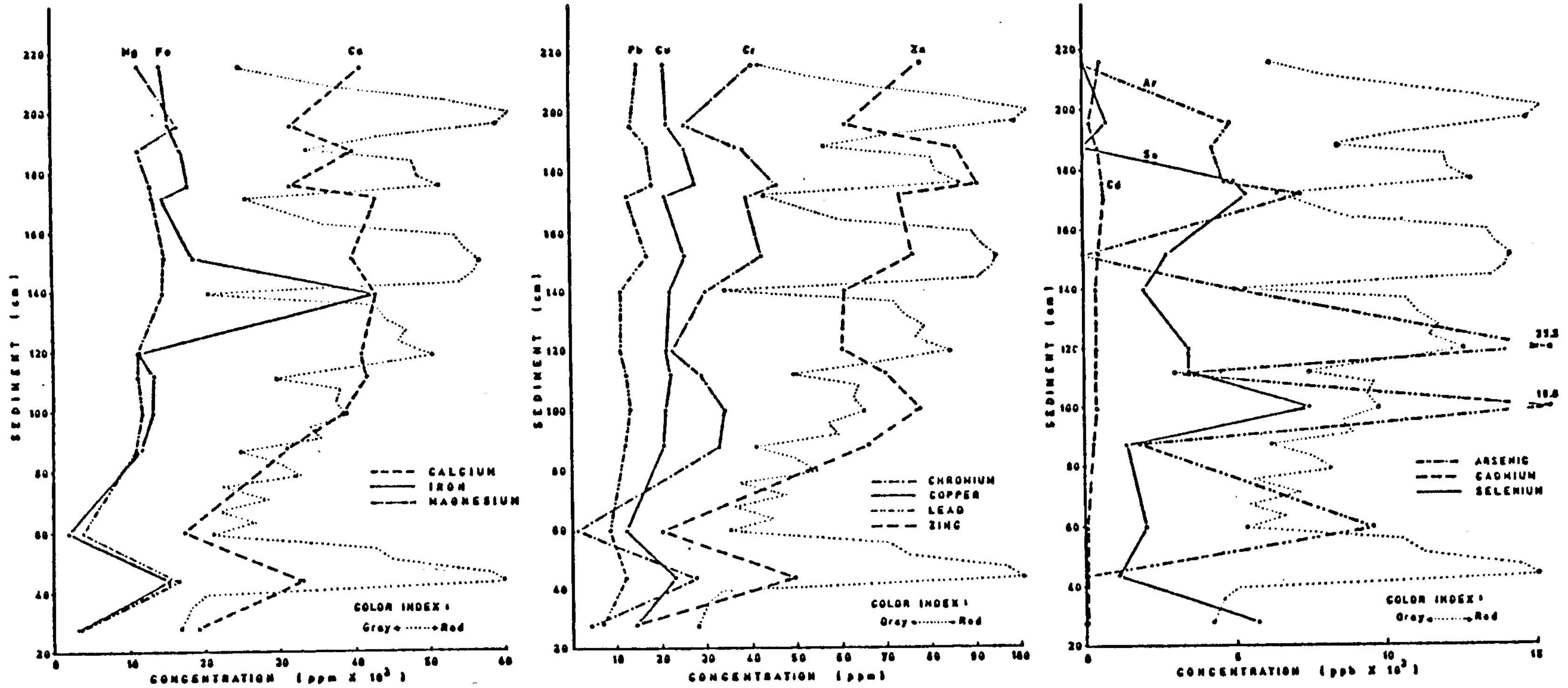

Figure 31. Analyses of 1976 sediment core from Halls Crossing for concentrations of calcium, iron, magnesium, chromium, copper, lead, zinc, arsenic, cadmium, selenium, and color index.

No consistent relationships are apparent.

The evidence from the two cores also does not indicate a consistent increase or decrease in concentration of any of the elements. Concentrations of cadmium, copper, and lead remain relatively low and most consistent. Concentrations of both selenium and arsenic fluctuate widely.

To determine the relationships within the several heavy metals and between them and silt or color, several statistical analyses were performed. In Table 30 are given the results of the nonparametric Spearman correlation coefficient tests for 1974 and 1976 drill cores. There is not good agreement of the correlations between the two cores. Those significant correlations common to both cores are underlined. Only the pairing of cadmium-calcium, cadmium-zinc, copper-magnesium, and magnesium-color are consistent in both cores, all being positively correlated except cadmium-calcium in the 1974 core. In the 1974 core in which it is possible to correlate to percentage silt concentration, only cadmium and zinc have significant correlations and both are negative, indicating a positive relationship to some other factor in opposition to the silt cycle. Cadmium is also negatively correlated to the color index (red as high value) while magnesium is positively correlated to increased red color. In the 1976 core one aberrant value for iron was dropped from the statistical analysis.

As indicated by the 1976 core, all significant correlations are positive and iron is most often correlated with other metals, namely cadmium, chromium, copper, lead, magnesium, zinc, and color. It is followed by cadmium, copper, lead, and zinc which are correlated with five elements and by chromium which is significantly correlated with four other metals. These are followed by magnesium and calcium; arsenic and selenium have no

Table 30. Significant correlation coefficient of heavy metal concentrations, silt, and color of drill cores at Halls Crossing by nonparametric Spearman correlation coefficient tests. (*P ≤ .05 significant; **P ≤ .01 highly significant; ***P ≤ .001 very highly significant)

1974 Drill Core

	As	Cd	Ca	Cr	Cu	Fe	Pb	Mg	Se	Zn	Silt	Color
As	-											
Cd		-										
Ca		-0.6044*	-									
Cr				-								
Cu					-							
Fe						-						
Pb							-					
Mg					0.6409**			-				
Se				0.5372*					-			
Zn		0.6227*						-0.5613*		-		
Silt		-0.5413*								-0.7896***	-	
Color		-0.6659**						0.5276*				-

1976 Drill Core

	As	Cd	Ca	Cr	Cu	Fe	Pb	Mg	Se	Zn	Color
As	-										
Cd		-									
Ca		0.5429*	-								
Cr		0.8681***		-							
Cu					-						
Fe		0.5604*		0.7418**	0.8690***	-					
Pb		0.7305**		0.8493***	0.6512**	0.8308***	-				
Mg					0.6240*	0.7747**		-			
Se									-		
Zn		0.8549***		0.8789***	0.5248*	0.6374*	0.9197***			-	
Color					0.6726**	0.7033**		0.7099**			-

significant correlations.

CONCENTRATIONS OF HEAVY METALS IN PLANKTON

Calcium concentrations in plankton are quite variable (Figure 32). The range of concentrations was 202 ppm to 1.37×10^5 ppm. The highest annual mean was 2.16×10^5 ppm. Magnesium concentrations ranged from 1.24×10^4 ppm to 766 ppm (Figure 33). The highest annual mean was 5,875 ppm. Magnesium was approximately one to two orders of magnitude lower in concentration than calcium.

Cadmium ranged in concentration from below detectable limits to 5.18×10^5 ppb (Figure 34). The highest annual mean was 1.10×10^5 ppb. Chromium concentrations ranged from below detectable limits to 8.25×10^5 ppb. The highest annual mean was 1.24×10^5 ppb. Sampling in March and August 1974 indicated only trace amounts of chromium in the plankton (Figure 35).

Copper concentrations ranged from below detectable limits to 8.20×10^5 ppb (Figure 36). The highest annual mean was 5.01×10^5 ppb at Site 6. Zinc concentrations were very high at most reservoir sites in March 1975. For the entire reservoir the range of concentrations was from below detectable limits to 7,768 ppm. The highest annual mean was 3,181 ppm at Site 5 (Figure 37). None of the other elements investigated displayed such relatively high levels at any one collecting period.

Lead concentrations in Wahweap Bay at Sites 1 (swimming beach area) and 2 (near Wahweap Marina) and at the dam, Site 3, are of interest (Figure 38). The annual means respectively were 2.50×10^5, 7.02×10^5, and 1.2×10^5. Examination of Figure 38 indicates that lead was higher at Site 2 than at Site 1 at four of the six sampling dates. None of the other

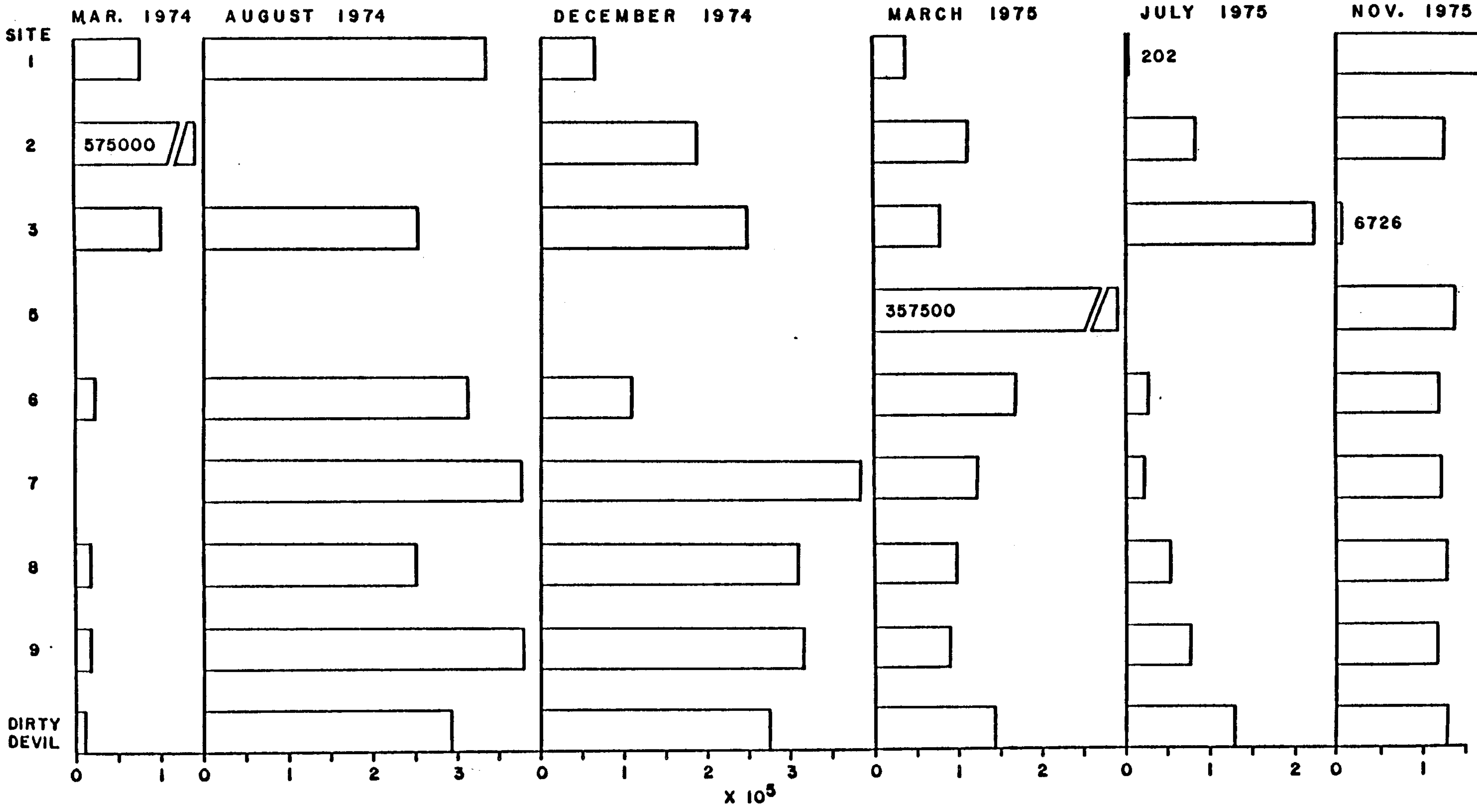

Figure 32. Seasonal distribution of calcium concentrations in net plankton collected at nine Lake Powell sites (unites are ppm).

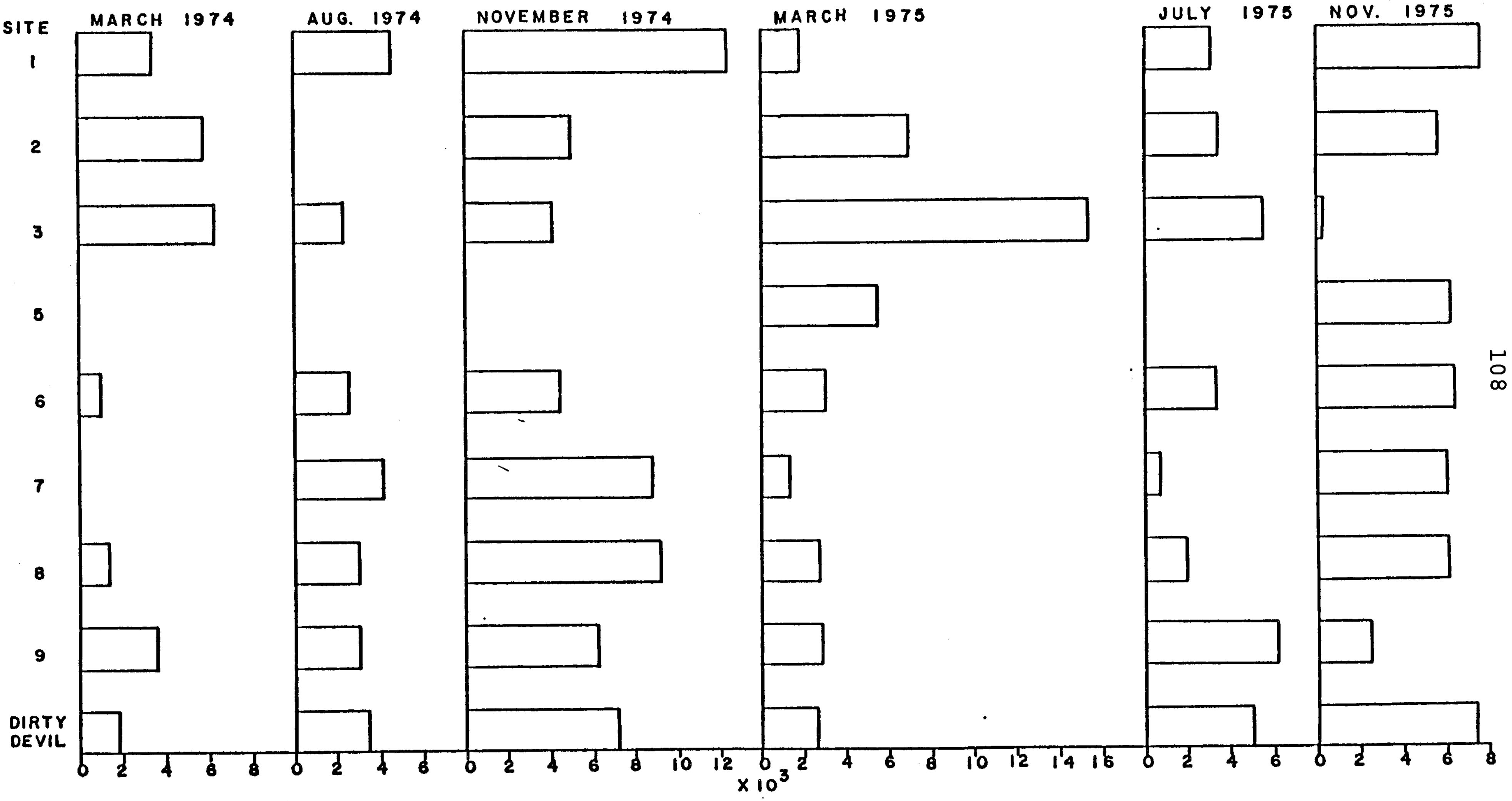

Figure 33. Seasonal distribution of magnesium concentrations in net plankton collected at nine Lake Powell sites (units are ppm).

