on the substrata, as well as lower the pH of the stream (Boult et al. 1994, Robb and Robinson 1995). These effects usually result in drastic reductions in benthic macroinvertebrate abundance and diversity (e.g., Dills and Rogers 1974, Letterman and Mitsch 1978, Scullion and Edwards 1980). While there are some studies of recovery of stream ecosystems following treatment for mining pollution in the Western USA (e.g., Chadwick et al. 1986, Nelson and Roline 1996), there are very few published studies of stream recovery in watersheds where AMD from coal mining has been treated. In the monitoring aspect of this study, our objective was to compare the impact of the installed vertical flow system at Jennings Environmental Education Center on the stream ecosystem of Big Run Creek. We sampled biological and chemical parameters upstream and downstream of the AMD discharge, prior to and after installation of the passive treatment system.

Methods

Detailed methods were provided in the QA/QC work plan written for this study. Below is a brief summary of the methods. Chemical and biological parameters were measured in Big Run Creek upstream and downstream of the AMD discharge source, prior to and following installation of the vertical flow system to treat the discharge. Samples were taken quarterly, February, May, August, November, from July 1996 to May 1999, with exceptions described below.

Water Chemistry

Quarterly sampling and analysis of water chemistry in Big Run Creek was supposed to be done by the U.S. Bureau of Mines Pittsburgh office and the PA Bureau of Mining and Reclamation. When it was learned they were not sampling the stream, Slippery Rock University began monitoring water chemistry in August 1997, although a few basic parameters were measured prior to that. Temperature, dissolved oxygen, pH, alkalinity and acidity were measured in the field following Standard Methods (APHA 1989). In August 1997 we began monitoring of 13 dissolved elements, Fe, Mn, Ni, Co, Pb, Al, Cu, Zn, Cd, Cr, Si, Mg and Ca. Water samples for element analysis were filtered in the field through a 0.45 micrometer Millipore Filter and fixed with concentrated HNO_3 to a $pH < 2.0$. Since we were not required to take samples for element analysis, they were given low priority and have yet to be analyzed. The samples will be analyzed using a Perkin Elmer Plasma 400 inductively coupled plasma spectrophotometer as outlined in APHA 1989. The results should be available by September 1999.

Sediment Chemistry

Sediment was sampled from the stream using an acid washed shovel beginning in October 1996. Because sediment particle size can greatly influence metal sorption, metals analysis was done on the clay fraction of the sediment. Areas that had an abundance of clay sediment were sampled at the 2 sites. Clay was separated from other particle sizes by settling. The resulting clay was dried, weighed and digested following EPA Method 3050A. The samples were analyzed for the same 13 elements as for the water samples using a Perkin Elmer Plasma 400 inductively coupled plasma spectrophotometer as outlined in APHA 1989.

Macroinvertebrates and Algae

Macroinvertebrates were sampled beginning in July 1996, although a we unofficially began sampling riffles before that date. Macroinvertebrates in riffles were sampled using a Surber sampler. Three replicate Surber samples were taken upstream and downstream on each date and were preserved in 70% ethanol. In the laboratory, individuals were sorted and identified to the lowest taxonomic level possible (usually genus). Macroinvertebrates in pool areas were sampled using an Ekman Dredge following the same procedure.

Monitoring of periphyton began in July 1996. Epilithic periphyton algae (algae that grows on rocks) was sample from rocks in riffle areas using an SG-92 sampler following the protocols of the USGS National Water Quality Assessment (NAWQA) monitoring program (Porter et al. 1993). Three replicate samples were taken upstream and downstream on each date. Epipelic periphyton (algae that grows on the sediment surface) was sampled following the coring method of NAWQA (Porter et al. 1993), 3 replicates per site per date. Samples were preserved with Lugol's Solution. Algal counts for density were done in Palmer Cells with diatoms lumped into one taxonomic category. The sample was then digested in HNO_3, rinsed, dried onto coverslips and mounted in NAPHRAX for diatom identification (DeNicola et al. 1990). All algae were identified to species. Although quarterly samples have been counted from July 1996 to November 1997 thus far, only the July 1996 to May 1997 data have been entered into the data based and analyzed.

Leaf Packs

Leaf packs containing 5 g of dried sugar maple leaves were placed upstream and downstream of the treatment discharge in the fall of 1996, 1997 and 1998. Packs were removed over the next six months following placement and the leaves dried and weighed.

Metal Concentration in Invertebrate Tissue

Given the extremely low density of the macroinvertebrate fauna in Big Run Creek, it was difficult to collect enough of one type of organism to measure concentrations of metal in their tissues. In the summer of 1996, 0.28-0.41 g wet weight of hydropsychid caddisfly larvae were collected upstream and downstream of the AMD/treatment input. The organisms were digested following EPA Method 3050A for sediments. The samples were analyzed for the same 13 elements metals as for sediment samples using a Perkin Elmer Plasma 400 inductively coupled plasma spectrophotometer as outlined in APHA 1989. We were unable to collect enough organisms in the summers of 1997 and 1998 for a similar analysis.

Results

Physical Parameters

Discharge in the Big Run Creek varied from about 0.01 to 0.18 m^3/s (Fig 2). Flows were highest in August 1997 following a thunderstorm, but in general were high in winter and spring. There was little difference in flow between upstream and downstream as the discharge of the AMD/treatment input (ca. 0.002 m^3/s) contributed very little to the stream discharge in most seasons.

Temperature in the stream varied seasonally from 4 to 17 C (Fig. 3).

Water Chemistry

Dissolved oxygen in Big Run Creek was usually around 10 mg/l in the stream, which was near saturation or supersaturated in most seasons (Fig. 4).

Values for pH varied between 5.0 and 7.2 in the stream. Prior to treatment, the pH downstream of the AMD input was always 1.0 to 0.1 pH units less than upstream. After the treatment system was installed in the fall of 1997, pH values were usually slightly higher downstream than upstream (Fig. 5).

Alkalinities ranged from about 1-42 mg/l $CaCO_3$, and acidities were 4-20 mg/l (Figs. 6 and 7). There were only 1 or 2 measurements of alkalinity and acidity, prior to installation of the treatment system, making interpretation of post treatment trends difficult. Both alkalinity and acidity values were about the same upstream as downstream following installation of the treatment system (Figs. 6 and 7).

Sediment Chemistry

Iron in the clay fraction of the sediment was higher downstream than upstream on all but one of the sample dates (Fig. 8). After installation of the vertical flow system in the fall of 1997 there was no consistent change in the concentrations. Aluminum concentration was usually higher at the upstream site with no apparent changes occurring after installation of the treatment system (Fig. 9). Manganese in the sediment decreased by about 6 fold starting in May of 1997, about 4 months prior to the completion of the treatment system (Fig. 10). Concentrations of calcium, magnesium and silicon had no apparent trends related to installation of the treatment system (Figs.11-13). The other metals (Ni, Zn, Cd, Cr, Co, Cu, and Pb) were at much lower concentrations than the above elements (Figs. 14-20). Nickel and zinc were higher upstream than downstream on most sample dates, but overall there were no other trends for the trace metals.

Macroinvertebrate Density

The density of macroinvertebrates in riffles both upstream and downstream of the AMD treatment was very low, never reaching greater than 300 individuals/m^2 (Fig. 21). There were no apparent seasonal changes, although highest densities were generally in summer and fall samples. In general, densities increased slightly both upstream and downstream after the treatment system was installed in the fall of 1997 (Figs. 21 and 22). The increase was higher downstream of the treatment input than for upstream following installation, but the differences are probably not significant given the temporal variance.

In general, macroinvertebrate densities in pool areas were higher and more variable than for riffles, but still low relative to what would be expected in an unimpacted stream (Fig. 23). There were several dates where no invertebrates were collected in three replicate Ekman samples at a site. As in riffle areas, there was a great deal of temporal variability in pools and no apparent effect of the treatment system downstream of its input. In fact, macroinvertebrate densities in pool samples after treatment started went down, downstream of the input (Fig. 24). This was mainly a result of the usually large density found upstream in November 1996 (Fig. 23).

Macroinvertebrate Species Composition

Fifty-four taxa were identified from riffle areas in Big Run Creek in the study (Table 1). The most abundant taxa were the Dipterans, Tipula, Hexotoma and Atherix, and hydropsychid caddisflies. Diversity was extremely low, rarely being greater than 2.0 (Fig. 25) (0 is a single species in a sample). There was little change in diversity in riffle areas after treatment began (Fig. 26).

Detrended correspondence analysis plots samples in ordination space based on their similarity in species composition. DCA ordination of Surber samples taken in riffle areas showed that macroinvertebrate community composition was not related to whether the sample came from upstream, downstream, or before or after treatment (Fig. 29).

Twenty taxa were identified from pool areas, with chironomids making up most of the what was found (Table 2). Although we generally identify chironomids to genus, we did not believe the extra information would be useful given the depaperate fauna and obvious lack of trends in the macroinvertebrate assemblages. Overall, diversity in samples from pool areas was extremely low (Fig. 27). Although diversity in downstream samples pooled following treatment was higher than for pooled samples before treatment, the extremely low values indicate treatment did not substantially improve macroinvertebrate diversity in pool areas of Big Run (Fig. 28).

Leaf Pack Decomposition

Leaf packs placed in Big Run Creek prior to treatment in 1996 had a slightly faster rate of decomposition upstream than downstream of the AMD discharge (i.e., weight loss was faster) (Fig. 30). Leaf packs placed in the stream in the fall 1997 coincided with the start of the treatment system. Rate of decomposition was approximately the same upstream and downstream given the variation among replicates (Fig. 31). Leaf decomposition was much slower in the 1998 packs and downstream packs slowed very little decomposition after 18 weeks (Fig. 32). It was observed that packs were partially to fully buried under sediment at the downstream site in the 1998 packs.

Periphyton Density

Epilithic periphyton density was highest in the spring of 1997 and 1998 (Fig. 33). Upstream density was higher than downstream on most dates, particularly in the spring season. Epipelic densities also tended to be higher in the spring, although not always at both sites. There were no overall differences in density between upstream and downstream epipelon (Fig. 34). Neither epilithic or epipelic periphyton density appeared to be affected by installation of the treatment system in the fall of 1997.

Periphyton Species Composition

Over 150 species of algae were found in epilithic and epipelic periphyton assemblages in Big Run Creek (Table 3, 4 and 5). Although the species richness was very high on most sample days, diversity was low because 2 species dominated, the cyanobacteria Phormidium tenue (sp # 148) and the diatom Achnanthes minutissima (#102) (Tables 3 and 4). The remaining species in most samples were rare diatoms. Diversity was higher in epipelic assemblages, which had more rare diatom species than the epilithon. In general, diversity was similar upstream and downstream in both types of assemblages for the same date (Fig. 35).

The percent similarity among epilithic samples (replicates pooled) indicated that samples from upstream and downstream on the same date were more closely related than they were to samples from other dates (Table 6). Therefore, the epilithic algae were more influenced by seasonal differences than whether the samples came from upstream or downstream.

The May 1996 upstream and downstream epipelic samples were less similar to all other epipelic samples, as Phormidium tenue did not dominate on this date (Tables 4 and 7). As occurred for the epilithic periphyton, epipelic communities were more similar based on date than on whether they came from upstream or downstream (Table 7).

Because of the time it takes to count and identify algae, the periphyton samples taken after the treatment system was installed have yet to counted or analyzed. As a result, no statements about the affects of the treatment on periphyton species composition can be made at this time.

Metal Concentration in Caddisfly Tissue

The concentration of aluminum and zinc in the tissue of hydropsychid caddisflies collected in Big Run Creek were higher than that found in a neaby unimpacted stream, Wolf Creek (Table

8). Iron concentrations were higher in organisms in Wolf Creek however. Values for other heavy metals were at or near zero in the all the above organisms.

Discussion

Chemistry

Temperatures were low and dissolved oxygen values high for each season in Big Run Creek indicating there were no negative impacts for these parameters on organisms in the stream. Big Run had pH values as low as 5.0 on some dates both upstream and downstream. As a rule of thumb, serious biological impacts occur below pH 5.5, and these periods of low pH probably had detrimental affects on macroinvertebrate abundance and diversity in the stream. The relatively low alkalinities in the stream indicate there is little capacity to buffer periodic inflow of acids. Even though pH's were generally greater than 6 during the study, these short periods of low pH can still have a significant impact on invertebrates. Overall, alkalanity, acidity and pH values have improved in the stream since 1977. Twenty-two years ago, Horansky (1980) found pH values of 4.0-5.9, alkalinities of 0-4 mg/L and acidities of 2-43 mg/L at the same location.

There appears to have been a slight improvement in downstream pH relative to upstream following the installation of the vertical flow treatment system. There also is an indication that alkalinity may have increased slightly and acidity decreased slightly downstream following treatment, but interpretation is difficult given the few before treatment samples and the temporal variability.

Low pH and alkalanity upstream of the Jennings input indicates there are additional AMD impacts above the treatment system in the watershed. Topographic maps (USGS) and Horansky (1980) show several old strip mines and one deep mine in the upper watershed of Big Run Creek, which are likely to affect the stream (Fig. 1).

Concentrations of elements in the clay sediment were highly variable among sample dates, which made interpretation of the data difficult. Concentrations of Fe and Al were within the range of what we have found for nonimpacted streams in the area using the same method. There was no effect of the treatment system on the chemistry of the clay sediment sampled, but our methods may not have been appropriate to address whether treatment affected the overall sediment chemistry. Areas of clay were very scarce in the stream, found in just a few locations near the bank. Therefore, the chemistry of these areas were probably not representative of the stream bottom as a whole, and do not reflect what benthic organisms encounter as they do not live in clay. In addition, since clay is composed of aluminum silicates, the values of these 2 elements in the sample may reflect the kind of clay mineral rather than additional amounts sorbed from AMD input.

Macroinvertebrates and Litter Decomposition

Benthic macroinvertebrates and algae in streams integrated temporal and spatial changes in chemical parameters and can be a more informative source of water quality information than discrete chemical measurements. Macroinvertebrate densities in both riffle and pool areas of Big Run were extremely low indicating serious impairment to the community. For example, we found macroinvertebrate densities in riffles in two unimpacted streams in the Slippery Rock Creek watershed to be about 10 times higher during the same period. Although over 50 macroinvertebrate taxa were identified during the study, the diversity of Big Run Creek is also low relative to unimpacted streams. The riffle community was dominated by hydropsychid caddisflies and Dipterans, particularly Hexotoma, Tipula and Chironomidae. Pools were almost entirely composed of chironomid larvae. Other studies of impacts of AMD on stream macroinvertebrate communities have shown similar results. For example Letterman and Mitsch (1978) found AMD greatly decreased macroinvertebrate density, and had smaller effects on diversity, with hydropsychid caddisflies and dipterans being most tolerant. Our results for macroinvertebrate taxonomic composition, diveristy and density values were very similar to what was found 22 years ago in Big Run Creek by Horansky (1980).

Values for macroinvertebrate density and diversity at the upstream and downstream sites have remained approximately the same before and after treatment, indicating there has been no improvement in the community downstream of the passive treatment system after its installation in the fall of 1997. Although there may have been a slight improvement in pH and alkalinity downstream following treatment, this apparently has not improved the conditions enough to increase the macroinvertebrate community, probably because of continued AMD impacts farther upstream in the watershed. In addition, if recovery has started to occur, there is not an immediate upstream source of invertebrates to colonize the area, and colonization from areal insects can take several years. In a Rocky Mountain stream severely impacted by AMD, it took 5-10 years to get a substantial recovery in macroinvertebrates following a dramatic improvement in stream water quality (Chadwick and Canton 1986). Woolcock (1972) found very limited recovery of invertebrates on the North Branch of Slippery Rock Creek 7 months following installation of a limestone treatment plant that raised pH and alkalanity of the stream. Horansky (1980) found a slightly improved macroinvertebrate community several miles downstream of our sites, where Big Run enters Slippery Rock Creek, presumably because of dilution of some of the AMD impacts and in the inflow of a relatively of a less impacted tributary. The substratum of Big Run Creek in the vicinity of the Jennings vertical flow system is not coated with iron precipitates, and is not buried with fine sediments, as can be typical in streams draining mining areas. Relatively good, physical, substratum conditions should be favorable for macroinvertebrate recovery if the additional upstream AMD discharges are treated.

It maybe that low concentrations of some toxic heavy metals is the main impact on the macroinvertebrate fauna of Big Run Creek. The high concentrations of Al and Zn in found in hydropsychid caddisflies in Big Run Creek relative to unimpacted Wolf Creek suggests there is a posibility that toxic effects from these elements are the cause of the low macroinvertebrate density in the stream. Although concentrations of Fe were higher in Wolf Creek caddisflies, this element is relatively nontoxic and naturally abundant in the tissue of these organisms. Relatively low concentrations of Al and Zn have been found to be toxic to macroinvertebrates in streams impacted by mineral mining in the Western USA (Cain et al. 1992). We plan to collect more organisms this year and carry out in field bioassays of metal accumulation in Big Run to futher examine this possiblity.

Terrestrial leaf litter is the major energy source for small streams like Big Run Creek. Decomposition of litter is controlled by bacteria and fungal colonization of leaves and macroinvertebrate shredders of leaves. In general, low pH conditions in a stream results in decreased microbe (fungi and bacteria) colonization and decreased shredding activity (Griffith and Perry 1993). In Big Run, leaf pack decomposition was slower downstream of the AMD input in 1996 but there were no differences between upstream and downstream sites in 1997 after treatment had begun. This would suggest there was a possible improvement in the utilization of this important energy source following treatment. Unfortunately, burial of the downstream packs in 1998 prevented acquiring additional reliable data to examine this possible effect.

Periphyton

In low order streams such as Big Run Creek, periphyton is usually controlled by canopy shading and the amount of light reaching the stream. Periphyton densities in Big Run are comparable as to what would be expected in a similar sized nonimpacted stream. The higher periphyton densities in spring, before leaf out in the canopy, is also typical of small streams. Most of the impact of AMD on periphyton in Big Run Creek is a reduction in diveristy. The diversity of the periphyton communities in Big Run Creek is low, reflecting primarily the dominance of the cyanobacteria Phormidium. During most of the year, but particularly in the summer, this alga is observed to cover most of the rocks in a thick felt mat. This species is a typical alga found in low light situations but whether its dominance is related to a tolerance of a particular condition caused by AMD is not known. It appears to be more dominant on the rocks upstream of the AMD input than downstream and we have collected tissue from both sites to compare metal concentrations associated with the algal filaments. The dominant diatom, Achnanthes minutissima, is typical of disturbed conditions in streams, and has been found to be abundant in streams receiving AMD.