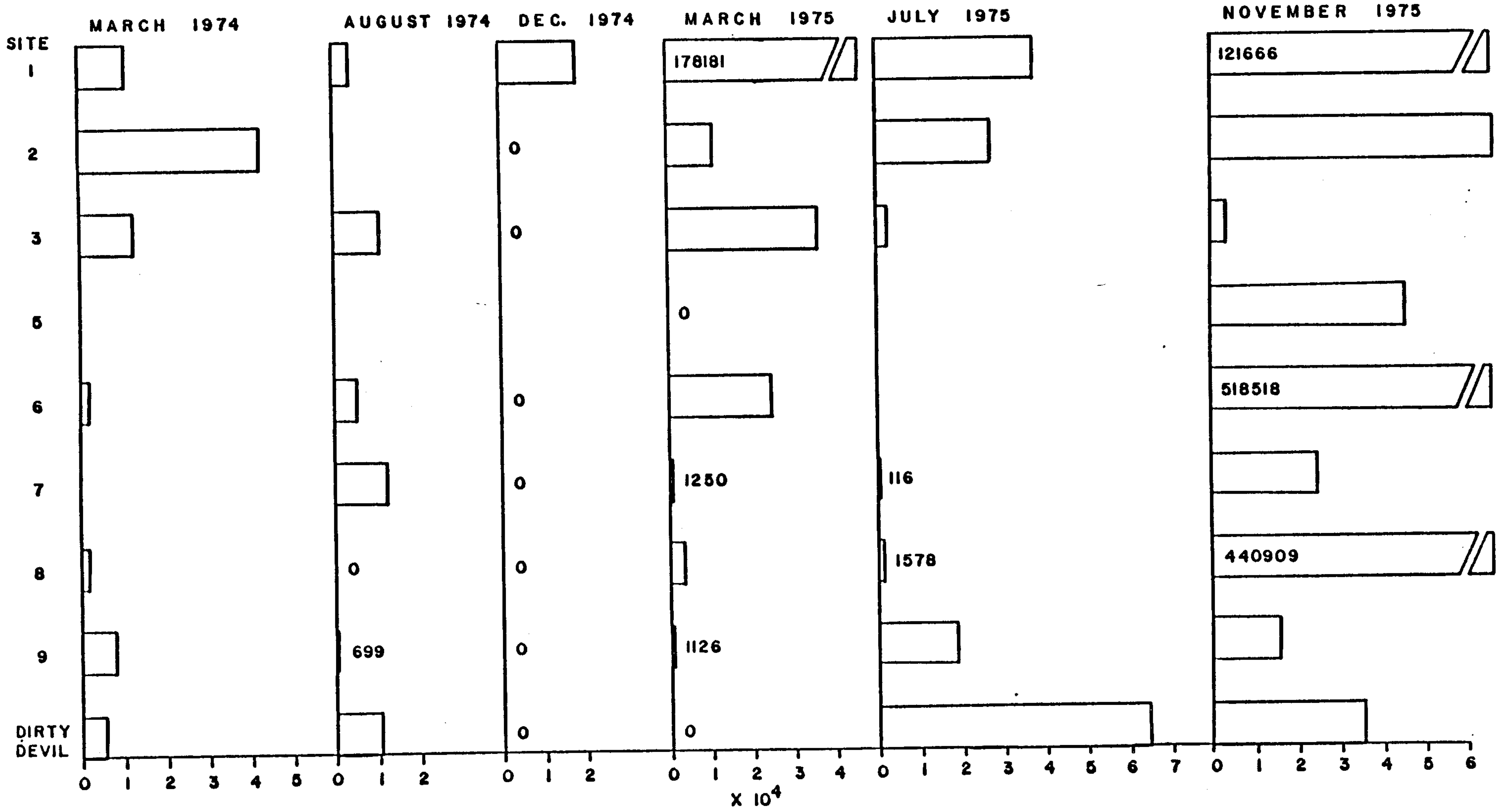

Figure 34. Seasonal distribution of cadmium concentrations in net plankton collected at nine Lake Powell sites (units are ppb).

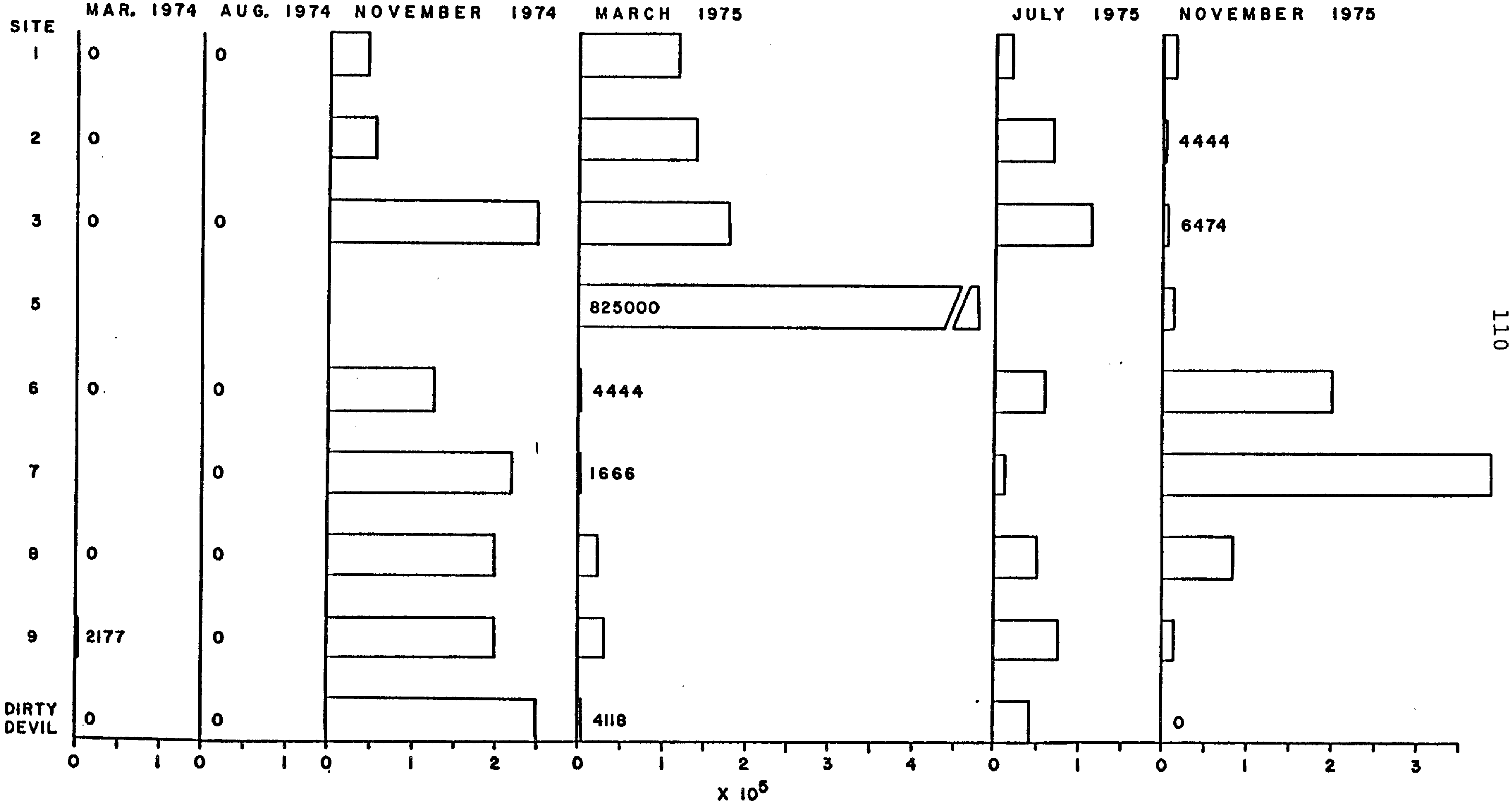

Figure 35. Seasonal distribution of chromium concentrations in net plankton collected at nine Lake Powell sites (units are ppb).

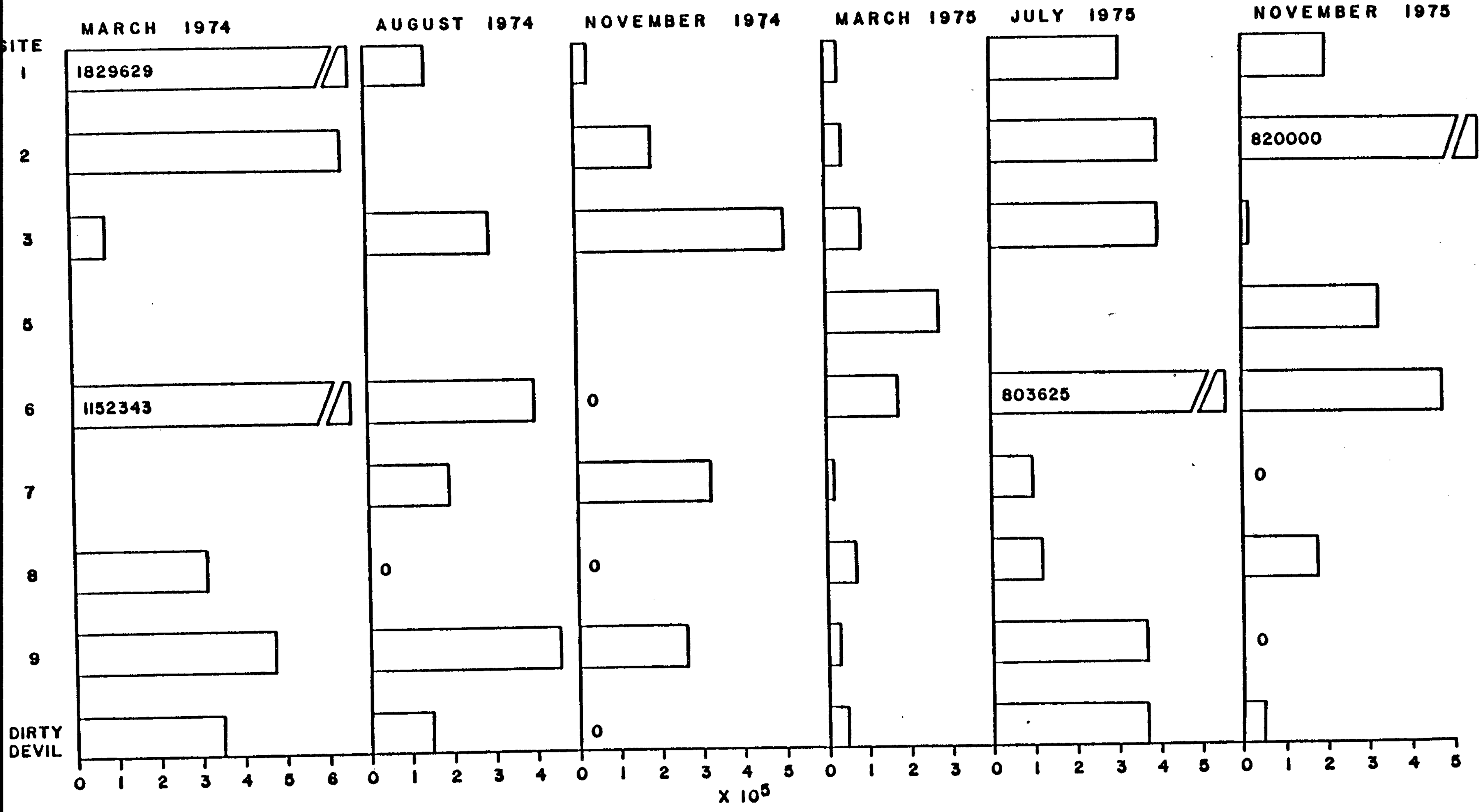

Figure 36. Seasonal distribution of copper concentrations in net plankton collected at nine Lake Powell sites (units are ppb).

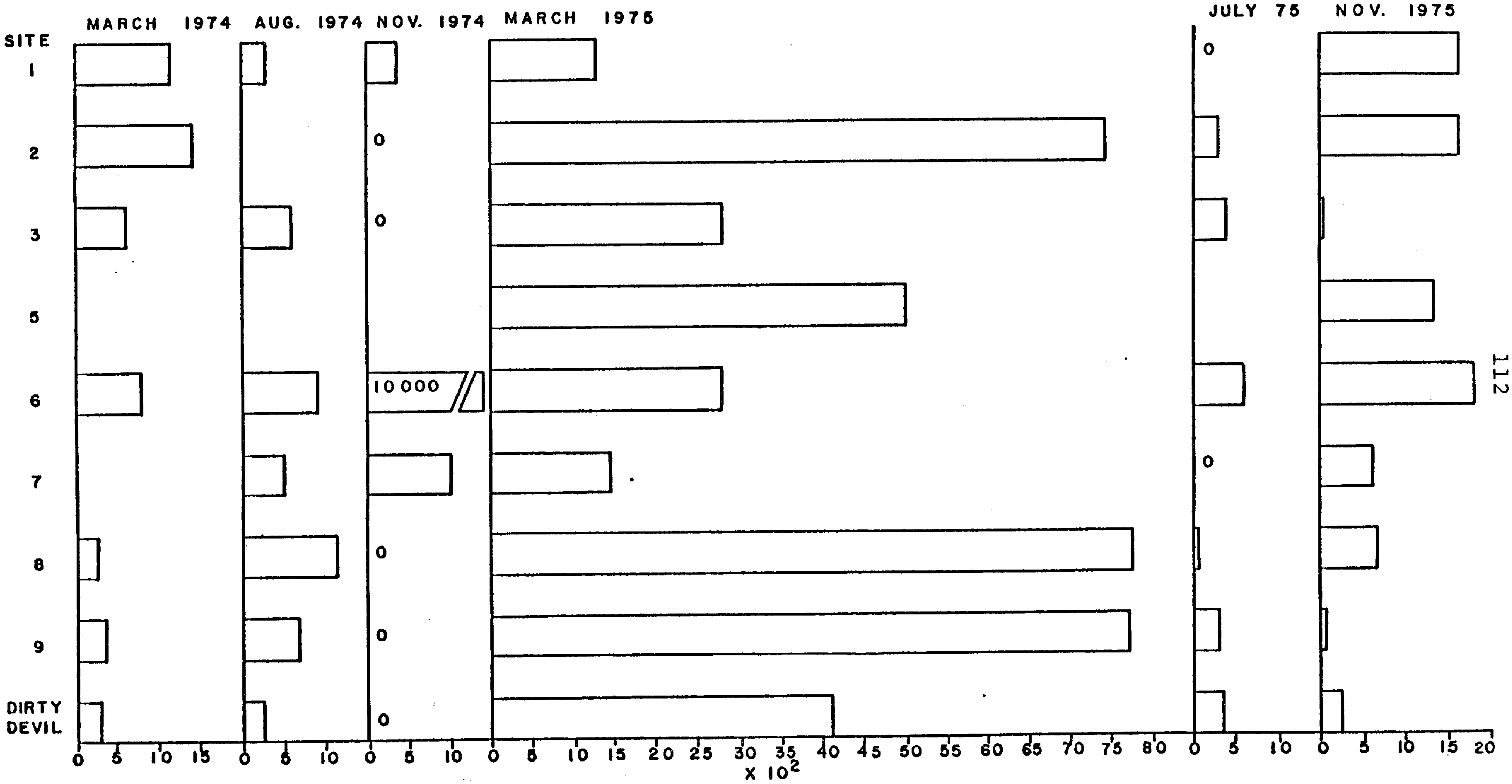

Figure 37. Seasonal distribution of zinc concentrations in net plankton collected at nine Lake Powell sites (units are ppm).

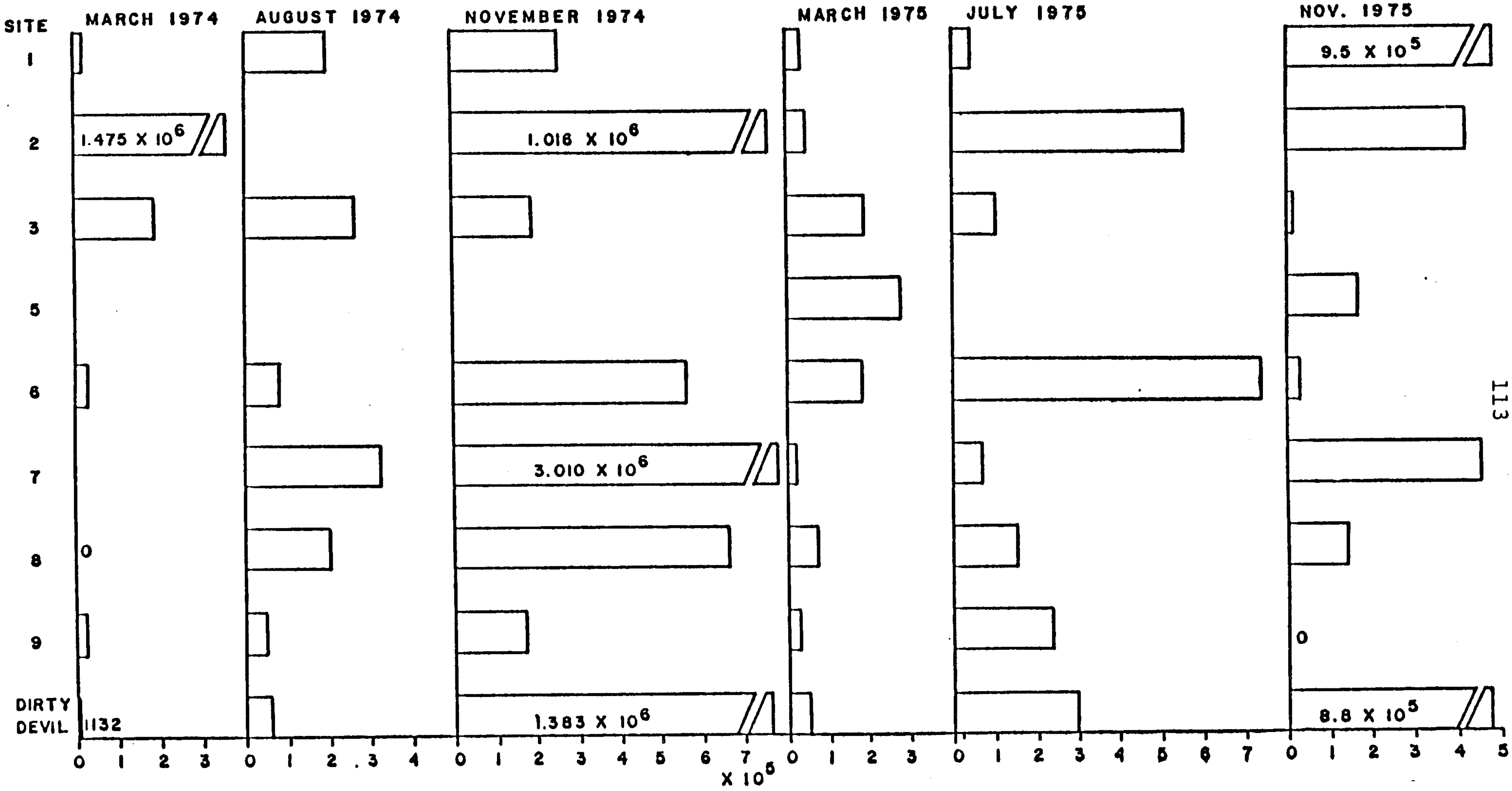

Figure 38. Seasonal distribution of lead concentrations in net plankton collected at nine Lake Powell sites (units are ppb).

elements investigated shows this pattern. This supports the hypothesis that lead from boating and marinas can pollute Lake Powell.

The range for all reservoir sites was from below detectable limits to 3.01×10^6 ppb. The highest annual mean was 7.80×10^5 ppb at Site 7. The annual mean at Site 2 was 7.02×10^5 ppb. For contrast, the mean annual concentration at Site 8, above the Halls Crossing-Bullfrog Bay marina areas was 2.10×10^5 ppb.

Examination of Figure 38 does indicate relatively higher lead concentrations in the Dirty Devil Arm of upper Lake Powell. There are no marinas in this arm and the higher concentrations could be due to particulate matter taken in by the zooplankton and to silt adsorbed to algae.

Iron concentrations within the reservoir ranged from 13 ppm to 7,750 ppm (Figure 39). The highest mean annual concentration was 5,517 ppm. The data are characterized by variability. Selenium also was extremely variable and ranged from below detectable limits to 3.07×10^5 ppb. Out of 26 collections, 18 were below detection limits. There is no explanation for this great range in analyses. Mean concentrations of arsenic ranged from 3510 ppb to 9.39×10^5 ppb. Mean concentrations were highest at Site 3 located in front of the dam. The lowest mean concentration occurred at Site 1 near the Wahweap Swimming Beach.

Levels and Concentration Factors for Net Plankton

Concentrations for the various elements of public health significance ranged from below detectable levels to high values (Table 31). These represented concentrations above water levels in the reservoir of a thousand to a millionfold (Table 32).

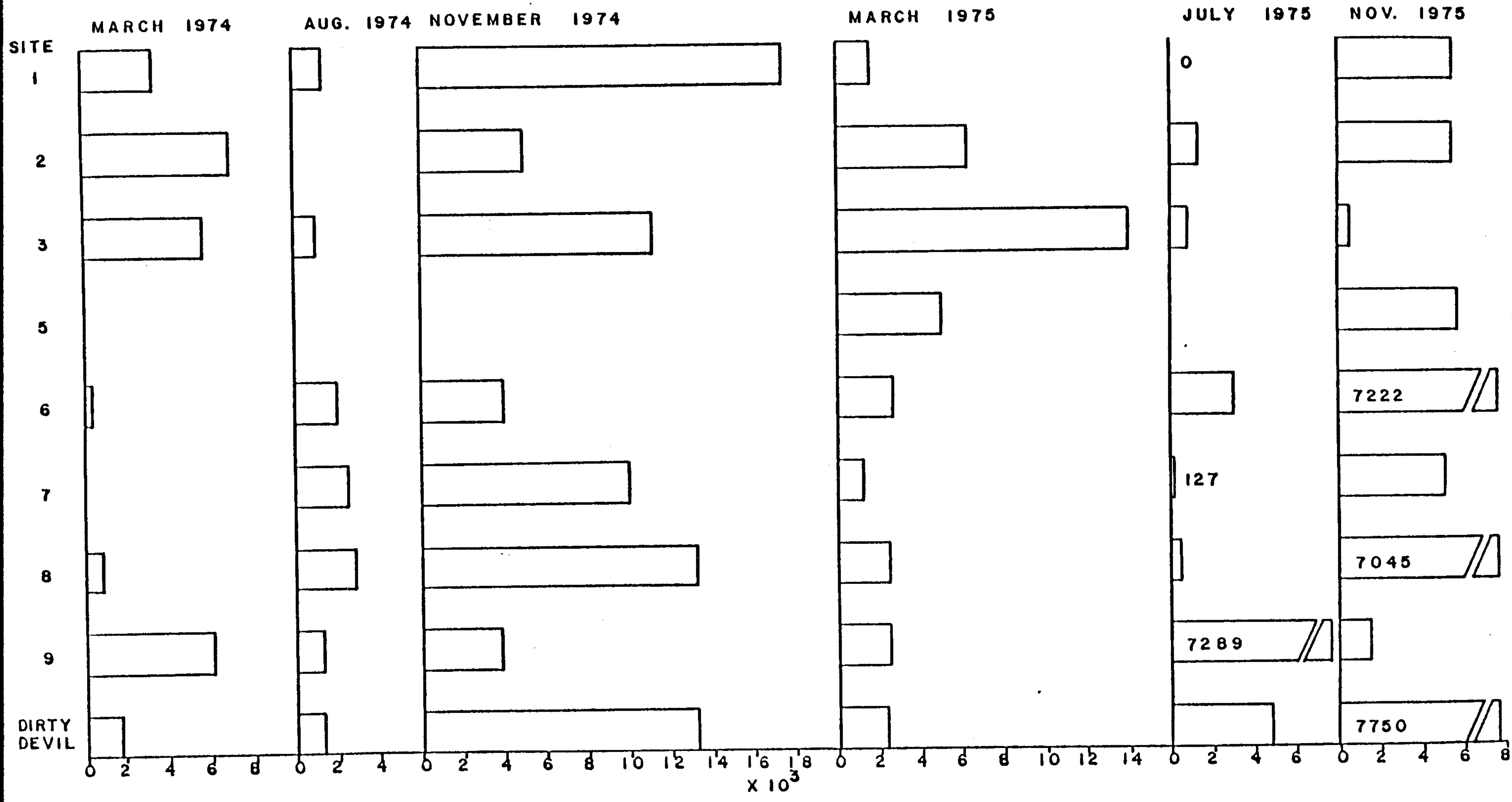

Figure 39. Seasonal distribution of iron concentrations in net plankton collected at nine Lake Powell sites (units are ppm).

Table 31. Ranges of selected metallic cation concentrations in the net plankton of Lake Powell

	Range
CADMIUM	<D.L. - 5.18×10^5 ppb
CHROMIUM	<D.L. - 8.25×10^5 ppb
COPPER	<D.L. - 8.20×10^5 ppb
ZINC	<D.L. - 7,768 ppm
LEAD	<D.L. - 3.01×10^6 ppb
IRON	13 - 7,750 ppm
SELENIUM	<D.L. - 3.07×10^5 ppb

Table 32. Concentration factors (CF) for selected elements in net plankton. The ratio used is concentration in plankton ÷ concentration in water. The CF for mercury is based on periphyton

Element	Average CF	Low CF	High CF
CADMIUM	2.16×10^5	2.08×10^4	7.34×10^5
CHROMIUM	1.26×10^6	1.71×10^5	2.75×10^6
COPPER	1.80×10^5	3.94×10^4	4.62×10^5
IRON	7.94×10^5	3.50×10^5	1.26×10^6
LEAD	1.01×10^6	6.26×10^4	2.35×10^6
ARSENIC	4.93×10^5	2.26×10^3	2.64×10^6
SELENIUM	3.55×10^4	2.68×10^3	8.39×10^4
ZINC	3.12×10^5	9.22×10^4	6.36×10^5
MERCURY	3.20×10^4		

Chromium in aquatic species has been little studied and a concentration of 3.5 ppm for plankton is given in a report by the National Academy of Sciences (NAS, 1974a). Chromium levels in Lake Powell plankton reached a high of 0.008 ppm which is considerably below this. Even if our samples consisted of all algae, the levels are below toxic levels for a few species of algae (NAS, 1974b). The level is also below the LC_{50} for Daphnia of 0.05 ppm hexavalent chromium. A concentration factor for chromium averaged 1.26×10^6 (Table 32). Martin and Knauer (1974) list a concentration factor of 7,800 for phytoplankton. Since our samples include both phytoplankton and zooplankton, it is hard to make a comparison.

Lead concentration factor averaged 1.01×10^6 for Lake Powell plankton. A concentration factor of 1,500 is listed for zooplankton of Lake Washington (Schell and Barnes, 1974).

Copper concentration factor averaged 1.80×10^5. The highest concentration in plankton was 820 ppm. This is above levels at which toxic effects due to concentrations in water are known to effect plankton organisms. These threshold levels in water range from 0.15 to 250 ppm (FWPCA, 1968). Lake Powell water levels were on the order of ppb. Apparently the concentration factor in toxicity investigations has not been determined, but the levels must be above 10^5 times. In an analysis of copper content in various algae (FWPCA, 1968), the range was 19 to 290 ppm. Evidently levels of 820 ppm are not toxic. Concentration factors of copper in phytoplankton have been recorded at 2,800 and in zooplankton at 1,800 (Martin and Knauer, 1974). These factors are an order of magnitude below the lowest concentration factor in Lake Powell plankton (Table 13).

Cadmium concentration factor averaged 2.16×10^5 and the highest concentration found in the plankton was 518 ppm. Little data for comparison are available. Zinc concentration factor averaged 3.12 x 10^5 and the highest plankton concentration was 7,768 ppm. Concentration factors of 5,500 in phytoplankton and 8,800 in zooplankton have been recorded (Martin and Knauer, 1974). Selenium and arsenic concentration factors averaged respectively 3.55 x 10^4 and 4.93 x 10^5. Little comparative data are available for zinc, selenium, and arsenic.

LEVELS AND CONCENTRATION FACTORS FOR FISH FLESH

The concentration factors for the ratio of fish flesh to water are given in Table 33. Mercury displays a range of factors from 8,000 to 43,000 which are higher than the other elements. Mercury is most likely concentrated through food chains since tissues which indicated immediate contact with water, such as skin and gills, were very low in concentration (Standiford et al., 1973).

Selenium displays concentration factors of 2,656 to 5,050. Iron also displays relatively high concentration factors of 1,600 to 2,560. Cadmium displays relatively low concentration factors of 31 to 115.

In recent years a considerable amount of attention has been directed to the concentrations of heavy metals in edible portions of fish and their potential for toxic effects in man. Values indicated here (Table 34) represent total metal concentrations. With the possible exception of selenium, the heavy metal levels reported do not appear to constitute a health hazard to humans. The non-heavy metal cations, calcium and magnesium concentrations in fish flesh are also reported.

Table 33. Concentration factors for selected elements in fish flesh. The ratio used is mean concentration in flesh ÷ mean concentration in water

Element	Bass	Trout	Walleye	Crappie
Cadmium	31	93	115	80
Chromium	277	175	78	352
Copper	359	913	297	241
Iron	1,760	2,560	1,600	1,600
Lead	235	43	141	125
Arsenic	756	136	65	597
Selenium	5,050	---	2,656	6,971
Zinc	532	340	383	532
Mercury	31,000	8,000	43,000	20,000

Table 34. Mean concentrations and standard errors of measurements for cations in fish flesh. The number analyzed is indicated below each fish type

	Fe mg/g	Ca mg/g	Mg mg/g	Cu mg/kg	Cr mg/kg	Cd mg/kg	Zn mg/g	As* mg/kg	Se* mg/kg	Pb mg/kg
Largemouth	.011	2.817	1.476	.822	.305	.007	.025	1.333	12.165	.152
Bass	±.002	±1.073	±.050	±.084	±.091	±.003	±.001	±.373	±2.462	±.040
(12)										
Black	.010	1.270	1.716	.553	.387	.018	.025	1.048	16.801	.081
Crappie	±.002	±.124	±.029	±.032	±.085	±.014	±.001	±.322	±2.902	±.026
(12)										
Walleye	.010	.556	1.388	.681	.086	.026	.018	.151	6.395	.091
(12)	±.001	±.058	±.025	±.105	±.032	±.003	±.001	±.080	±.958	±.026
Rainbow	.016	.502	1.176	2.090	.192	.021	.016	.241	--	.028
Trout	±.002	±.039	±.042	±.385	±.075	±.013	±.005	±.052		±.013
(6)										

* Based on N = 6.

The question of whether the levels reported for Lake Powell fish result from bioaccumulation or direct contact with water can be partially answered by considering the levels of the element in the gills and skin of the species investigated. The assumption is made that a high gill and/or skin level represents immediate contact. These concentrations can be compared to stomach levels which have been rinsed free of contents (Table 35). Only the cations of public health significance are considered.

It has been proposed that the uptake of copper by fishes occurs via the food chain (Lagler et al., 1962). Our personal observations of stomach contents indicate that threadfin shad (Dorosoma petenense) serves as the major food source for all four test species. Copper levels in these stomach contents were consistently high, with a mean value in excess of 10 mg/kg. The relatively high copper levels observed in the stomach tissue of three species, coupled with high levels in the primary food source, support the hypothesis of copper uptake via the food chain (Table 35). One other element in the table that supports this hypothesis of bioaccumulation through food chains is mercury. The other elements that support the hypothesis of uptake via contact with the water environment are lead, selenium, and zinc. Arsenic, cadmium, and chromium appear to be taken up via both pathways (Table 35). A full discussion of heavy metal concentrations in Lake Powell fishes has been presented by Bussey et al. (1976).

HEAVY METALS IN SOILS AND TERRESTRIAL VEGETATION

The chemistry of heavy metal cations in soils is extremely complex with many interactions. The absorption of these elements by plants from the soil is even more complex in its interactions and many interactions are unknown. There is no intent here to

Table 35. Mean concentrations of selected heavy metals in gill, skin, and stomach tissue of Lake Powell fish

	COPPER mg/kg	CHROMIUM mg/kg	CADMIUM mg/kg	ZINC mg/kg	ARSENIC mg/kg	SELENIUM mg/kg	LEAD mg/kg	MERCURY mg/g
Largemouth	2.320±0.242(G)	0.035±0.024(G)	0.215±0.080(G)	0.152±0.027(G)	1.746±0.928(G)	33.110±12.410(G)	3.825±1.645(G)	42.7(G)
Bass	1.139±0.273(S)	0.845±0.146(S)	0.260±0.006(S)	0.132±0.008(S)	0.344±0.152(S)	7.165±0.866(S)	0.355±0.072(S)	17.4(S)
(12)	3.758±0.316(St)	0.327±0.083(St)	0.074±0.010(St)	0.084±0.003(St)	1.194±0.240(St)	14.351±1.814(St)	0.177±0.051(St)	79.2(St)
Black	2.216±0.200(G)	0.798±0.270(G)	0.243±0.066(G)	0.166±0.031(G)	0.944±0.805(G)	13.010±4.037(G)	3.222±0.731(G)	11.6(G)
Crappie	0.686±0.102(S)	0.656±0.119(S)	0.030±0.009(S)	0.138±0.009(S)	0.865±0.244(S)	8.714±1.232(S)	0.452±0.122(S)	5.5(S)
(12)	4.971±0.420(St)	0.681±0.160(St)	0.163±0.024(St)	0.089±0.003(St)	2.418±1.039(St)	14.270±2.596(St)	0.116±0.060(St)	27.2(St)
Walleye	2.313±0.237(G)	0.446±0.160(G)	0.195±0.064(G)	0.290±0.120(G)	0.643±0.289(G)	12.259±0.672(G)	3.232±1.329(G)	51.1(G)
(12)	0.758±0.058(S)	0.176±0.064(S)	0.064±0.016(S)	0.160±0.007(S)	0.612±0.152(S)	3.770±0.675(S)	0.297±0.119(S)	22.5(S)
	1.880±0.268(St)	0.043±0.017(St)	0.204±0.029(St)	0.082±0.003(St)	0.761±0.213(St)	9.784±7.568(St)	0.080±0.016(St)	87.3(St)
Rainbow	1.900±0.266	0.272±0.105(G)	0.042±0.010(G)	0.477±0.114(G)	0.068±0.016(G)	---	0.493±0.191(G)	94.4(G)
Trout	1.278±0.195	0.637±0.540(S)	0.030±0.017(S)	0.108±0.012(S)	0.274±0.097(S)	---	0.068±0.021(S)	13.1(S)
(12)	3.666±0.522	0.411±0.164(St)	0.022±0.003(St)	1.254±0.489(St)	0.475±0.066(St)	---	0.052±0.032(St)	89.3(St)

* Based on N = 7, N = 7, N = 8, and N = 3 respectively

review the literature pertinent to the soil-plant relationships. One recent review of trace elements in soil-plant-animal systems is that of Nicholas and Egan (1975). Nor, is it the intent here to review the vast literature relating to the effect of deficiencies or toxic excesses of the elements considered. However, a few pertinent relationships of the site, soils, and vegetation are given. An extensive review is Drucker and Wilding (1977).