Installation of the treatment system has not affected periphyton density. Once the later samples are counted for algae we will be able to assess whether species composition has changed downstream of the treatment input.

Recommendations for future monitoring of AMD recovery

This study has collected a wealth of chemical and biological information on the conditions in Big Run, which has shown no substantial changes in the conditions of the stream since installation of the passive treatment system at the Jennings Environmental Education Center. While the study has provided an excellent baseline data base for documenting any future changes in the water quality of the stream, there are several aspects of the study design and methods that can be improved to provide the critical information in a less time consuming and more efficient manner. We think the following recommendations could greatly improve the approach taken to monitoring stream recovery following installation of AMD treatment systems.

1) Given the effort to analyze all the chemical and biological parameters, and because treatment efforts in a watershed usually extend over many years, we feel sampling quarterly is not merited for routine monitoring. It is perhaps best to sample quarterly for a year or two prior to treatment in a watershed to get baseline data on seasonal and discharge effects on chemical and biological parameters. Following that, samples taken once or twice a year for monitoring is probably sufficient to detect major changes in the water quality of the stream. For macroinvertebrates the best sampling times appear to be in very early spring and in late summer/early fall.

2) While it is important to analyze as many metals possible in water and sediment samples initially to see if there is a potential toxic problem with a trace metal, routine analysis of metals that have been shown to have an extremely low concentration can be eliminated.

3) While analyzing clay for sediment analysis eliminates substrate size affects, it is probably not representative of what benthic organisms are encountering. It is very difficult to sample metals from sediments accurately and effectively. Since most organisms are associated with rocks it might be more representative if scrapings of rocks in the streams were analyzed for metals. This would reflect iron, aluminum etc precipitates on the rocks that may affect invertebrates and algae.

4) Macroinvertebrate samples from pool areas usually have fewer individuals and lower diversity than riffle samples. Given the time needed to take and process Ekman samples in pools, they probably can be eliminated for monitoring without much loss of information.

5) In streams heavily impacted by AMD, macroinvertebrates are almost completely lacking while the periphyton flora can be quite abundant and species rich. Therefore, periphyton may provide more specific information on the biological recovery of heavily impacted streams.

6) More field bioassy and experimental studies are need to understand possible toxic effects of trace metals at very low concentrations in AMD impacted streams. While the water quality may be relatively good in terms of pH, alkalanity and Fe in some streams, low amounts of heavy metals in water or sediment can be impacting organisms.

7) Given the successful treatment by the vertical flow system at Jennings, further remediation of upstream AMD affects in the Big Run Creek watershed has the potential to greatly improve the macroinvertebrate and fish communities of the stream on the property of Jennings Environmental Education Center. This would increase the educational use of the stream for outdoor laboratories conducted at this facility.

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Figure Captions

Fig. 1. Map of Big Run Creek Watershed.

Fig. 2. Discharge in Big Run Creek.

Fig. 3. Temperature in Big Run Creek.

Fig. 4. Dissolved oxygen values in Big Run Creek.

Fig. 5. pH values in Big Run Creek. Arrows indicate the start of passive treatment for AMD.

Fig. 6. Alkalinity in Big Run Creek. Arrows indicate the start of passive treatment for AMD.

Fig. 7. Acidity in Big Run Creek. Arrows indicate the start of passive treatment for AMD.

Fig. 8. Concentration of iron in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 9. Concentration of aluminum in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 10. Concentration of manganese in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 11. Concentration of calcium in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 12. Concentration of magnesium in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 13. Concentration of silicon in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 14. Concentration of nickel in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

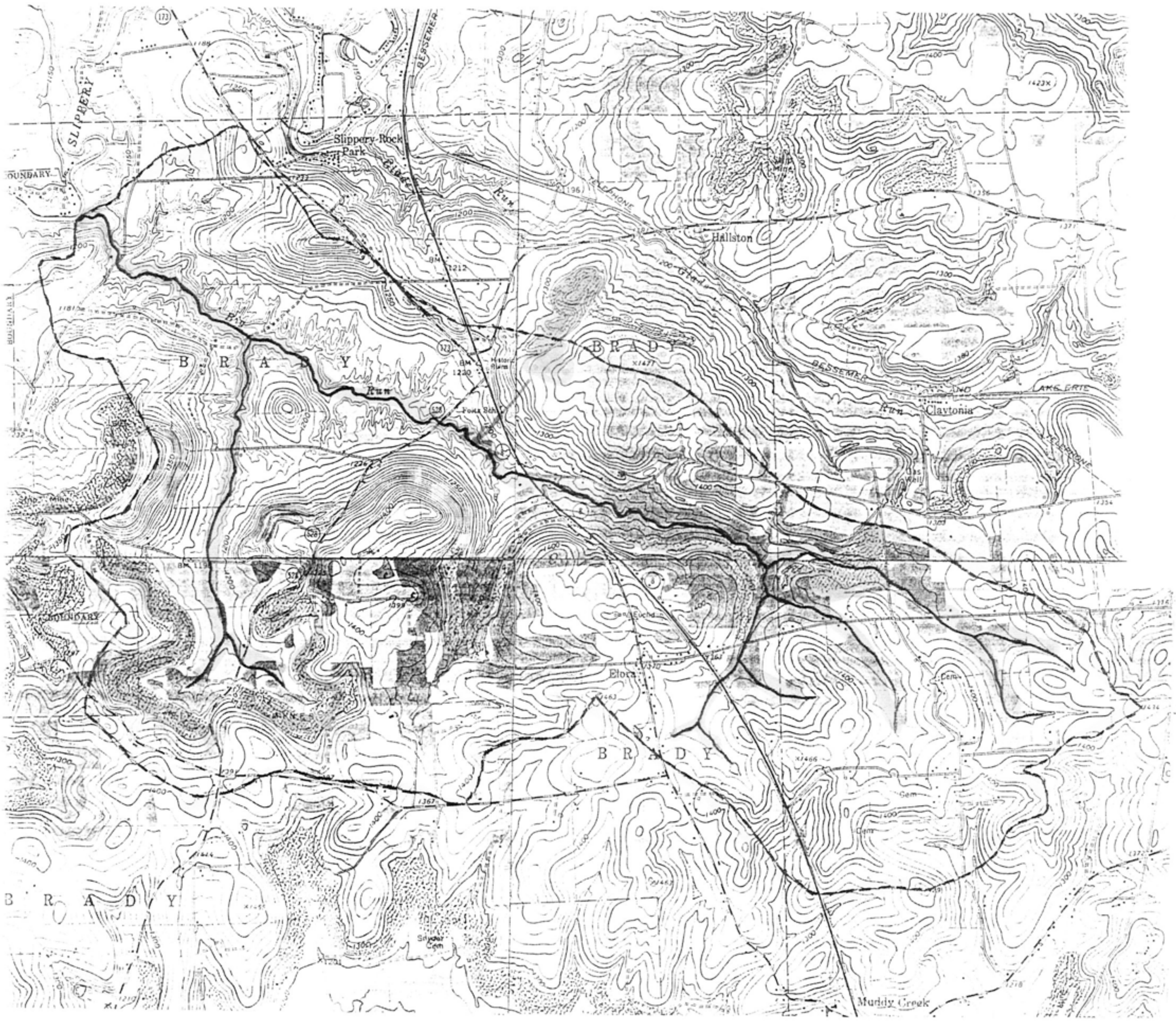
Fig. 15. Concentration of zinc in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

Fig. 16. Concentration of cadmium in the clay fraction of sediment. Arrows indicate the start of passive treatment for AMD.

passive treatment.

Fig. 34. Density of epipelic periphyton in Big Run Creek (n=3). Arrows indicate the start of passive treatment.

Fig. 35. Shannon diversity of epilithic and epipelic periphyton communities in Big Run Creek. (n=3)