In his discussion of the biological cycles for toxic elements in the environment, Wood (1974) classifies calcium, iron, and magnesium as noncritical but arsenic, cadmium, copper, lead, selenium, and zinc as very toxic and relatively accessible. All of these plus chromium were analyzed in this study.

During the stages of movement of toxic elements through the biogeocycle, e.g., bedrock - soil - water or aerial transport - aquatic solution or suspension - sediment or bacteria - plants - invertebrates - vertebrates, the elements may be subject to varying conversions, both physical and chemical. These conversions may also affect their toxicity. Thus the detoxification of an element by microorganisms may yield a product that either increases or decreases its toxicity to higher organisms (Wood, 1974). For example, arsenic compounds are reduced and methylated by anaerobes to yield products of extreme toxicity. These may be then readily oxidized to less toxic substances which, however, may be methylated to other toxic compounds. Therefore, arsenic is similar to the interconversions of the three inorganic forms of mercury catalyzed by microorganisms. Selenium also can be predicted to undergo similar metabolic reactions. Therefore, though the total concentration of such elements may not be a measure of toxicity, it becomes important rather than any single species of the element for in the dynamic system of the biological cycles slight perturbations may effect the natural equilibrium and concentrations of any particular toxic form (Wood, 1974).

The principal purpose of the study was to provide a baseline with some measure of the variability encountered as a comparison for future studies. With the increase in use of the area involving consumption of gasoline by autos and boats and with the increase in the use of fossil fuels such as coal in the area, there will be concern and evaluation of the impact on water, soils, and vegetation as a base of the food chain to animals and man.

One example of a potential increase in heavy metals in the area is from the burning of coal in electric generating plants. The amount of fly ash trapped by electrostatic precipitators in the U. S. has been estimated at 26 million metric tons per year (Gutenmann et al., 1976). Both this fly ash and the bottom ash have been used as soil amendments or as land fill. Plants growing on or over these "soils" absorb elements such as selenium, which may be concentrated in plant tissues. The concentration of selenium is 310 times greater in the electrostatically precipitated fly ash than in bottom ash, but it is 1100 times more concentrated in the extremely fine fly ash which escapes the precipitator and is released into the atmosphere (Andren, Klein, and Talmi, 1975; and Klein et al., 1975). Selenium also may be present in the vapor phase in elemental form as a result of reduction in coal combustion. It may be converted to more water soluble forms which are readily leached and absorbed by plants. The volatility of heavy metals has been reported by Bertine and Goldberg (1971) as follows: as oxides, sulphates, carbonates, silicates, and phosphates -- As,Hg>Cd>Pb,Bi,Tl>In,Ag,Zn>Ca,Ga>SN>Li,Na,K,Rb,Cs; as sulphides -- As,Hg>Sn,Ge>Cd>Sb,Pb≥Bu>Zn,Tl>In>Cu>Fe,Co,Ni,Mn,Ag; and as elements -- Hg>Ag>Cd>Zn>Sb≥Bi>Ti>Mg>Ag,Sn,Cu>In,Ga,Ge.

Sampling Sites for Soils and Plants

Sampling sites were located to represent both the area of Lake Powell, from Glen Canyon Dam and Wahweap Marina to near its upper limits at Hite; the major tributaries of the San Juan, Green, Dolores, and Gunnison rivers; and the main stem of the Colorado River at Moab, Utah and Grand Junction, Colorado. Their locations, as well as other sampling sites on Lake Powell, are indicated in Figure 1.

Soil samples composited from 30 separate collections of surface soils within the area of the plant collections and three representative species of vegetation including young stems, leaves, flowers, and fruits were taken in March, July, and November at each of the following sites. The species were *Atriplex confertifolia* (shadscale), *Oryzopsis hymenoides* (Indian ricegrass), and *Tamarix pentandra* (salt-cedar or tamarisk). At Wahweap Bay *Ephedra viridis* (Mormon tea) was substituted for *Atriplex* and at the mouth of the San Juan, *Ephedra* was substituted for *Tamarix*. *Oryzopsis* was sampled from all seven collecting stations. These species were selected because of their importance, widespread distribution, and variety of growth forms. A brief description of the sites follows.

Samples at Wahweap were obtained above the marina area in sandy soils derived mainly from Entrada sandstone. Collections were from areas with adjacent heavy traffic use.

The San Juan River site was just northeast of its confluence with the Colorado River, the most isolated of all the samples with no auto traffic within many miles. The sandy soils here would have been derived mainly from Navajo sandstone.

The Mexican Hat, Utah site was southeast of the bridge across the San Juan River. Soils are thin mantles of sand overlying sandstones.

Halls Crossing samples were obtained from the dune sand area on top of the hill south of the marina in an area of predominantly Navajo sandstone.

Hite samples were obtained about one-quarter mile north of Hite Marina and east of the road. This area is dominated by Moenkopi formation, a gypsiferous siltstone and sandstone.

Only sediment and water samples were obtained from the Green River at Green River, Utah, the Dolores River at Gateway, and the Gunnison River at Grand Junction.

At Moab samples were taken from the west bank of the Colorado River both northwest and southwest of the highway #163 bridge. Sandy deposits here lie over the Chinle formation and under Wingate sandstone.

At Grand Junction, Colorado samples were obtained from along the south bank of the Colorado River south of Clifton. Here there is a layer of alluvium over deep beds of the upper part of Mancos shale. Much of the surrounding valley is irrigated and planted to orchards and other crop plants. The surrounding area is well populated.

The mean values for the heavy metal concentrations in soils, _Atriplex_, _Oryzopsis_, and _Tamarix_ derived from sampling in 1974 and 1975 at seven stations are given in Table 36.

Arsenic

In the soils (Figure 40) arsenic values vary the greatest

Table 36. Summary of mean concentrations of heavy metals in soils and three common species of plants from each of seven collecting sites. Means based on three replicates each for six sampling dates, 1974-75.

	Arsenic (ppm)		Cadmium (ppb)		Calcium (ppm)		Chromium (ppm)		Copper (ppm)		Iron (ppm)		Lead (ppm)		Magnesium (ppm)		Selenium (ppb)		Zinc (ppm)	
Soils																				
W.B.[1]	1.27	2.99*	61	44	8,654	16,205	3.6	8.4	3.3	4.1	2,363	5,975	9.2	8.6	2,423	6,679	322	384	10.7	19.7
S.J.	4.88		49		16,830		8.4		5.7		6,298		8.2		5,783		312		23.4	
H.C.	0.74		24		13,346		6.1		1.7		5,229		7.0		6,064		267		19.9	
H.M.	5.07		42		25,991		15.4		5.7		10,008		9.9		12,446		636		24.7	
M.	2.02	4.29**	150	218	12,397	42,772	13.5	20.6	14.9	15.6	6,074	11,276	14.2	17.9	6,392	8,383	400	635	24.0	39.7
G.J.	8.88		416		50,495		26.6		18.2		16,267		20.9		9,221		1,123		60.1	
M.H.	1.97		87		65,423		21.8		13.7		11,488		18.6		9,537		382		35.0	
Atriplex confertifolia																				
W.B.	-		-		-		-		-		-		-		-		-		-	
S.J.	1.30	1.56	343	366	19,641	20,104	.68	1.18	2,34	2.69	345	432	2.94	4.12	9,251	10,893	2,486	2,420	12.3	13.2
H.C.	1.07		357		16,524		1.19		3.34		385		4.97		12,630		3,535		13.2	
H.M.	2.33		397		24,147		1.68		2.38		567		4.45		10,798		1,240		14.2	
M.	0.14	0.47	470	466	18,295	20,213	1.37	1.40	4.63	3.82	341	396	10.38	10.96	6,909	7,594	1,643	2,531	18.7	16.9
G.J.	0.81		471		20,010		1.40		3.64		497		18.36		7,014		5,079		21.2	
M.H.	-		458		22,335		1.44		3.19		350		4.14		8,858		872		10.7	
Oryzopsis hymenoides																				
W.B.	1.32	0.88	288	310	4,963	3,723	1.00	1.32	2.96	2.75	329	332	9.64	5.76	1,432	1,548	1,359	626	11.4	11.7
S.J.	0.32		257		2,752		1.15		2.75		288		3.15		1,232		358		4.6	
H.C.	0.79		330		3,559		.94		2.60		261		3.79		1,769		538		6.4	
H.M.	1.07		365		3,637		2.17		2.69		450		6.46		1,759		248		24.5	
M.	0.51	0.54	402	428	2,612	4,207	2.35	2.97	4.09	3.82	344	532	13.85	17.00	1,713	1,695	740	452	8.1	8.7
G.J.	0.68		537		5,372		4.35		4.10		859		33.08		1,684		455		11.9	
M.H.	0.43		346		4,638		2.21		3.28		393		4.08		1,688		162		6.1	
Tamarix pentandra																				
W.B.	1.07	2.25	335	835	12,785	13,201	1.69	1.75	3.85	5.23	160	229	9.40	6.25	8,103	9,752	1,710	3,704	12.6	20.0
S.J.	-		-		-		-		-		-		-		-		-		-	
H.C.	0.77		1,230		17,697		1.89		5.86		322		6.51		12,875		1,982		27.9	
H.M.	4.19		941		9,122		1.66		5.97		206		2.85		8,279		7,419		19.5	
M.	0.01	0.7	2,491	1,249	13,111	12,885	1.39	1.53	5.69	6.02	143	171	6.31	27.35	4,066	6,629	2,998	5,026	37.8	28.6
G.J.	0.54		863		10,555		1.81		6.83		188		70.07		6,252		9,051		38.3	
M.H.	1.55		392		14,990		1.40		5.54		181		5.66		9,570		3,030		9.8	

[1] W.B. - Wahweap Bay, S.J. - San Juan, H.C. - Halls Crossing, H.M. - Hite Marina, M. - Moab, G.J. - Grand Junction, M.H. - Mexican Hat. The first four are Lake Powell sites.

*Mean value for Lake Powell sites.

**Mean value for non-Lake Powell sites.

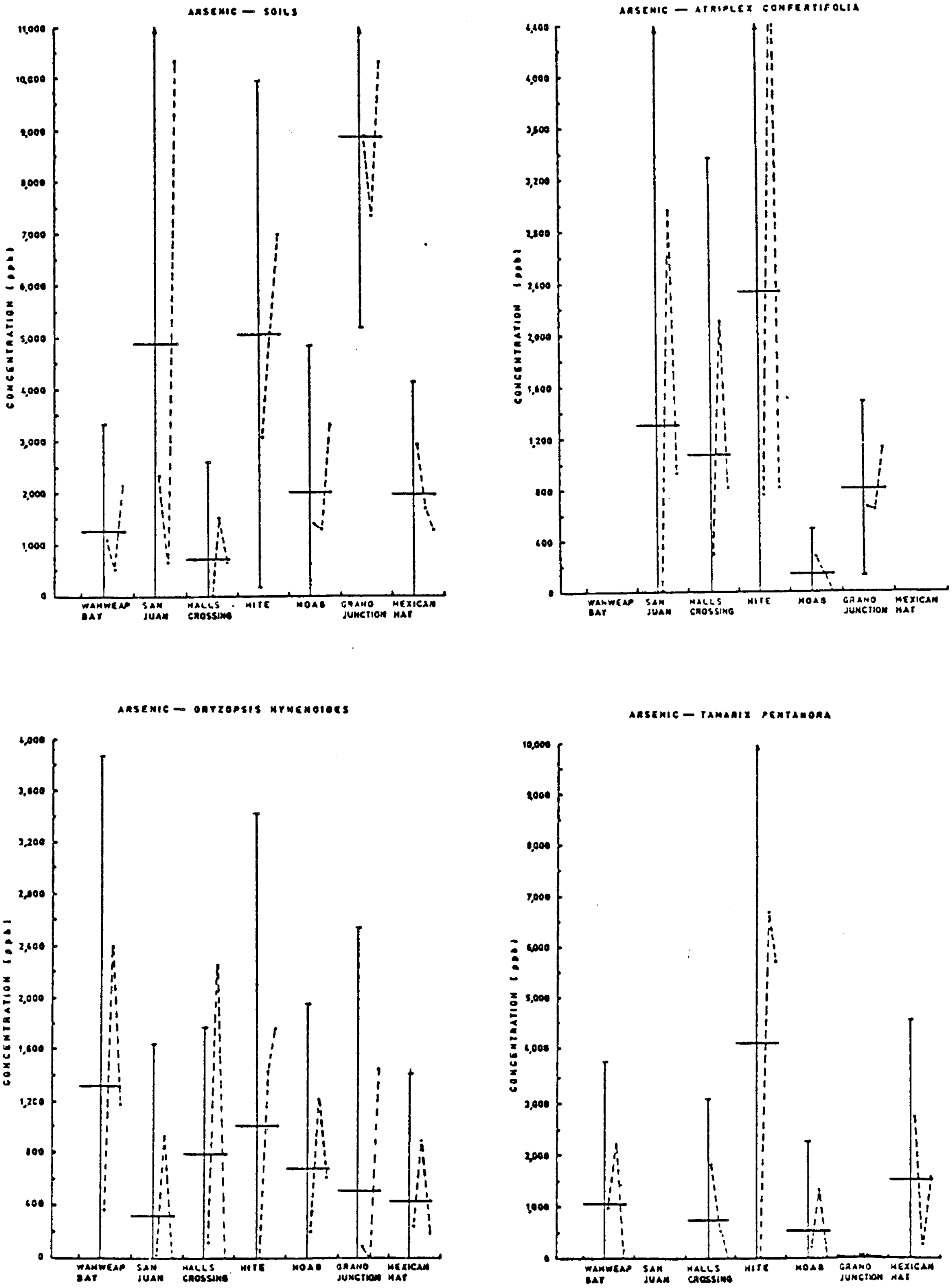

Figure 40. Concentrations of arsenic (1975) with means and 95% confidence limits for soils, <u>Atriplex confertifolia</u>, <u>Oryzopsis hymenoides</u>, and <u>Tamarix pentandra</u>.

in the San Juan Site, which is the most isolated from human activity, and within a large area of relatively uniform Navajo sandstone. Only Grand Junction is significantly higher in concentration than Wahweap, Halls Crossing, Moab, or Mexican Hat. Higher concentrations at Grand Junction might be expected because of the agricultural activity of the area requiring pesticides in orchard practice. While the majority of soils are higher in arsenic in November than in July, in the majority of the plant samples, arsenic is lower in November (Figure 40). None of the plant species are significantly higher or lower than the same species at other sites - this, in spite of the significantly higher concentration in the soil at Grand Junction. Unexplainably, Tamarix has the lowest concentration at Grand Junction and is lower than any other species at any site. It does appear that Oryzopsis is most uniform in its intake of arsenic regardless of the concentration in the soil.

Mean annual values in soils vary from 743 ppb at Halls Crossing to 8,878 ppb at Grand Junction with individual values ranging from 32 ppb to 10,614 ppb. Mean annual values range from 144 to 2,331 ppb in Atriplex; 319 to 1,321 ppb in Oryzopsis; and 14 to 4,189 in Tamarix.

Cadimum

Cadmium values are relatively low and consistent in soils except for higher values at Moab and Grand Junction, the latter having concentrations significantly higher than all others except Moab (Figure 3). Both Moab and Grand Junction are within shale belts, the former Chinle, the latter Mancos. No seasonal patterns are discernible in either soils or plants. The annual mean concentrations are highest for Atriplex (Figure 3) and Oryzopsis (Figure 41) at Moab and Grand Junction, though not significantly so. Like arsenic, significant differences in

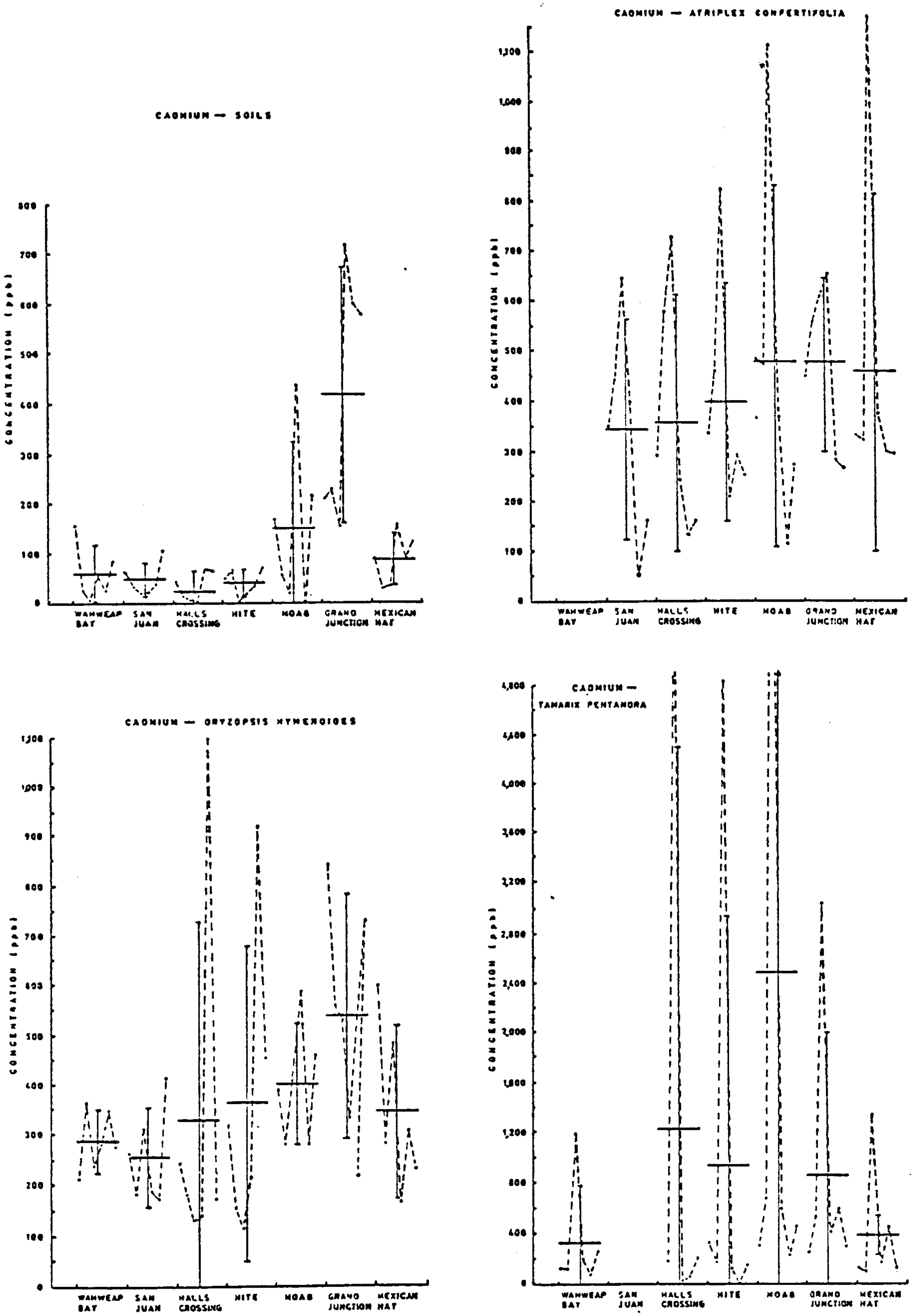

Figure 41. Concentrations of cadmium (1974-75) with means and 95% confidence limits for soils, _Atriplex confertifolia_, _Oryzopsis hymenoides_, and _Tamarix pentandra_.

soils may not result in significantly different concentrations within the plant. The mean concentrations for Tamarix (Figure 41) are considerably higher than for the other two species and and more variable.

Mean annual values in soils range from 24 to 416 ppb; for Atriplex from 343 to 471 ppb; for Oryzopsis from 257 to 537 ppb; and for Tamarix from 335 to 2,491 ppb.

Calcium

Varying seasonal patterns are suggested for calcium in soils within and between sites (Figure 4). In half the years the lowest value is in July.

Calcium concentrations at Grand Junction are significantly greater than at Wahweap, San Juan, Halls Crossing, and Moab and those at Mexican Hat on the San Juan River are significantly higher than at Wahweap, Halls Crossing, and Moab. For Atriplex (Figure 42) the highest mean value does not occur where the calcium concentration in soil is highest but at the intermediate level at Hite. Concentrations in this shrub are significantly higher than at Halls Crossing and probably at Moab. It is reasonable that calcium, which is not scarce in any of the area, is most readily available from the gypsiferous sandstones of the Moenkopi formation at Hite. In Oryzopsis (Figure 42) calcium concentration is significantly higher at both Grand Junction and Mexican Hat than at San Juan and Moab. There are no significant differences in calcium concentrations for Tamarix (Figure 42) between sites. However, this species does show an almost consistent seasonal trend of highest concentrations in July. This is a period of full leaf and flower production, while leaves, flowers, and fruits are sparse in March and November.

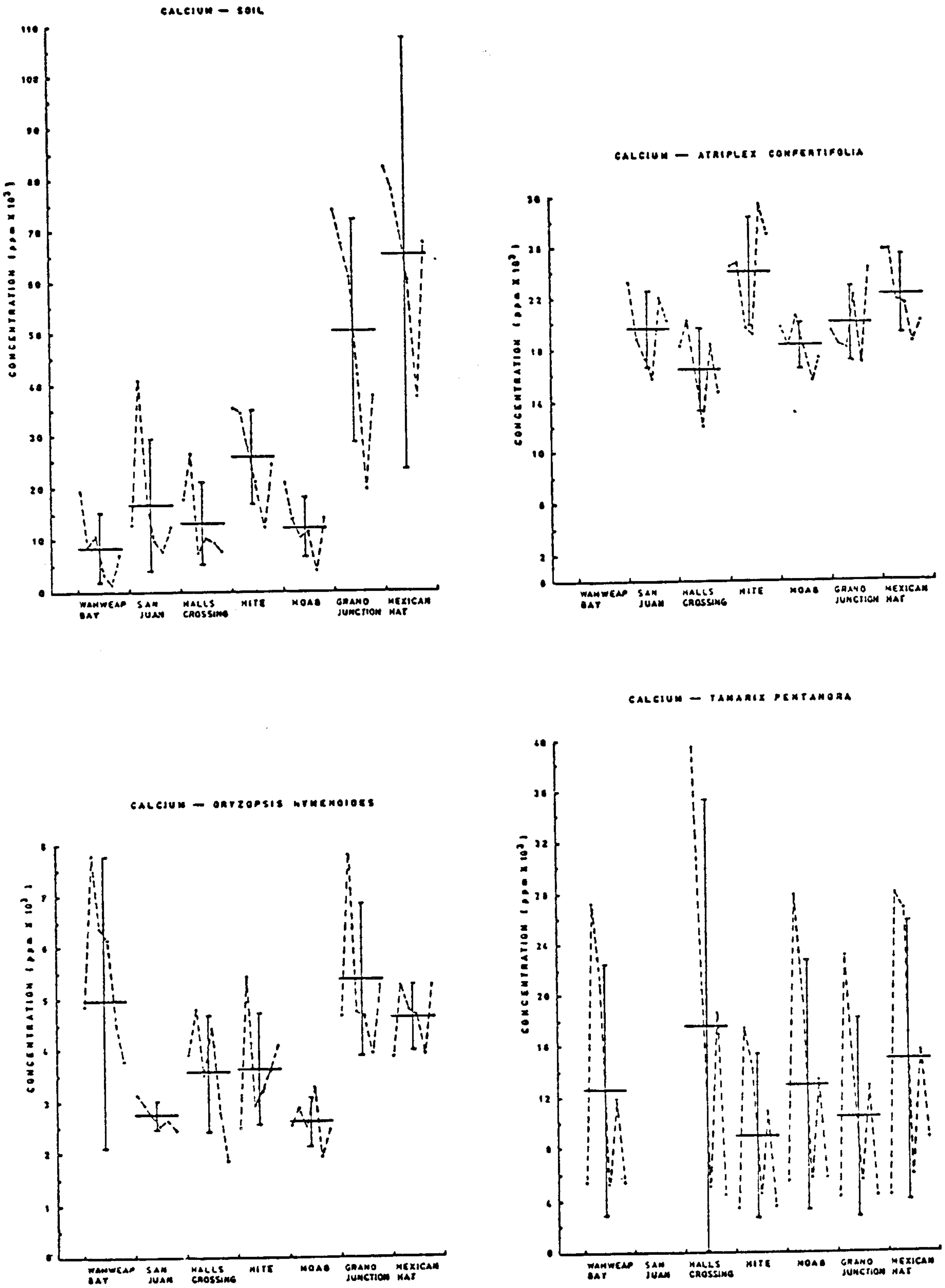

Figure 42. Concentrations of calcium (1974-75) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

Calcium is commonly abundant and sometimes excessively so in this region. High concentrations cause an interaction role with other cations such as iron, manganese, zinc, and boron reducing their availability (Bidwell, 1974).

Mean values for calcium range in soils from a low of 8,654 ppm at Wahweap to a high of 65,423 ppm at Mexican Hat. However, none of the plant species show this relationship. Values for *Atriplex* range from 16,524 to 24,147 ppm; *Oryzopsis* from 2,612 to 5,372 ppm; and *Tamarix* from 9,122 to 17,697 ppm.

Chromium

The chromium concentration of soil at Hite is significantly higher than at Wahweap; those at Grand Junction and Mexican Hat are significantly higher than at Wahweap, San Juan, and Halls Crossing (Figure 43). In the majority of years the concentration of chromium in surface soils is highest in July. Once again, the significantly higher concentrations in surface soils are not reflected in significantly higher concentrations in the three plant species *Atriplex*, *Oryzopsis*, and *Tamarix* (Figure 43).

Mean annual concentrations of chromium in soils range from 3.6 to 26.6 ppm; while concentrations in *Atriplex* are 0.68 to 1.68 ppm; in *Oryzopsis* are .94 to 4.35 ppm; and in *Tamarix* are 1.39 to 1.89 ppm.

Copper

Only Grand Junction soil has a mean copper concentration in surface soils significantly higher than at Wahweap, San Juan, Halls Crossing, or Hite (Figure 44). Concentrations at Moab and Grand Junction are also significantly higher than at Halls Crossing. Thus, the Lake Powell sites are lower in copper

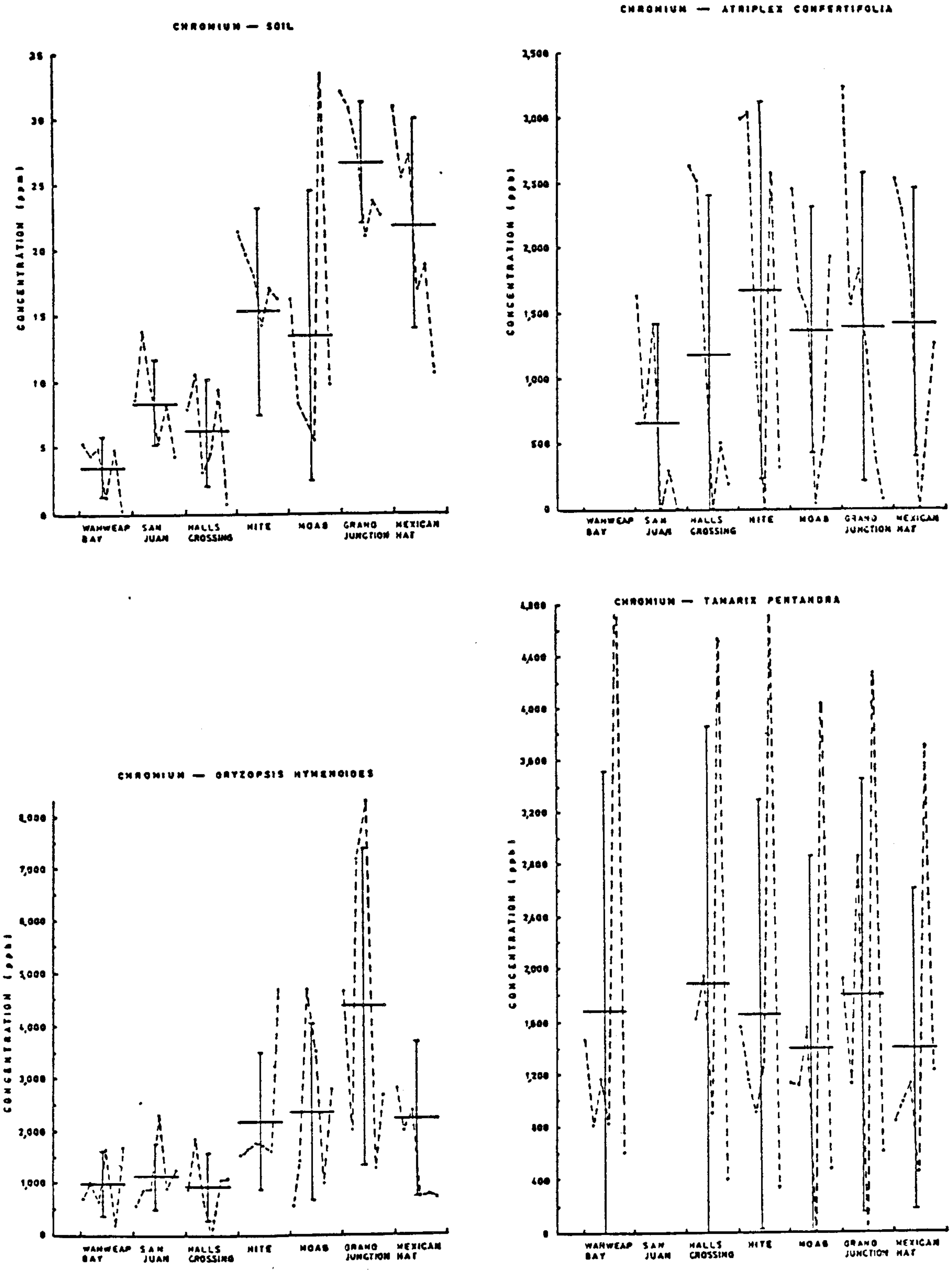

Figure 43. Concentrations of chromium (1974-75) with means and 95% confidence limits for soils, Atriplex confertifolia, Oryzopsis hymenoides, and Tamarix pentandra.

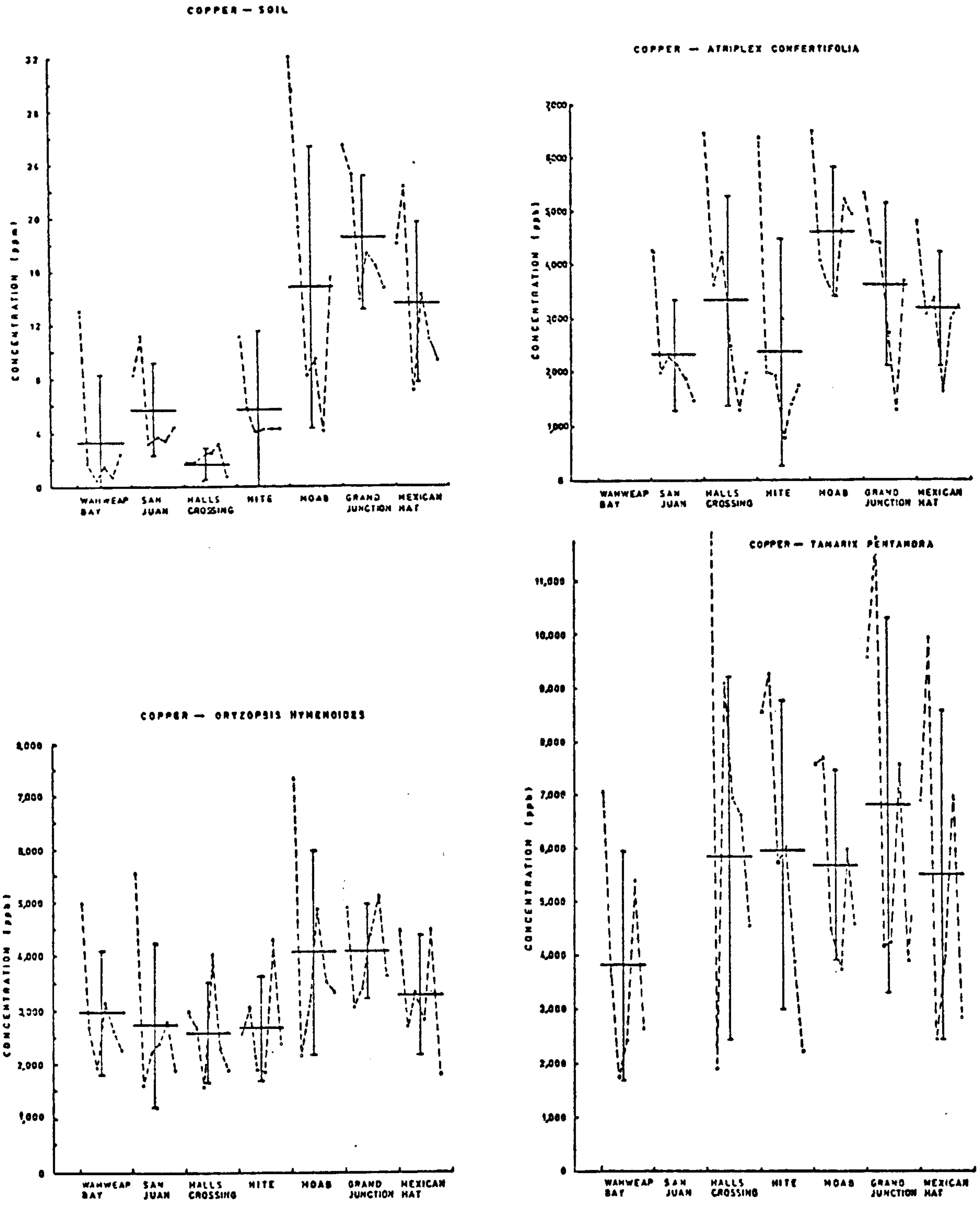

Figure 44. Concentrations of copper (1974-75) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

concentration than tributary sites. Copper is often associated with manganese and iron oxides in soils, and in many soils more than 99 percent of copper is present as a complex often with organic compounds (Nicholas and Egan, 1975). No seasonal pattern is discernible. In Atriplex the only significant differences in copper concentration are the high at Moab and the low at San Juan (Figure 44). The significant differences in surface soil concentrations between Halls Crossing and the soils at Grand Junction and Mexican Hat are not reflected in the plant uptake. For Oryzopsis (Figure 44) and Tamarix (Figure 44) there are no significant differences in copper. As usual, the concentrations in Tamarix fluctuate widely but without a seasonal pattern.