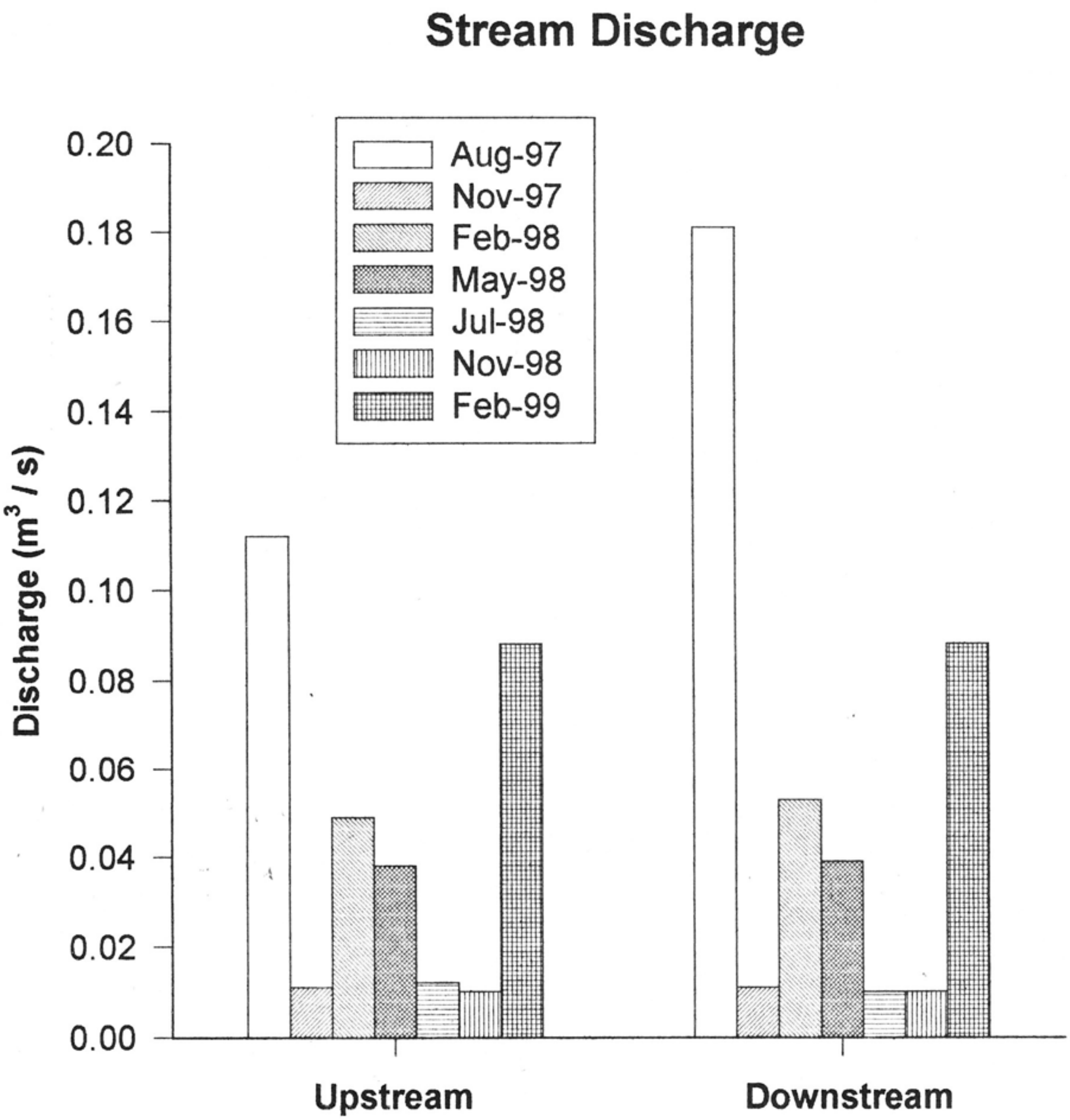
Stream

Watershed Boundary

Input from Jennings (Deep Mine)

Mines &Sample Site

Figure 1



Stream Discharge
Aug-97
Nov-97
Feb-98
May-98
Jul-98
Nov-98
Feb-99
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
Discharge (m3 / s)
Upstream
Downstream

Figure 2

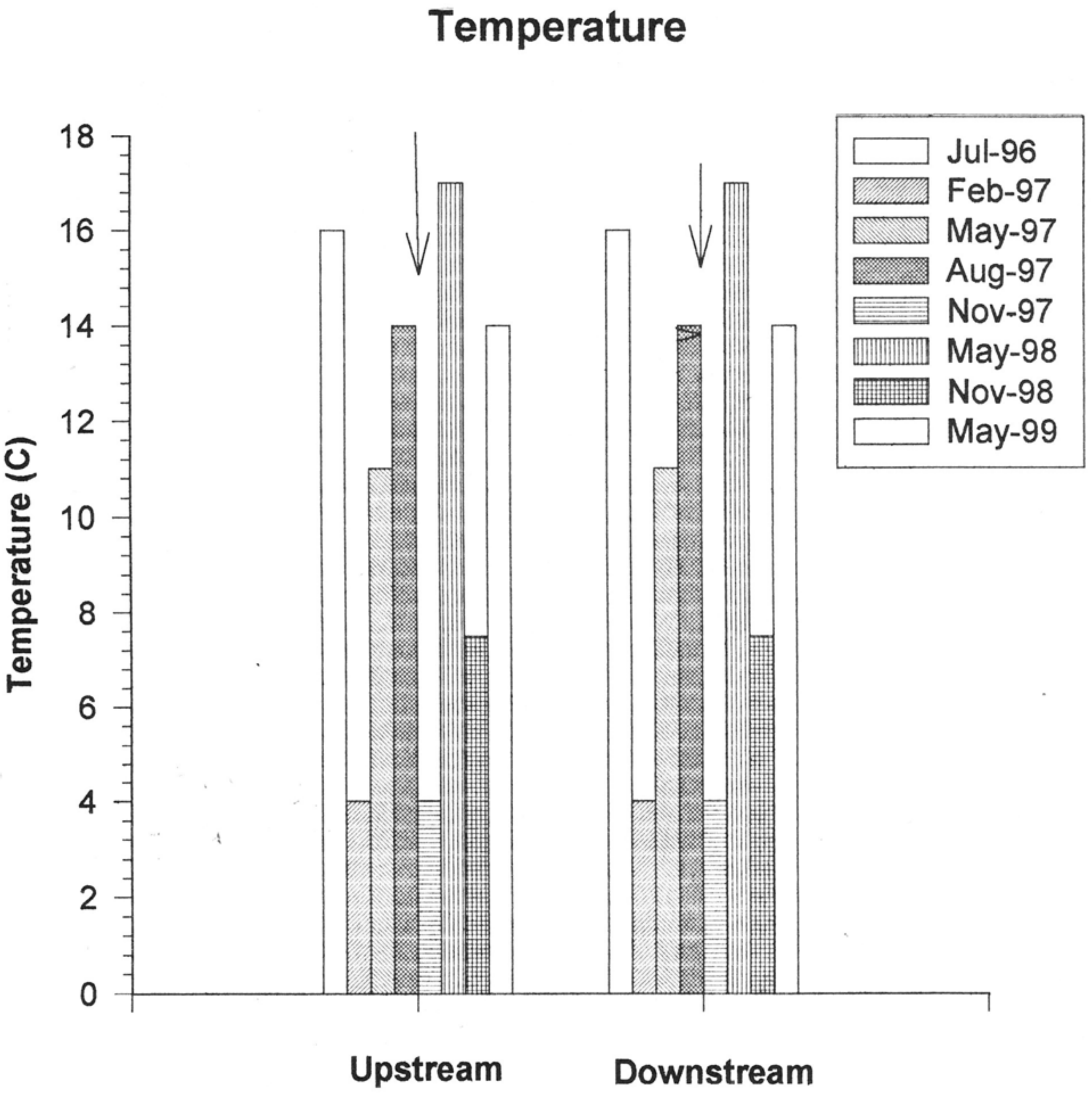
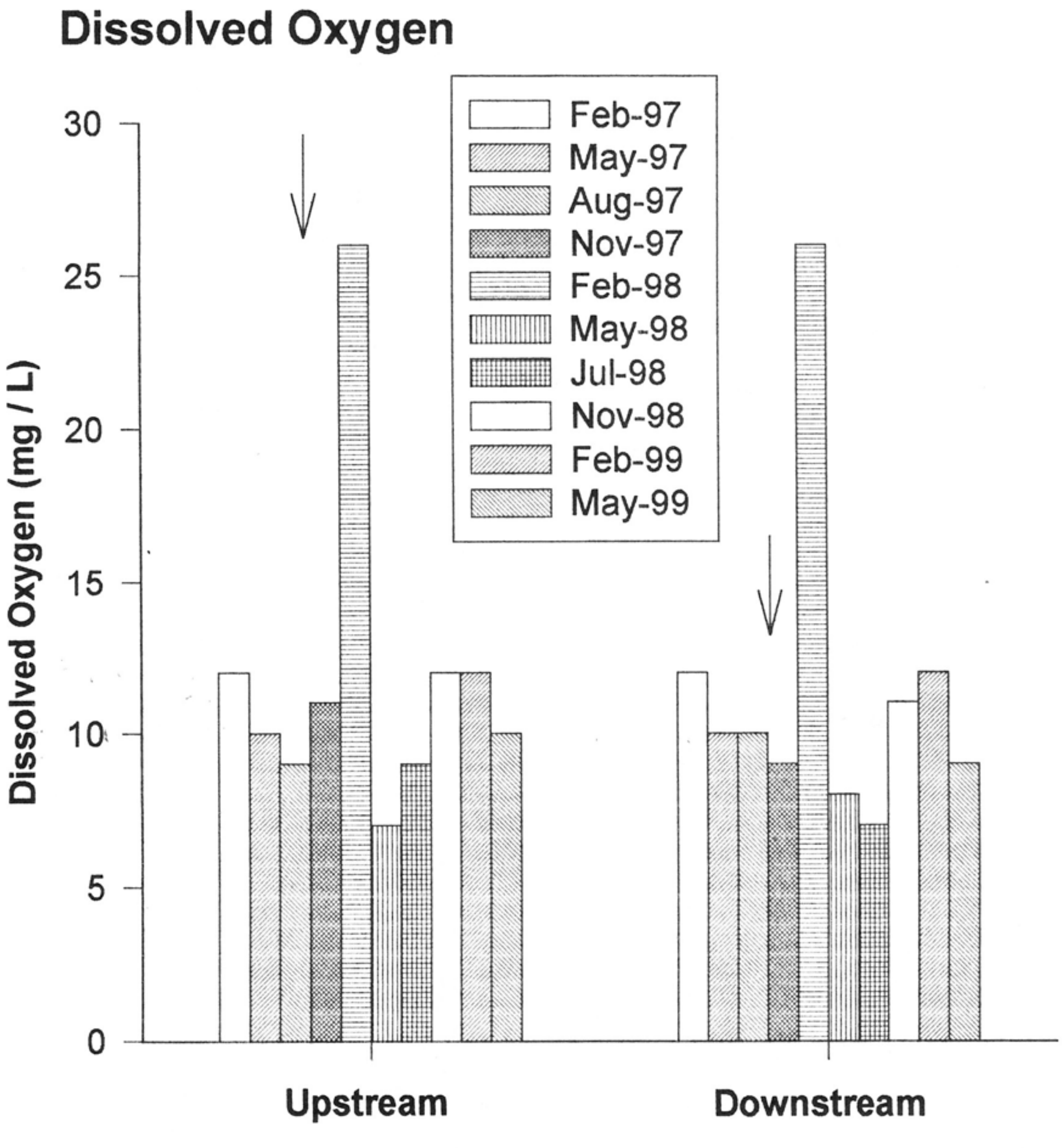
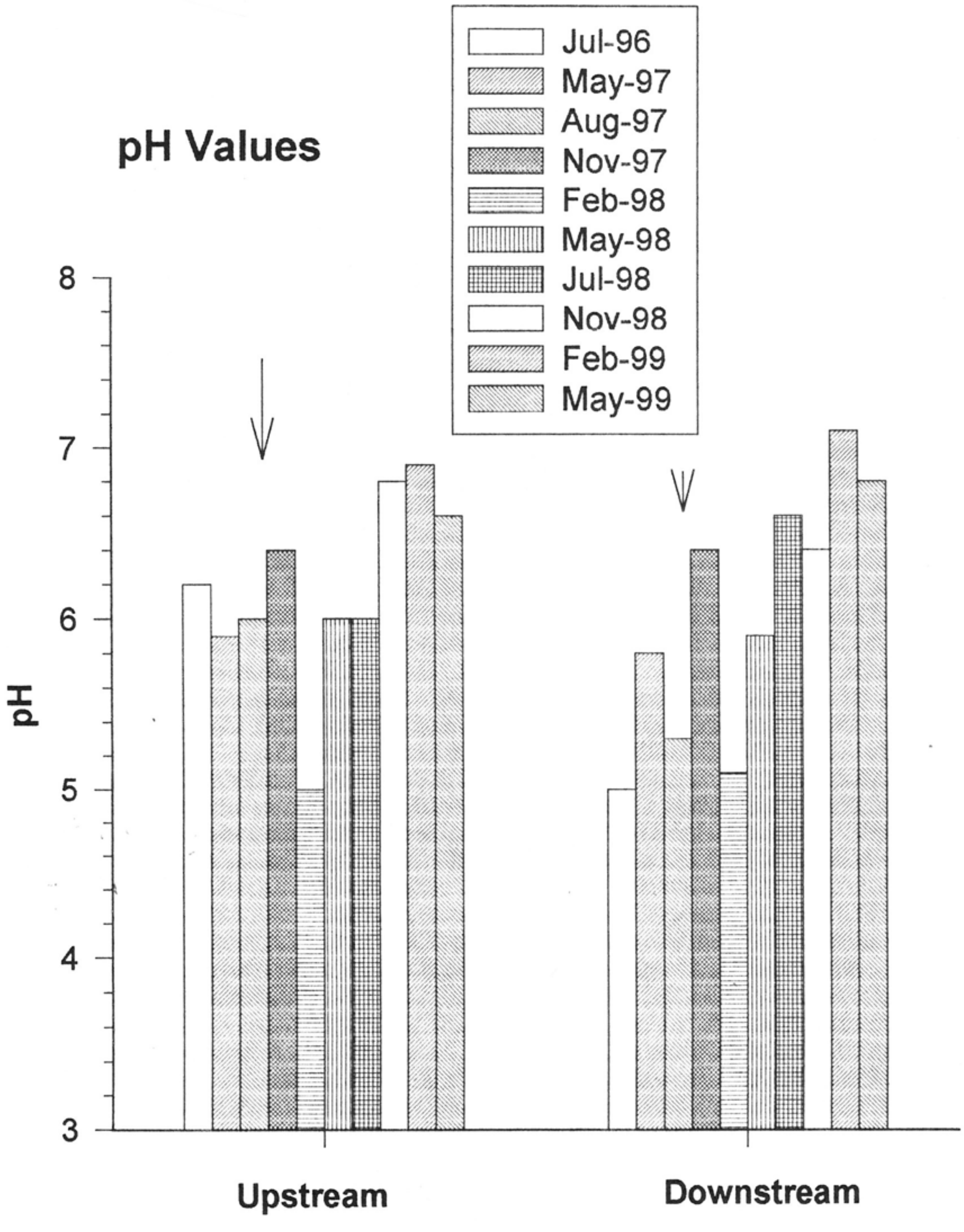