Mean annual concentrations vary from a low of 1.7 ppm at Halls Crossing to a high of 18.2 ppm at Grand Junction. The range of mean concentrations for Atriplex is 2.34 ppm at San Juan to 4.63 ppm at Moab; for Oryzopsis, 2.60 ppm at Halls Crossing to 4.10 ppm at Grand Junction; and for Tamarix, 3.85 ppm at Wahweap to 6.83 ppm at Grand Junction. Therefore, like the soils the lowest values are from Lake Powell sites and highest values from tributaries or upstream sites. Copper concentrations in Grand Junction soils are approaching the 20 ppm which Bohn (1972) reported as a level at which it becomes a phytotoxic material. Copper concentrations also tend to reduce the availability of zinc.

Iron

Wahweap Bay is significantly lower in surface soil concentration of iron than all other sites, except Halls Crossing (Figure 45). Grand Junction is significantly higher than all other sites, while Hite and Mexican Hat are significantly higher than all sites except Grand Junction. After weathering from

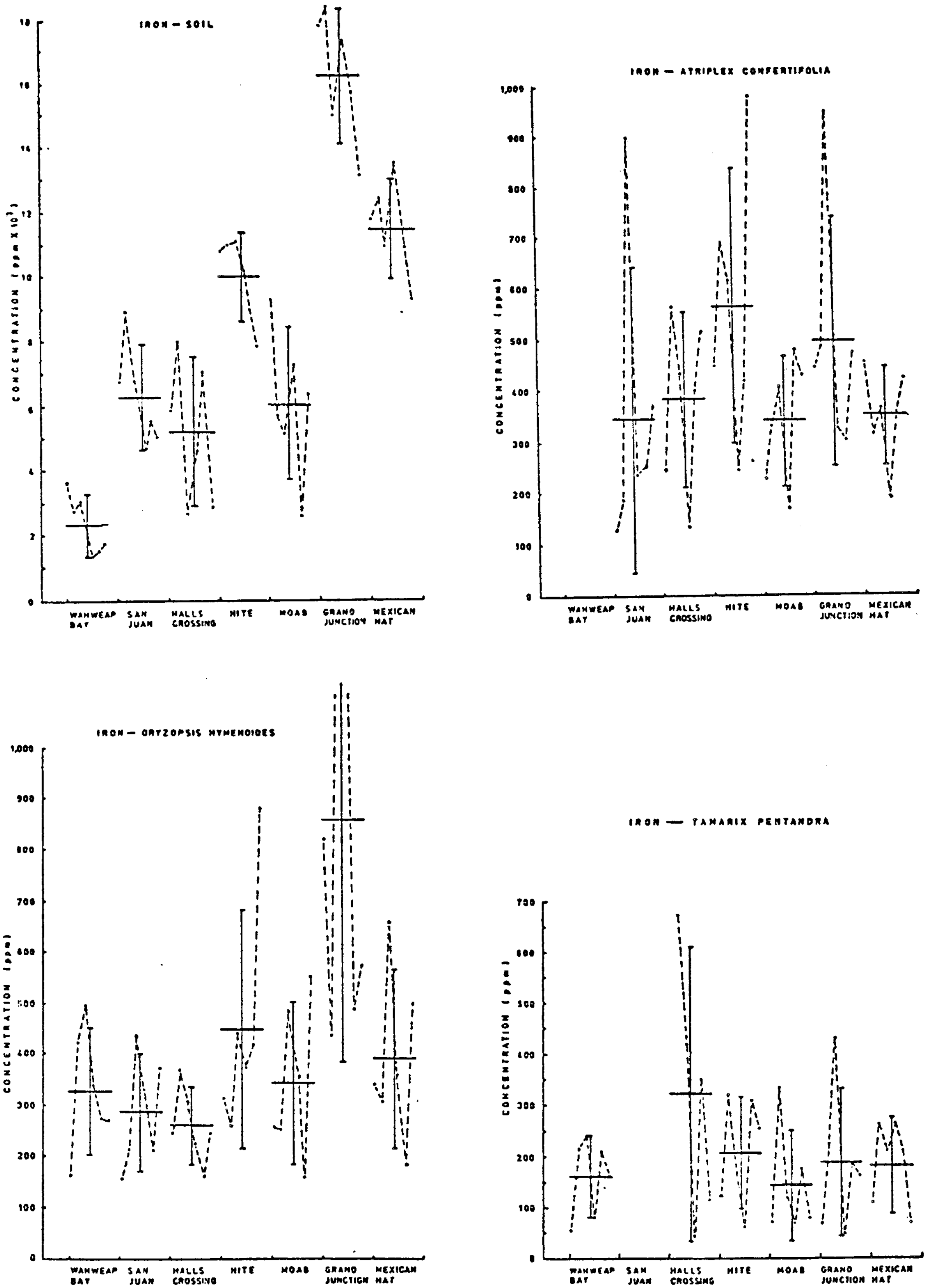

Figure 45. Concentrations of iron (1974-75) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

rock material, iron in the soil occurs as free oxides or in the clay minerals substituting for aluminum. In alkaline areas such as this area, iron is relatively insoluble and thus relatively unavailable for plant absorption. The problem is not a deficiency but an unavailability linked to alkalinity. It is therefore not surprising to find no significant differences in iron concentration in plants between sites, e.g., Atriplex (Figure 45). However, Oryzopsis at Grand Junction does have a significantly higher concentration than at Halls Crossing (Figure 45). The iron concentrations in Tamarix are all relatively low and not significantly different. There appears to be the highest concentration in Tamarix in the July samples (Figure 45).

The mean annual concentration of iron in soils is lowest at Wahweap (2,363 ppm) and highest at Grand Junction (16,267 ppm). The range of mean concentrations in plants is 341 to 567 ppm for Atriplex; 261 to 859 ppm for Oryzopsis; and 143 to 322 ppm for Tamarix.

Lead

The only significant difference in lead content of surface soils is between the high at Grand Junction and the low at Halls Crossing (Figure 46). Again, the mean values for the sites along Lake Powell are lower than the tributary and upstream sites. Lead concentrations in surface soils tend to be outstandingly higher than at increased depths (National Academy of Sciences, 1972). This results from accumulation of lead through plant organic material as insoluble complexes. Some is from precipitation and if near population centers is from industrial fumes and auto exhaust. It has been reported (Bertine and Goldberg, 1971) that more lead has been added to the land and oceans by the use of tetraethyl lead in gasoline than naturally by rivers from weathering. In Atriplex (Figure 46) the concentration of

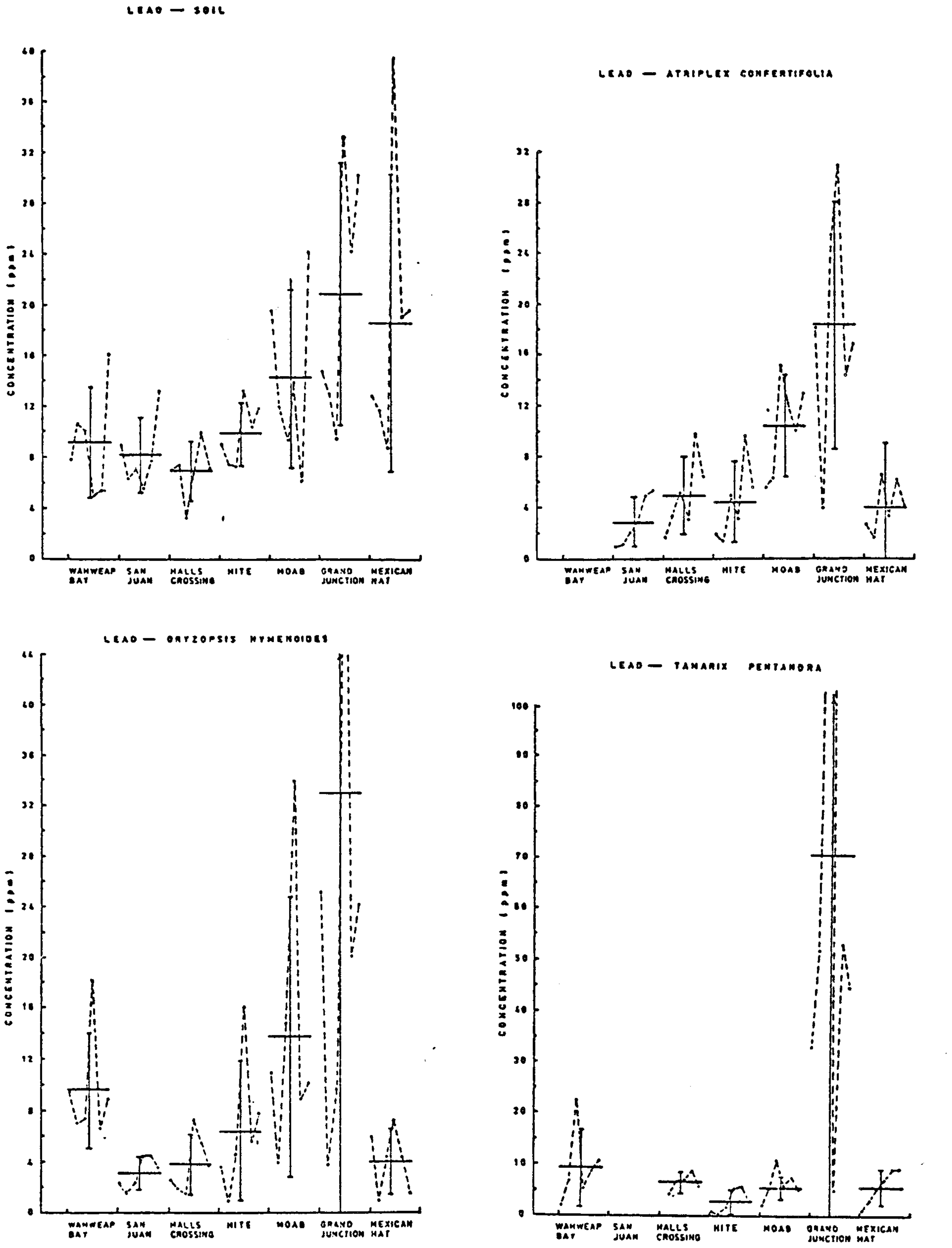

Figure 46. Concentrations of lead (1974-75) with means and 95% confidence limits for soils, Atriplex confertifolia, Oryzopsis hymenoides, and Tamarix pentandra.

lead is significantly higher at Moab than at San Juan; that of the Grand Junction sample, also highest in the soil, is significantly higher than at San Juan, Halls Crossing, and Hite. Possible causes of the high concentration at Grand Junction could be the proximity to highway traffic and the use of chemicals in the surrounding agricultural lands. For Oryzopsis (Figure 46) only the samples at Wahweap and San Juan are significantly different. There is no traffic or agriculture for miles around the San Juan Site and although the soil levels at Wahweap are relatively low, the lead concentration of the vegetation may be increased from auto exhaust from the traffic around the marina. At most sites the November samples have the highest concentration of lead. Although not significantly different, the annual mean lead concentration of Tamarix at Wahweap is also higher than at other Lake Powell sites (Figure 46). No Tamarix samples are significantly different from site to site, although the mean annual concentration is much greater at Grand Junction, as it is for the other two plant species.

Mean annual lead concentrations in soils range from a low at Halls Crossing of 7.0 ppm to a high at Grand Junction of 20.9 ppm. Concentrations in Atriplex range from 2.94 ppm at San Juan to 18.36 ppm at Grand Junction; in Oryzopsis from 3.15 ppm at San Juan to 33.08 ppm at Grand Junction; and in Tamarix from 2.85 ppm at Hite to 70.07 ppm at Grand Junction.

Magnesium

The outstanding site for soil concentration of magnesium is at Hite, which might be expected as magnesium is especially common to limestones. The Chinle formation which lies above the Moenkopi exposed at Hite provides outwash from its claystones, siltstones, and limestones, some of which are dolomitic and have a high Mg:Ca ratio. The soil concentrations at Hite are significantly higher than at Wahweap and Moab and probably at San Juan (Figure 47). The concentration at Wahweap is significantly lower than all other sites except San Juan and Halls Crossing. These three sites are far removed from any source of limestone. Magnesium, essential for plant growth, is commonly deficient in sandy soils. However, it is quite soluble and readily transported. Atriplex shows a response to the high magnesium concentrations in the soil at Hite by having significantly higher concentrations than occur at Moab, Grand Junction, or Mexican Hat (Figure 47). Concentrations at Moab are significantly lower than at Halls Crossing or at Hite. Oryzopsis shows no significant differences between sites and is distinctly low in its concentration of magnesium (Figure 47). Tamarix shows no significant differences but the annual means are generally related to concentrations of magnesium in the respective soils (Figure 47).

Annual mean values of magnesium in soils range from a low of 2,423 ppm at Wahweap to a high of 12,446 ppm at Hite. The range in mean annual values for Atriplex is from 6,909 ppm at Moab to 12,630 ppm at Halls Crossing; for Oryzopsis from 1,232 ppm at San Juan to 1,769 ppm at Halls Crossing; and for Tamarix from 4,066 ppm at Moab to 12,875 ppm at Halls Crossing.

Selenium

Selenium tends to have low concentrations in igneous rocks and higher in sedimentary rocks, especially in shales. Because of the attraction of selenium to organic matter it increases in proportion to organic debris and may cause variations in concentrations in sandstones. Unfortunately, total selenium is not a good index of plant-available selenium. Under alkaline, well-aerated conditions selenium is present as selenate, which unlike selenite, is soluble and does not form either insoluble

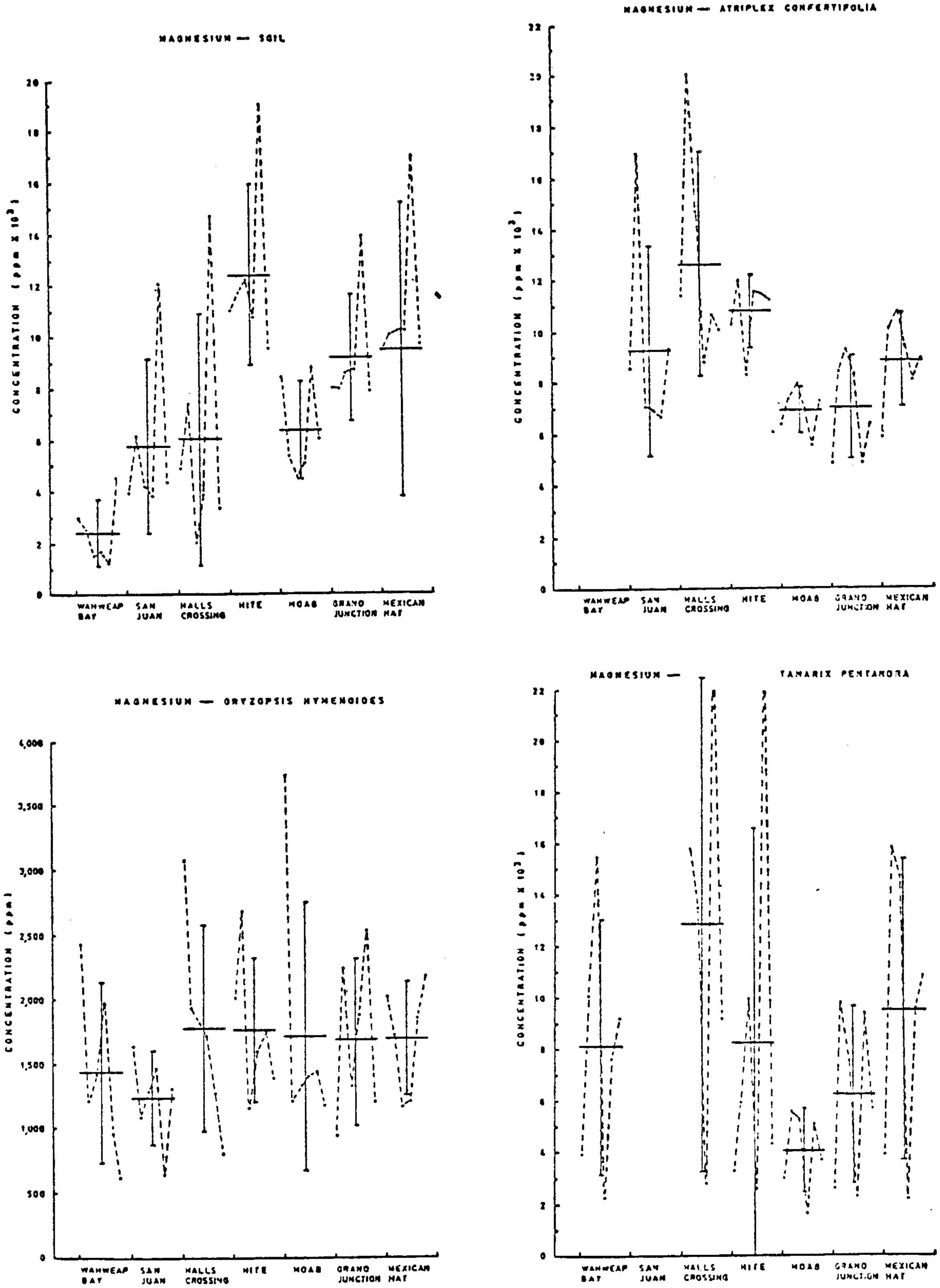

Figure 47. Concentrations of magnesium (1974-75) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