Temperature
Temperature (C)
18
16
14
12
10
8
6
4
2
0
Upstream
Downstream
Jul-96
Feb-97
May-97
Aug-97
Nov-97
May-98
Nov-98
May-99

Figure 3



Dissolved Oxygen
30
25
20
15
10
5
0
Dissolved Oxygen (mg / L)
Feb-97
May-97
Aug-97
Nov-97
Feb-98
May-98
Jul-98
Nov-98
Feb-99
May-99
Upstream
Downstream

Figure 4



pH Values
Jul-96
May-97
Aug-97
Nov-97
Feb-98
May-98
Jul-98
Nov-98
Feb-99
May-99
8
7
6
5
4
3
pH
Upstream
Downstream

Figure 5

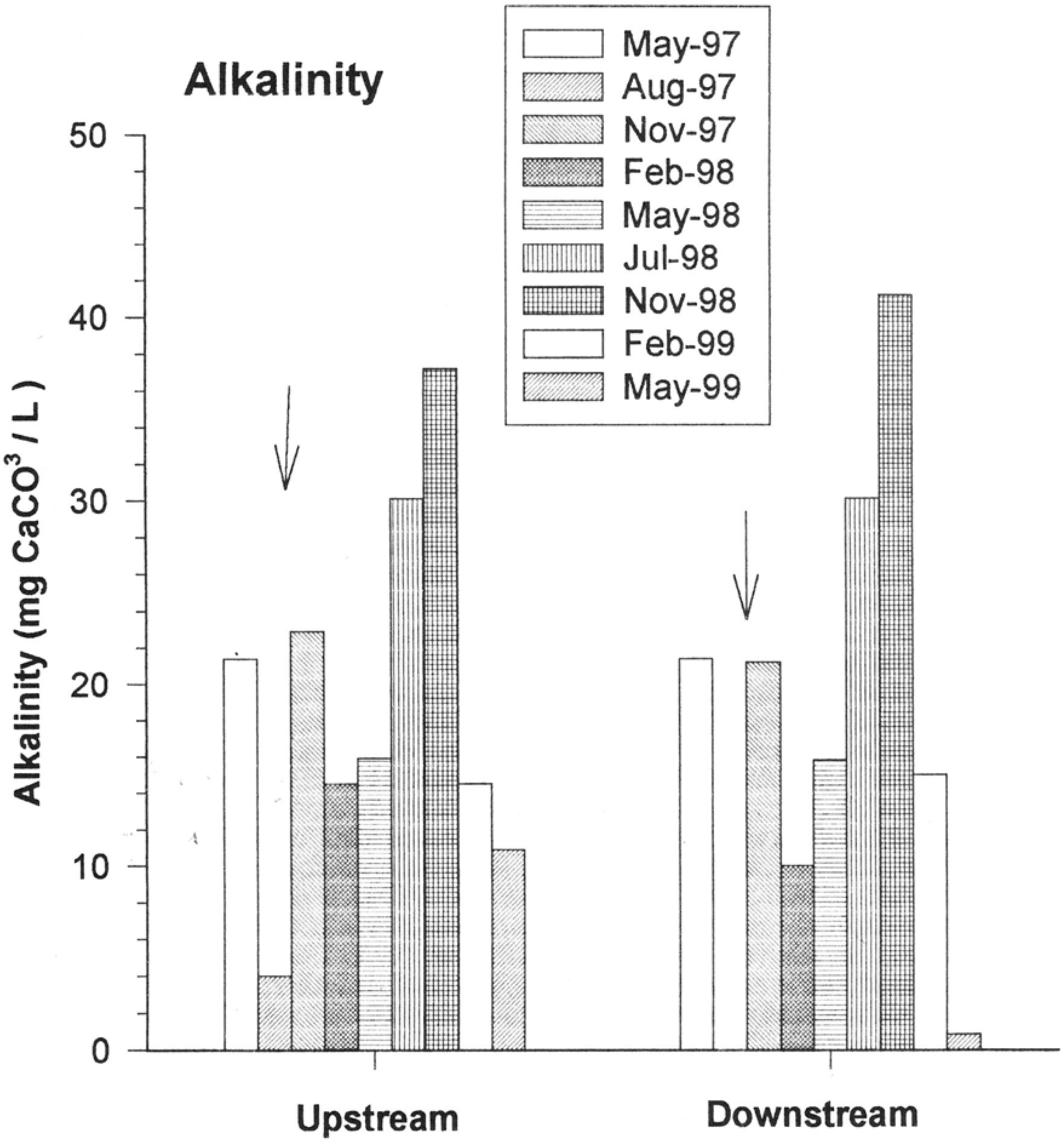
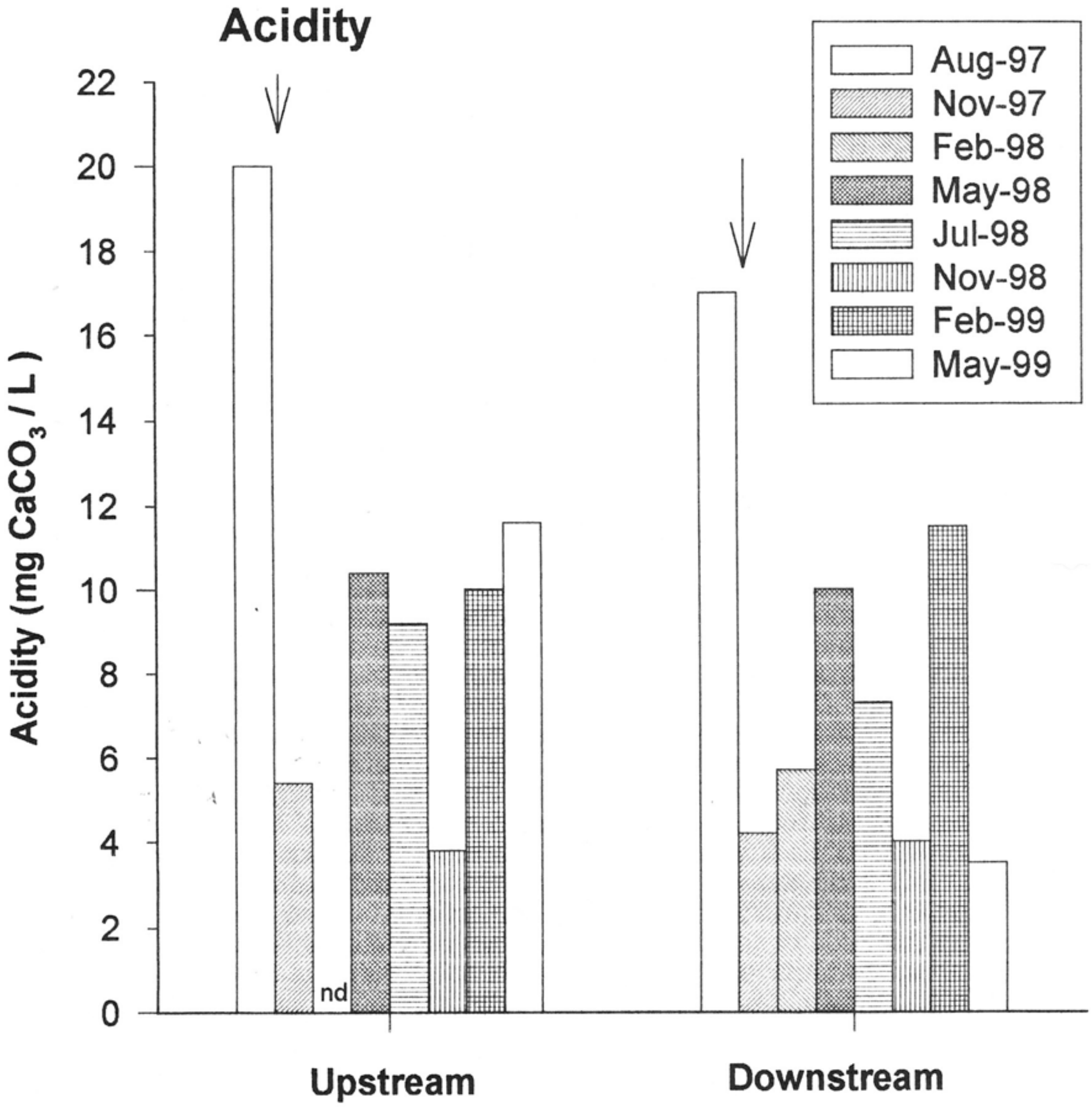

Alkalinity
Alkalinity (mg CaCO3 / L)
50
40
30
20
10
0
May-97
Aug-97
Nov-97
Feb-98
May-98
Jul-98
Nov-98
Feb-99
May-99
Upstream
Downstream

Figure 6



Acidity
Aug-97
Nov-97
Feb-98
May-98
Jul-98
Nov-98
Feb-99
May-99
Acidity (mg $CaCO_3$ / L)
0
2
4
6
8
10
12
14
16
18
20
22
nd
Upstream
Downstream

Figure 7

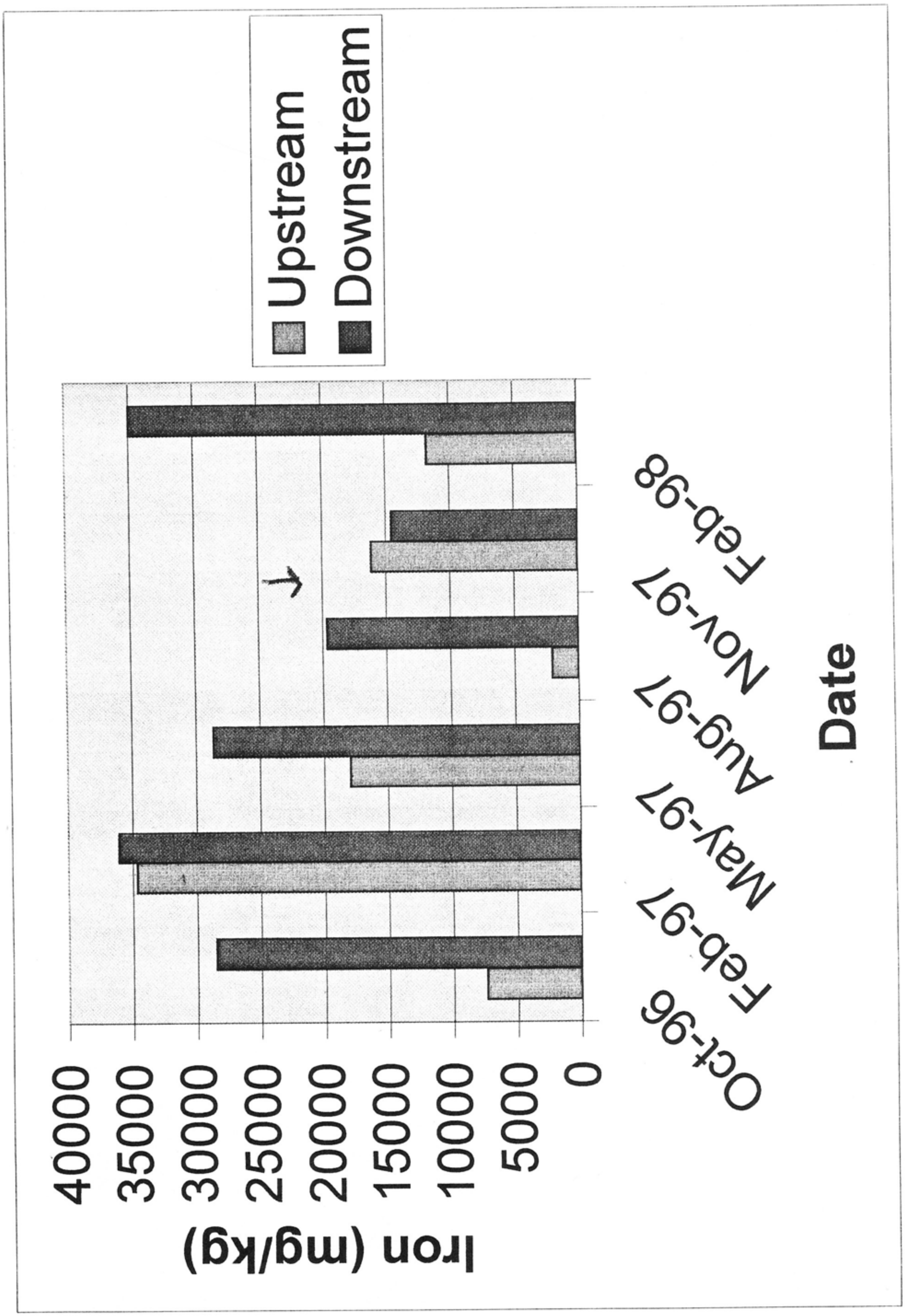
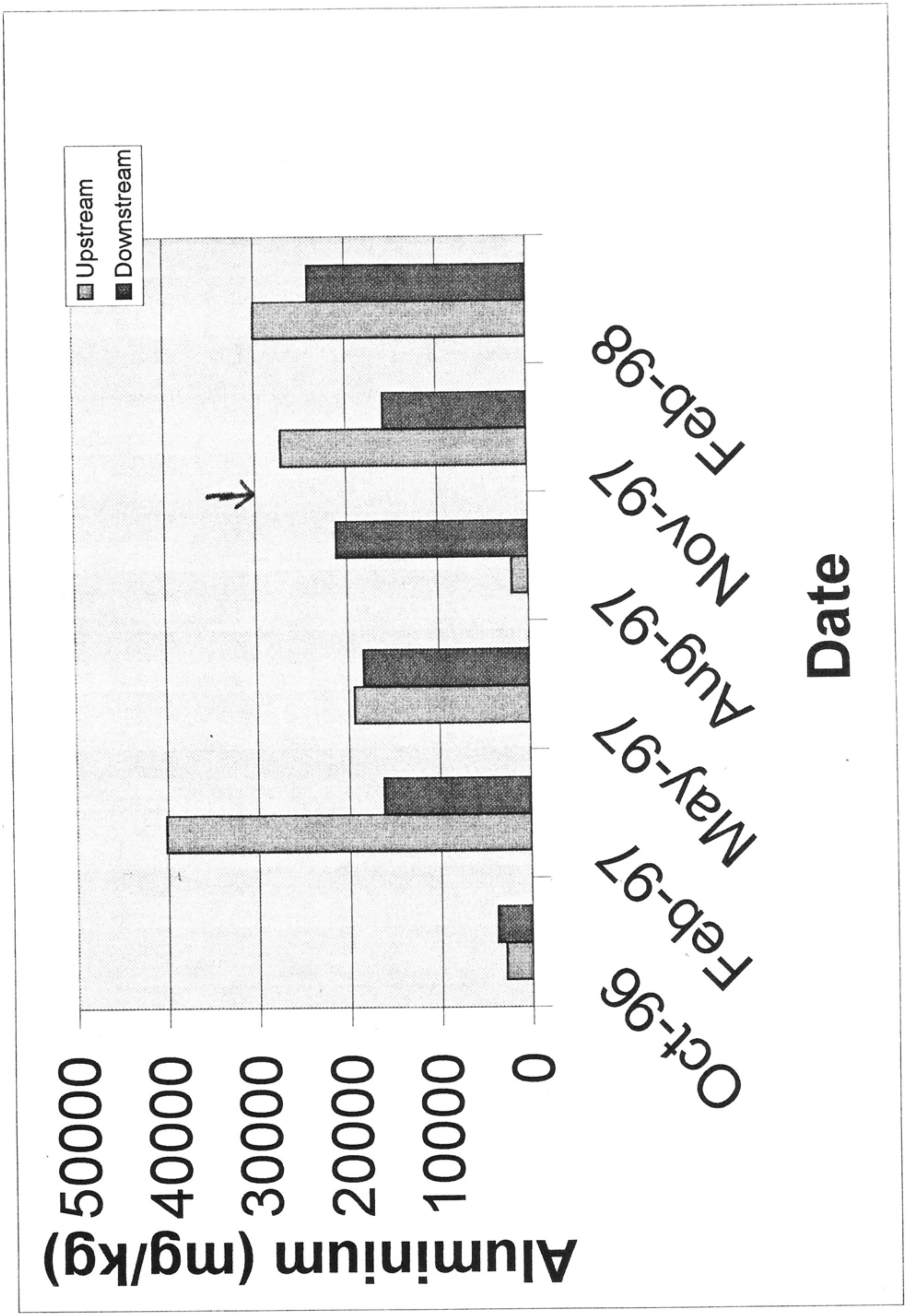
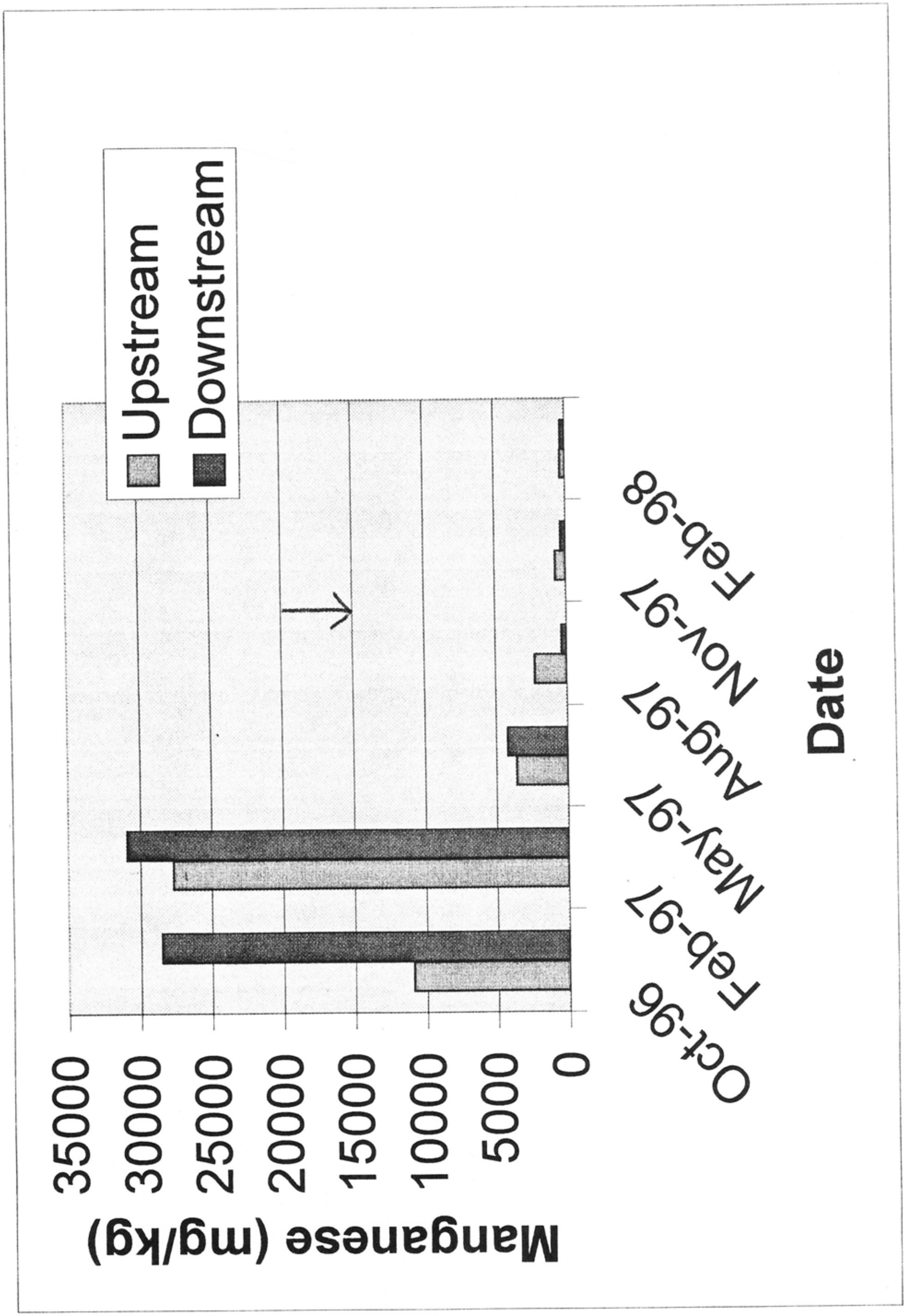

Iron (mg/kg)
400000
350000
300000
250000
200000
150000
100000
50000
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 8



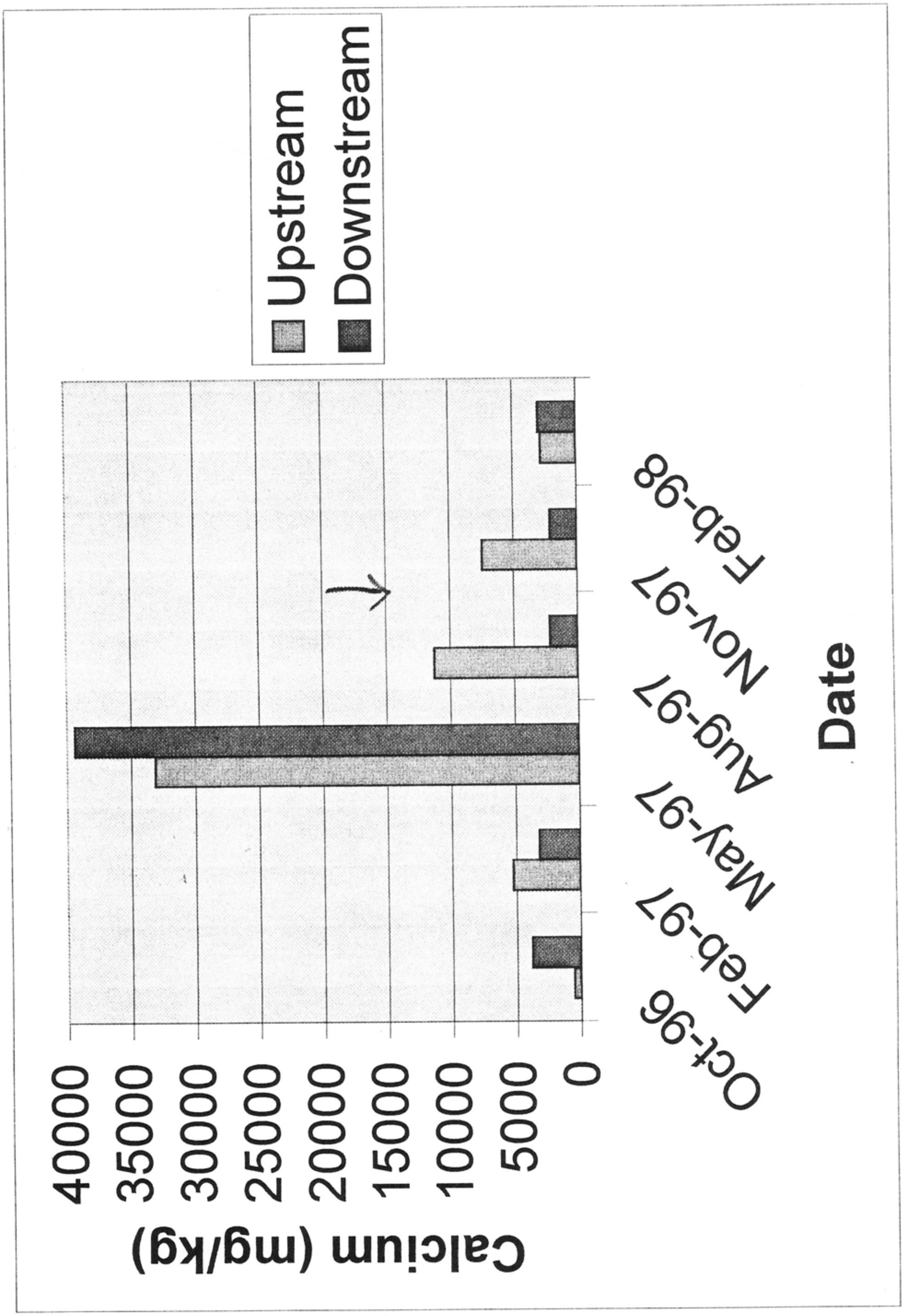
Aluminium (mg/kg)
500000
400000
300000
200000
100000
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 9