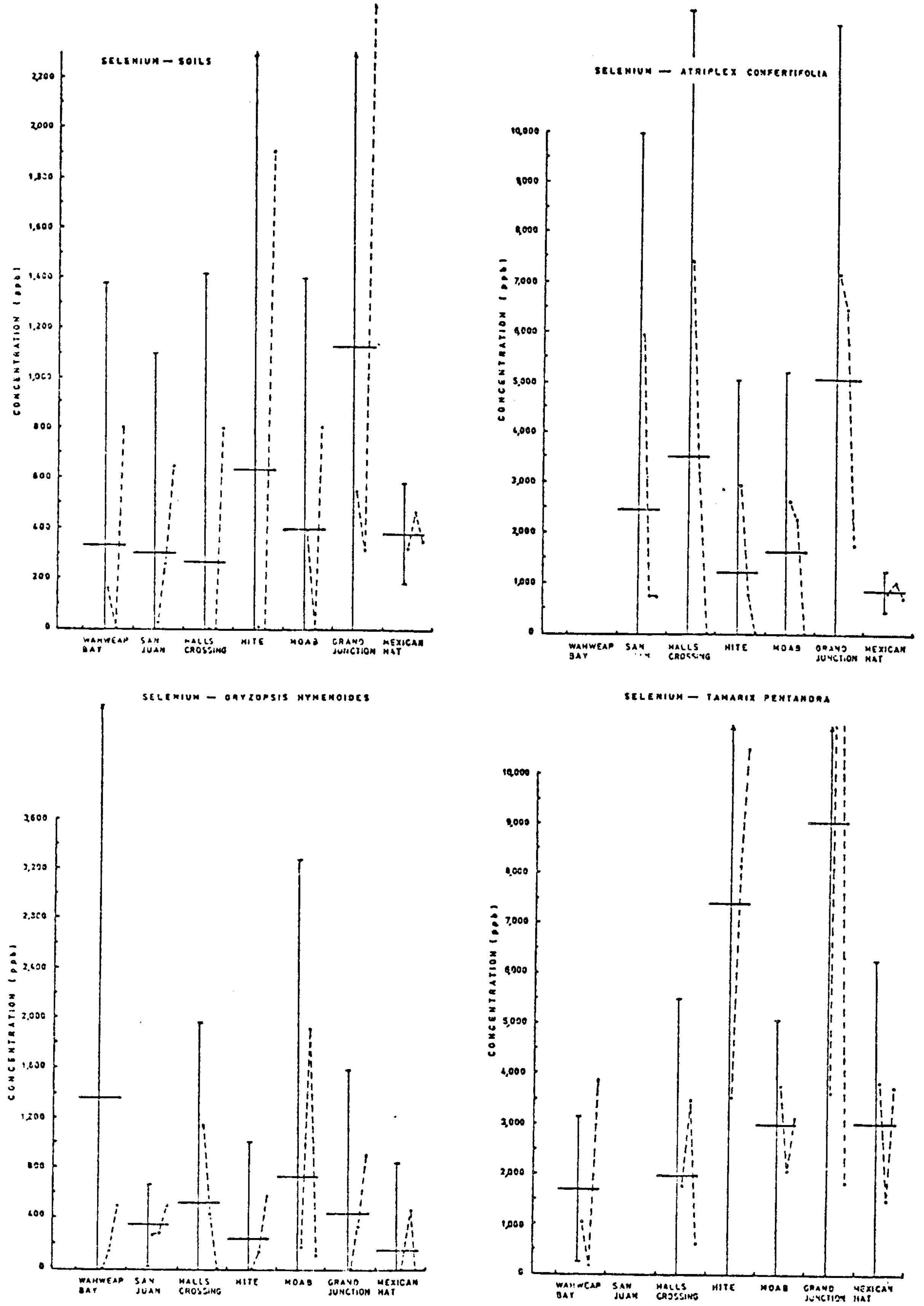

Figure 48. Concentrations of selenium (1975) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

salts or stable adsorption complexes. Lake Powell is in the area of the U. S. where 60 percent of all forage contains >0.1 ppm of selenium and in some low, alkaline soils may have plants which become toxic (Nicholas and Egan, 1975). Toxicity levels to livestock are reached at 4 to 5 ppm of selenium in forage (Schipper, Whitman, Moraghan, 1974). None of the sites have soils which are significantly different than others (Figure 48). The mean value at Grand Junction appears to be highest, as would be expected as the alluvium is a thin mantle over a deep bed of Mancos shale. The soil at Hite is relatively high and may be related to the presence of outwash from the shale beds of the overlying Chinle formation in that area. In *Atriplex*, which is sometimes reported as a selenium accumulator, there are no significant differences but the mean annual value of plants at Grand Junction is the highest (Figure 48). Values for the grass *Oryzopsis* are relatively low and there are no statistical differences between sites (Figure 48). Values in *Tamarix* are relatively high but with no statistical differences (Figure 48).

Mean annual values of selenium for soils range from 267 ppb at Halls Crossing to 1,123 ppb at Grand Junction. The range for *Atriplex* is from 872 ppb at Mexican Hat to 5,079 ppb at Grand Junction; for *Oryzopsis* from 162 ppb at Mexican Hat to 1,359 ppb at Wahweap; and for *Tamarix* from 1,710 ppb at Wahweap to 9,051 ppb at Mexican Hat.

Zinc

Zinc is known to accumulate in manganese and iron sediments, so it probably has the same association in soils. It is also known to enter into layer lattice silicate structures. In alkaline soils the monovalent hydroxy cation would be important and generally about half the zinc would be in complexes often with organic compounds (Nicholas and Egan, 1975). Inhibition of zinc absorption is caused by the presence of copper, but not by iron, and also by an increase in the pH (Nicholas and Egan, 1975).

Zinc concentration in surface soils is significantly higher at Grand Junction than at all other sites (Figure 49). It is suggested that this is due to the spraying in the area related to orchard practice. The concentration at Mexican Hat is significantly higher than all other areas except Grand Junction. The concentration at Wahweap is significantly lower than at San Juan and Hite. For *Atriplex* no sites are significantly different, although the mean value at Grand Junction, like soils, is the highest (Figure 49). For *Oryzopsis* the only significant difference is between the low value of the plants at San Juan and those at Grand Junction (Figure 49). Zinc concentrations in *Tamarix* show no significant differences between sites (Figure 49) but the annual mean values at Mexican Hat are lowest as they are also for *Atriplex*, even though the mean soil concentrations are next to the highest.

The mean annual concentrations of zinc in surface soils range from a low of 10.7 ppm at Wahweap to a high of 60.1 ppm at Grand Junction; in *Atriplex* from 872 to 5,079 ppm; in *Oryzopsis* from 162 to 1,359 ppm; and in *Tamarix* from 1,710 ppm at Wahweap to 9,051 ppm at Grand Junction.

Summary

In summary the concentrations of heavy metals in soils and plants at sites along Lake Powell are compared to the other sites in Table 36. The concentrations of elements in the soil are lower in the lake sites for all the heavy metal cations. However, the concentrations within the plant species do not always conform to the respective soil concentrations.

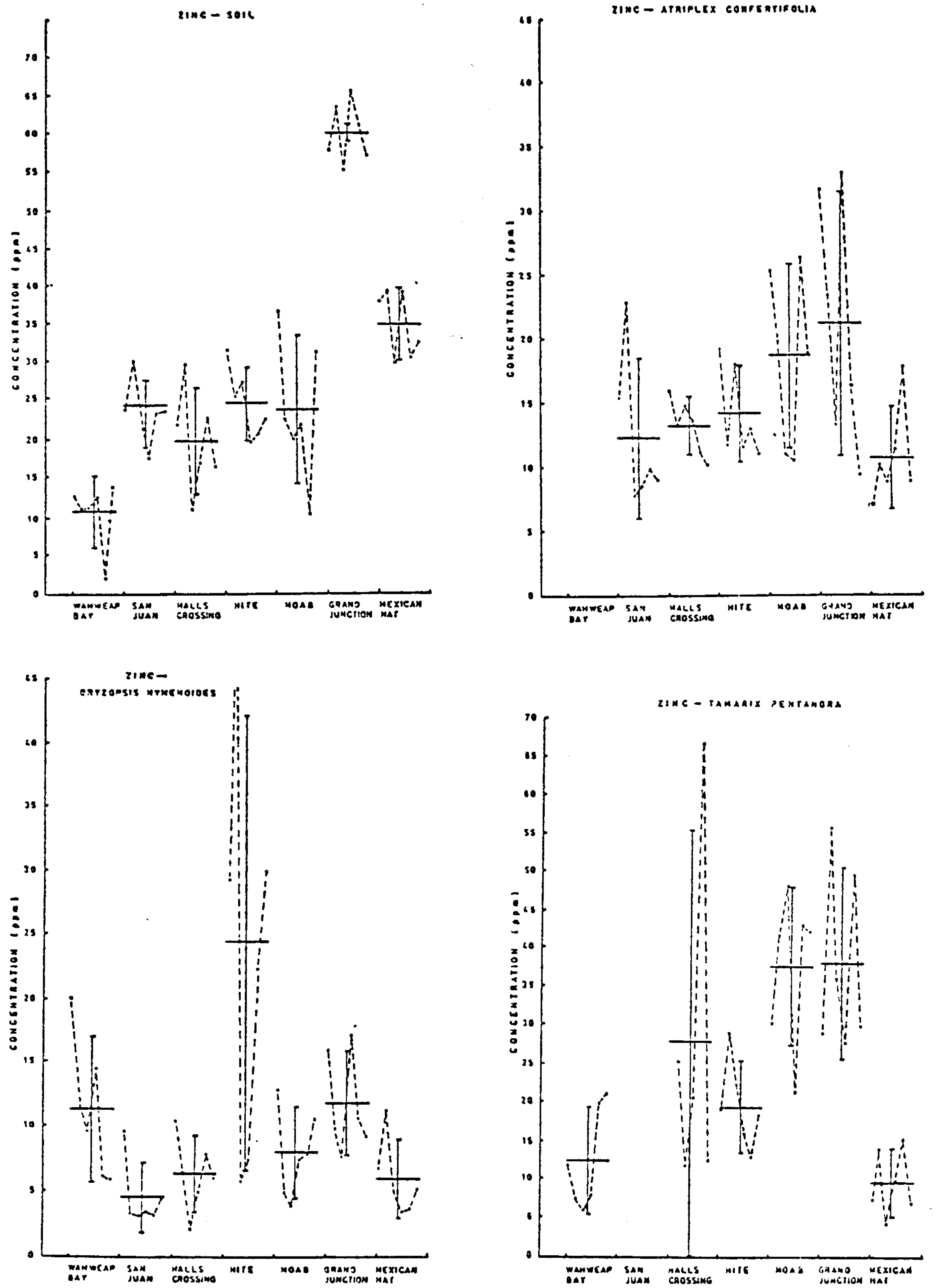

Figure 49. Concentrations of zinc (1974-75) with means and 95% confidence limits for soils, *Atriplex confertifolia*, *Oryzopsis hymenoides*, and *Tamarix pentandra*.

Concentrations in the lake sites are higher in Atriplex for arsenic, iron, and magnesium; in Oryzopsis for arsenic, selenium, and zinc; and in Tamarix for arsenic, calcium, chromium, iron, and magnesium.

For the individual sites the concentrations of all elements, except calcium and magnesium (both usually nontoxic), are highest at the Grand Junction Site located near a population center, highways, and agricultural practices. However, only half of the highest concentrations in the three plant species occur at Grand Junction. In the soils, Wahweap has the lowest concentrations of calcium, chromium, iron, magnesium, and zinc; while Halls Crossing soil has the lowest concentrations of arsenic, cadmium, copper, lead, and selenium. Again, however, these low soil concentrations are not reflected in the lowest concentrations in the plant species. The site having the most elements in lowest concentration in plants is the San Juan Site (which is not lowest in soil concentrations for any element). Here Atriplex has the lowest values for cadmium, chromium, copper, and lead; and Oryzopsis has the lowest values for arsenic, cadmium, lead, magnesium, and zinc.

The large number of values of cation concentrations in soils and plant species taken over a two-year period provide the opportunity of demonstrating the degree of absorption of soil elements by plants and the potential for some elements to be increased in concentration by plant bioamplification. This process varies both with elements and plant species. The species represented are from different taxonomic groups and also represent different growth forms. Atriplex confertifolia is a salt desert species typical of the Great Basin. It normally grows on relatively heavy soils, saline, and alkaline in nature. It is a woody shrub with a woody root system. Oryzopsis hymenoides is a grass typical of sandy soils from Mexico to Canada. As a bunchgrass it has an extensive, fine, fibrous root system. Tamarix pentandra is an exotic frequenting riparian and moist sandy shorelines. It is drought-tolerant, and common to alkaline and relatively saline soils. It is rapid growing and has a deep tap root as well as lateral, sprouting roots. Ephedra viridis is a nearly-leafless, green-stemmed bush with a woody root system. It is common to sandy upland soils.

In Table 37 is a summary combining all the collections of each of the above species and the soils from the sites at which each was collected. The values for the heavy metal concentrations and the number of measurements on which the mean is based are given. The absorption value of the species over that of the soil concentration is given as V/S.

Two elements, cadmium and selenium, are found in higher concentrations within all four species than in the soil. Among the four species the bioconcentration is greatest for Tamarix by a factor of about twice the other species. The only other examples of increased concentration in plant tissues are calcium in Ephedra, lead in Tamarix, and magnesium in Atriplex and Tamarix. Most elements are increased least by Oryzopsis. Members of the grasses are rarely cited as indicators or accumulators of specific elements.

HEAVY METALS IN COMPOSITE VEGETATION OF SHORELINE TYPES

During the study of the shoreline ecology of Lake Powell the vegetational species composition, percentage of foliage cover, and biomass of shoots for the principal vegetational types were determined (Potter and Pattison, 1976). For four

Table 37. Summary of mean concentrations of heavy metals from soil and plant samples from seven sites and six dates, 1974-75 (arsenic and selenium based on 3 dates).

	Arsenic (ppm)	Cadmium (ppb)	Calcium (ppm)	Chromium (ppm)	Copper (ppm)	Iron (ppm)	Lead (ppm)	Magnesium (ppm)	Selenium (ppb)	Zinc (ppm)
<u>Atriplex confertifolia</u>	1.13 (45)*	416 (108)	20,159 (108)	1.29 (108)	3.25 (108)	414 (108)	7.5 (108)	9,243 (108)	2,476 (54)	15.1 (108)
Soil	3.93 (108)	128 (108)	30,747 (108)	15.3 (108)	9.98 (108)	9,228 (108)	13.1 (108)	8,241 (108)	520 (108)	31.2 (108)
V/S**	0.29	3.25	0.66	0.08	0.33	0.04	0.57	1.12	4.76	0.48
<u>Oryzopsis hymenoides</u>	0.73 (63)	361 (126)	3,933 (126)	2.02 (126)	3.21 (126)	418 (126)	10.6 (126)	1,611 (126)	551 (63)	10.4 (126)
Soil	3.55 (126)	118 (126)	27,591 (126)	13.6 (126)	9.03 (126)	8,247 (126)	12.6 (126)	7,409 (126)	492 (126)	28.2 (126)
V/S	0.21	3.06	0.14	0.15	0.36	0.05	0.84	0.22	1.12	0.37
<u>Tamarix pentandra</u>	1.36 (54)	1,042 (108)	13,043 (108)	1.64 (108)	5.62 (108)	200 (108)	16.8 (108)	8,191 (108)	4,365 (54)	24.3 (108)
Soil	3.33 (108)	130 (108)	29,384 (108)	14.5 (108)	9.58 (108)	8,572 (108)	13.3 (108)	7,681 (108)	522 (108)	29.1 (108)
V/S	0.41	8.02	0.44	0.11	0.59	0.02	1.26	0.07	8.36	0.84
<u>Ephedra viridis</u>	1.93 (18)	229 (36)	19,103 (36)	0.47 (36)	2.67 (36)	200 (36)	4.7 (36)	3,422 (36)	914 (18)	8.8 (36)
Soil	3.08 (36)	55 (36)	12,742 (36)	6.0 (36)	4.52 (36)	4,330 (36)	8.7 (36)	4,103 (36)	318 (36)	17.1 (36)
V/S	0.63	4.16	1.50	0.08	0.59	0.05	0.54	0.83	2.87	0.51

*(N) Number of values on which mean is based.

**(V/S) Vegetation/Soil ratio, an increase in concentration in vegetation is represented by > 1.0.

of the vegetational types the percentage weight of each species was used to make up a composite sample representing the vegetation of that type. Plants were collected in May 1974. These samples were then used to test for the vegetational heavy metal composition. The four types tested were typical of shelfy terrace, domed terrace, talus, and dune sands.

The shelfy terrace type is located on the upper part of the Navajo sandstone which is thinly cross-bedded and cemented with calcite. It represents about 2.3 percent of the shoreline. The domed terrace type found principally within the Navajo sandstone has vegetation located principally in fracture lines and erosional depressions with pockets of sand; its extent is about 21 percent of the shoreline. Talus slopes are derived from a variety of strata of cliff-forming rocks and are composed of mixed sizes of rubble. They represent about 18 percent of the shoreline. Extensive areas of sand represent about 2.5 percent of the shoreline.

Table 38 summarizes the data for the mean concentration of ten heavy metals in the four types. The biomass in grams per square meter and the percentage foliage cover for each type had been determined to be as follows: shelfy terrace 11.7 g, 1.4 percent; domed terrace 13.8 g, 1.5 percent; talus 45.2 g, 5.0 percent; and dune sand 86.5 g, 5.0 percent.

The concentration of cadmium is significantly higher in the shelfy terrace and sand vegetation than it is in that of the domed terraces. Calcium is significantly higher only in the vegetation of the shelfy terraces which is likely related to the abundance of cementing calcite in this strata from which calcium would be readily available by solution of acid root excretions. The calcium concentration would be lower in the lower levels of Navajo sandstone forming domed terraces

Table 38. Mean concentrations of heavy metals and standard deviations in plant samples composited according to species composition of biomass in each of four vegetational types

Vegetational Types	As ppb	Cd ppb	Ca ppm	Cr ppb	Cu ppm	Fe ppm	Pb ppm	Mg ppm	Se ppb	Zn ppm
Shelfy Terrace										
$\bar{x}$	n.d.*	395	$17,364^{+}$	742	4.07	212	2.76	2,751	n.d.	18.4
SD$\pm$		128	663	313	.20	3	.09	87		1.2
Domed Terrace										
$\bar{x}$	668	182	14,400	717	2.61	193	2.45	$2,350^{-}$	n.d.	16.8
SD$\pm$	--	9	240	550	.05	8	.53	86		1.9
Talus										
$\bar{x}$	n.d.	253	14,239	750	4.53^{+}	150^{-}	1.43^{-}	$3,800^{+}$	n.d.	9.7^{-}
SD$\pm$		76	276	1,090	.28	.03	.04	229		1.2
Dune Sand										
$\bar{x}$	4,032	265	15,120	750	2.25^{-}	213	2.09	3,100	n.d.	12.2
SD$\pm$	--	35	833	173	.27	13	.12	87		.8

* n.d. not detectable

\+ significantly highest in concentration

\- significantly lowest in concentration and would have been partially removed in talus and dune sand deposits. There are no significant differences in chromium concentration between vegetational types. Copper is significantly highest in talus vegetation and higher in shelfy terrace than in the other two types. The copper concentration is significantly lowest in dune sand.

The iron concentration is significantly higher for vegetation of shelfy terraces and dune sand where greater oxidation might be expected. However, the significantly lowest concentration in vegetation of talus slopes is unexplained. The concentration of lead is significantly higher in vegetion of shelfy terraces than in that of talus or dune sand. The lead concentration of talus is significantly the lowest of all four types. Magnesium concentrations are significantly the highest in plants of talus. The only explanation offered might be that breakage along cliff faces frequently occurs along seep lines high in limestone, which contains more magnesium than the adjacent sandstone, and it becomes part of the talus material. Correspondingly the magnesium concentration is significantly lowest in the domed terraces of the Navajo sandstone. No detectable amounts of selenium were encountered in the vegetation of the four types sampled along the shoreline. The concentration of zinc is significantly higher in vegetation of shelfy and domed terraces than in the other two types; it is significantly lowest in the vegetation of talus.

SUMMARY

Since the upper Colorado River Basin is an area relatively free of industrial pollution, the concentrations of cadmium, chromium, copper, iron, lead, arsenic, selenium, and zinc reported by us represent natural background concentrations. Materials analyzed include water, sediments, plankton, fish, and terrestrial soils and plants.

Mass balance calculations for Lake Powell and its major tributaries indicate that Lake Powell serves as a metallic cation trap for all elements investigated except lead. Although more particulate phase lead is trapped in the reservoir than exits the impoundment, some 4.06×10^4 kg of lead in the dissolved phase leaves the reservoir. This indicates that the reservoir releases more dissolved lead than the input from the tributaries. We suggest that this difference is due to cultural inputs of lead in lower Lake Powell. For any management program, lead concentrations at the dam and Wahweap Bay should be included in routine analyses.

Analysis of water samples collected at tributary sites indicate occasional concentrations that exceed drinking water standards. Dissolved iron, selenium, and zinc exceeded the threshold standard at certain times. Analyses of surface and bottom waters within the reservoir were below the threshold standard except for dissolved iron. All elements at every tributary and reservoir site were within acceptable concentrations if the water is used for irrigation. Total lead concentrations in bottom waters of Lake Powell did approach the drinking water standard at certain times.

Estimated inputs of various elements from the Navajo Power Generating Station would not appreciably raise the concentrations of elements that are of public health significance in the surface waters of Lake Powell.

Cation concentrations in bottom sediments were found to be relatively low in comparison to similar sediments from other parts of the country. Therefore, we think that our values represent background concentrations. Distributional patterns of total lead in bottom sediments do suggest localized cultural inputs of this element.

In spite of the relatively low concentrations of elements in water and bottom sediments, plankton were capable of concentrating various cations a thousand to a millionfold above the levels in water. Although copper concentrations in plankton as high as 820 ppm were detected, there was no evidence that any element investigated was detrimental to the phytoplankton and zooplankton components.

In fish, mercury was concentrated some 8,000 to 43,000 times in muscle. These concentration factors were higher than for any other element. On the basis of comparing Lake Powell fish flesh concentrations to suggested threshold levels in foods, no elemental concentration in flesh from game fish collected in the reservoir is of public health significance except selenium. We believe that mercury and copper undergo bioaccumulation through food chains and that lead, selenium, and zinc display bioconcentration from water, and that arsenic, cadmium, and chromium are taken up by both mechanisms.

Concentrations of elements investigated in terrestrial plants and soils collected at reservoir and tributary sites, represent background levels and provide insight into the amount of variation in concentrations of cations. For all elements analyzed of public health significance, soil concentrations were highest at the Grand Junction, Colorado site. This location is near a population center, highways, and agricultural activities. However, not all elements analyzed in plant materials had their highest concentrations at this location. Concentrations in plant species do not always conform to concentrations in soils. Calculated absorption values for species over that of soil concentrations indicates that element uptake varies according to the chemical and biological species. _Tamarix_ displays the highest bioconcentration factor and _Oryzopsis_ the least. This confirms that grasses are generally poor indicators of heavy metal element concentrations in a region. Tamarix may be a useful indicator plant.

Analysis of elements in sediment cores did not indicate any pattern of increased concentrations of any cation in recent years within the reservoir.

All of the data analyzed in a variety materials represents baseline concentrations and should serve as an important standard of comparison for the future, particularly as regional population and industrialization increase in this energy-rich region.

LITERATURE CITED

Anderson, R.Y. 1975. Remote sampling of seasonal sedimentation Wahweap Bay, Lake Powell, Arizona, Utah. Prelim. Rep. to NSF. 38 pp.

Anderson, R.Y. 1977. Short term sedimentation response in lakes in western United States as measured by automated sampling. Limnology and Oceanography 22(3):423-433.

Andren, A.W., D.H. Klein, and Y. Talmi. 1975. Selenium in coal-fired stream plant emissions. Environ. Sci. Technol. 9(9):856-858.

Angino, E.E., L.M. Magnuson, and T.C. Waugh. 1974. Mineralogy of suspended sediment and concentration of Fe, Mn, Ni, Zn, Cu, and Pb in water and Fe, Mn, and Pb in suspended load of selected Kansas streams. Water Resources Research 10(6):1187-1191.

Bertine, K.K. and E.D. Goldberg. 1971. Fossil fuel consumption and the major sedimentary cycle. Science 173:233-235.

Bidwell, R.G.S. 1974. Plant Physiology. MacMillan Publ. Co., N.Y.

Bohn, N.L. 1972. Soil absorption of air pollutants. J. Environ. Qual. 1:373-377.

Bussey, R.E., D.E. Kidd, and L.D. Potter. 1976. The concentration of ten heavy metals in some selected Lake Powell game fishes. Lake Powell Research Project Bull. No. 34. 69 p. National Science Foundation Research Applied to National Needs.

Chen, K.Y., S.K. Gupta, A.Z. Sycip, J.C.S. Lu, M. Knezevic, and W.W. Choi. 1976. Research study on the effect of dispersion, settling, and resedimentation on migration of chemical constituents during open-water disposal of dredged materials. Final Report prepared for Environmental Effects Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss. 221 p.

Crecelius, E.A. and D.Z. Piper. 1973. Particulate lead contamination recorded in sedimentary cores from Lake Washington, Seattle. Environ. Sci. Technol. 7(11):1053-1055.

Drucker, H. and R.E. Wildung (eds.). 1977. Biological implications of metals in the environment. Proc. of Fifteenth Annual Hanford Life Sciences Symposium, Richland, Wa. ERDA Symposium Series No. 42. 682 p.

Federal Water Pollution Control Administration (FWPCA). 1968. Water Quality Criteria. Report of the National Technical Advisory Committee to the Secretary of the Interior. Superintendent of Documents, U.S. Government Printing Office, Washington, D.C. 234 p.

Gibbs, R.J. 1973. Mechanisms of trace metal transport in rivers. Science 180:71-73.

Gutenmann, W.H., C.A. Bache, W.D. Youngs, and D.L. Lisk. 1976. Selenium in fly ash. Science 191:966-967.

Holmes, C.W., E.A. Slade, and C.J. McLerrun. 1974. Migration and redistribution of zinc and cadmium in marine estuarine system. Environ. Sci. Technol. 8(3):255-259.

Iskandar, I.K. and D.R. Keeney. 1974. Concentration of heavy metals in sediment cores from selected Wisconsin lakes. Environ. Sci. Technol. 8(2):165-170.

Johnson, C.M. and A. Ulrich. 1959. Analytical methods for use in plant analysis. California Experimental Station, Bulletin 766, pp. 27-33.

Kharkar, D.P., K.K. Turekian, and K.K. Bertine. 1968. Stream supply of dissolved silver, molybdenum, antimony, selenium, chromium, cobalt, rubidium, and cesium to the ocean. Geochimica et Cosmochimica Acta, 32:285-298.

Kirkland, D.W. and R.Y. Anderson. 1969. Composition and origin of the Rita Blanca varves, pp. 14-46. In Anderson, R.Y. and D.W. Kirkland (eds.). 1969. Paleoecology of an early Pleistocene lake on the High Plains of Texas. Geol. Soc. of Amer. Memoir 113.

Klein, D.H., A.W. Andren, J.A. Carter, J.F. Emery, C. Feldman, W. Fulkerson, W.S. Lyon, J.C. Ogle, Y. Talmi, R.I. VanHook, and N. Bolton. 1975. Pathways of thirty-seven trace elements through coal-fired power plant. Environ. Sci. Technol. 9(10):973-979.

Kubota, J. 1974. Lead, Cd, Zn, Cu, and Co in streams and lake waters of Cayuga Lake Basin, New York. Environ. Sci. Technol. 8(3):243-248.

Lagler, K.F., J.E. Bardach, and R.E. Miller. 1962. Ichthyology. John Wiley and Sons, New York. 545 p.

Lambert, J.L. 1972. Inorganic analytical chemistry in aqueous systems, Chapt. 12. In Ciaccio, L.L. (ed.). 1972. Water and Water Pollution Handbook. Vol. 3. Marcell Dekker, Inc., New York.

Martin, J.H. and G.A. Knauer. 1974. p. 107. In Rubin, A.J. (ed.). 1974. Aqueous-Environmental Chemistry of Metals. Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

NAS. 1972. Lead: Airborne Lead in Perspective. National Academy of Sciences, Washington, D.C. pp. 28-29.

NAS. 1974a. Chromium. National Academy of Sciences, Washington, D.C.

NAS. 1974b. Geochemistry and the Environment, Vol. 1, The Relation of Selected Trace Elements to Health and Disease. Printing and Publishing Office, National Academy of Sciences, Washington, D.C. 113 p.

Nicholas, D.J.D. and A.R. Egan. 1975. Trace Elements In Soil-Plant-Animal Systems. pp. 111, 118, 123. Academic Press, N.Y.

Nix, J. and T. Goodwin. 1970. The simultaneous extraction of iron, manganese, copper, cobalt, nickel, chromium, lead, and zinc from natural water for determination by atomic absorption spectroscopy. Atomic Absorption Newsletter, 9(6):119-122.

Potter, L.D. and N.B. Pattison. 1976. Shoreline ecology of Lake Powell. Lake Powell Research Project Bull. No. 29. 238 p. National Science Foundation Research Applied to National Needs.

Standiford, D.R., L.D. Potter, and D.E. Kidd. 1973. Mercury in the Lake Powell ecosystem. Lake Powell Research Project Bull. No. 1. 21 p. National Science Foundation Research Applied to National Needs.

Schell, W.R. and R.S. Barnes. 1974. Lead and mercury in the aquatic environment of western Washington state. Chap. 3. In Rubin, A.J. (ed.). 1974. Aqueous-Environmental Chemistry of Metals. Ann Arbor Science Publishers, Inc., Ann Arbor, Mich.

Schipper, I.A., W. Whitman, and J. Moraghan. 1974. Selenium. North Dakota State Univ. Circ. V-594.

Stiff, M.J. 1971. The chemical status of copper in polluted fresh water and a scheme of analysis to differentiate them. Water Research 5(8):585-599, Pergamon Press.

Turekian, K.K. and M.R. Scott. 1967. Concentrations of Cr, Ag, M, Ni, Co, and Mn in suspended material in streams. Environ. Sci. Technol. 1(11):940-942.

Utah State University. 1975. Colorado River regional assessment study, parts I-IV. Utah Water Research Laboratory, Logan, Utah.

Walther, Eric G. 1976. Predicted transport of air pollutants from the Navajo and Kaiparowits generating stations into Lake Powell. Lake Powell Research Project Bull. No. 26, 40 p. National Science Foundation Research Applied to National Needs.

Wood, J.M. 1974. Biological cycles for toxic elements in the environment. Science 183:1049-1052.

Yeager, D.W., J. Chrolak, and E.W. Henderson. 1971. Determination of lead in biological and related material by atomic absorption spectrophotometry. Environ. Sci. Technol. 5(10):1020-1022.

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GLOSSARY

allocthonous	term applied to materials which have an external origin, not formed in situ
ambient	condition or concentration of surrounding environment
anaerobes	organisms living in the absence of free oxygen
bioaccumulation	increased concentration of a material as found in successive levels of a food chain, same as bioamplification and biomagnification
bioamplification	increased concentration of a material as found in successive levels of a food chain, same as bioaccumulation and biomagnification
bioconcentration	uptake of a substance by an organism in excess of its concentration in the immediate environment
biomass	weight or volume of organic material, usually living
calcite	a mineral, calcium carbonate, $CaCO_3$, principal constituent of a limestone
catalyzed	a reaction produced by a substance (catalyst) which is not used up in the reaction
claystone	rocks which are largely composed of clay sometimes bound by iron carbonate
confidence limits	the end points of a confidence interval, measure of the true value of a parameter

concentration factor	measure of the increase in concentration, as of an element from soil to plant
dolomitic	applied to rocks containing the mineral $CaMg(CO3)_2$
dredge, Eckman or Ponar	closing devices used to grab bottom sediment materials
effluent	anything that flows forth
electrostatic precipitators	device to remove a high percentage of particulate matter, fly ash, from smoke
estuarine	of or pertaining to an estuary, drainage channel into sea where tide ebbs and flows
graphite atomizer (HGA)	chamber for high temperature volatilization of certain chemical elements for atomic absorption spectrophotometry
gypsiferous	containing gypsum, a mineral $CaSO_4 \cdot 2H_2O$
igneous	formed by solidification from a molten state, in contrast to sedimentary
input-output budget	same as mass balance
Kemmerer bottle	a device for depth sampling of water
mass balance	as used here, measurement of amount of substance entering a lake versus amount leaving
nonparametric Spearman correlation coefficient	measure of correlation between two variables not randomly distributed

particulate material	as used here, refers to matter retained by a 0.45 μ pore size filter
phytoplankton	free-floating algae
phytotoxic	material inhibitive to plant growth
potable	water suitable for household use
ppb	measure of concentration, parts per billion or nanogram per liter
ppm	measure of concentration, parts per million or microgram per liter
riparian	pertaining to the banks of a body of water
siltstone	very fine-grained consolidated elastic rock composed principally of silt grade particles
spectrophotometer	optical instrument for comparing the intensities of corresponding colors of two spectra. Used for testing concentration of elements in a material
zooplankton	free-floating aquatic invertebrates

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