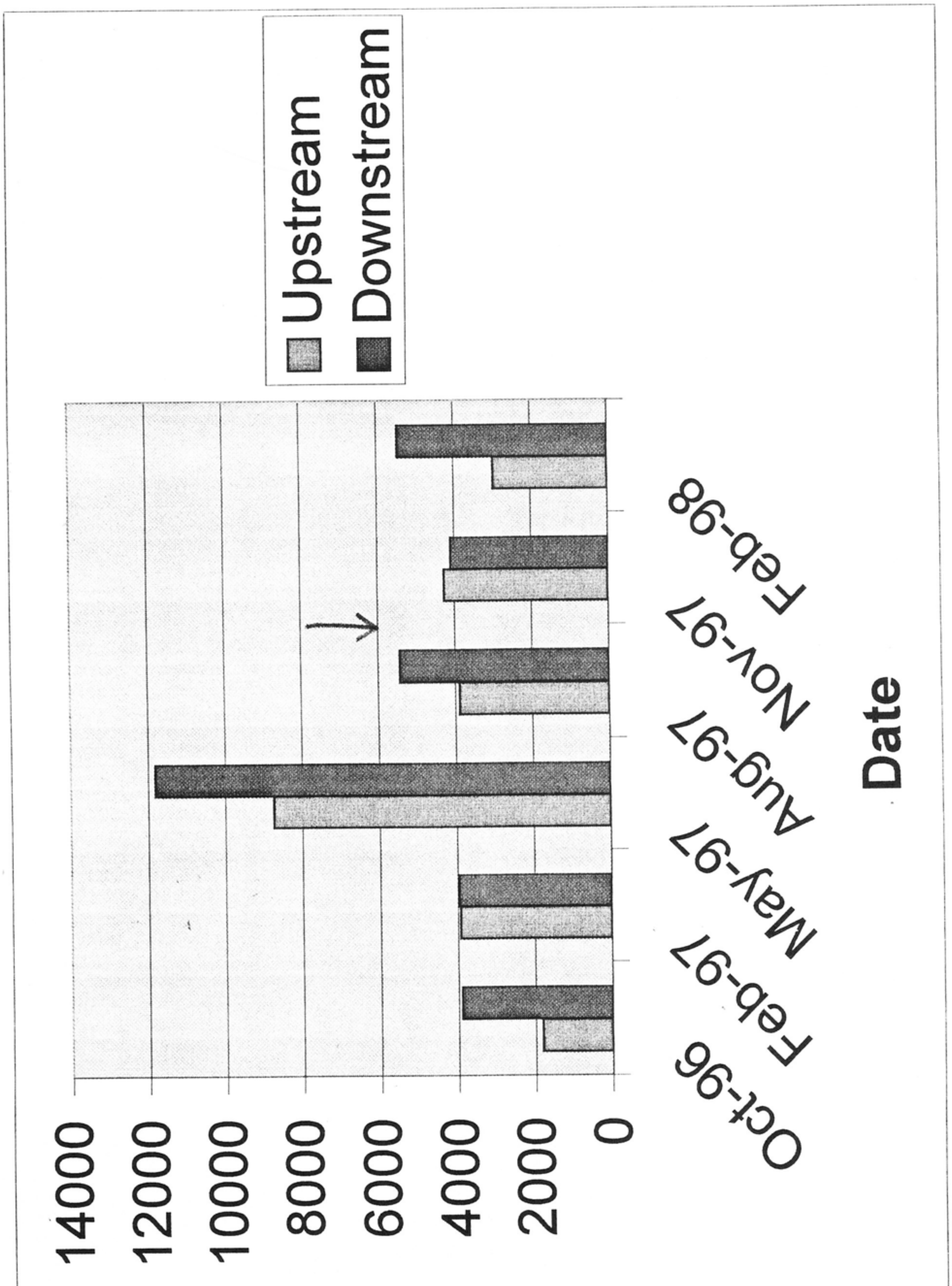
Manganese (mg/kg)
350000
300000
250000
200000
150000
100000
50000
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 10



Calcium (mg/kg)
400000
350000
300000
250000
200000
150000
100000
50000
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 11



Magnesium (mg/kg)
140000
120000
100000
80000
60000
40000
20000
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 12

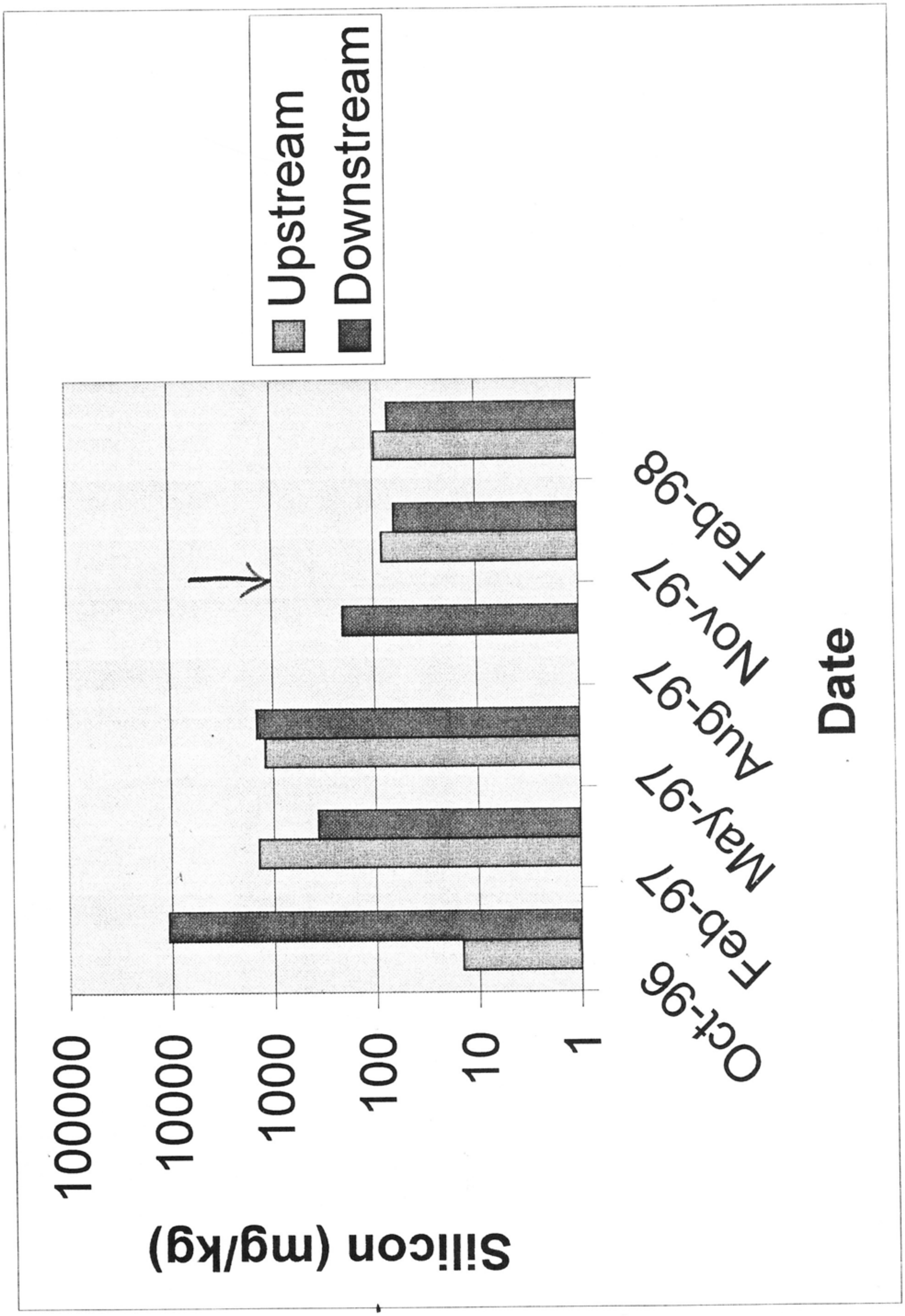

Silicon (mg/kg)
1000000
100000
1000
100
10
1
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 13

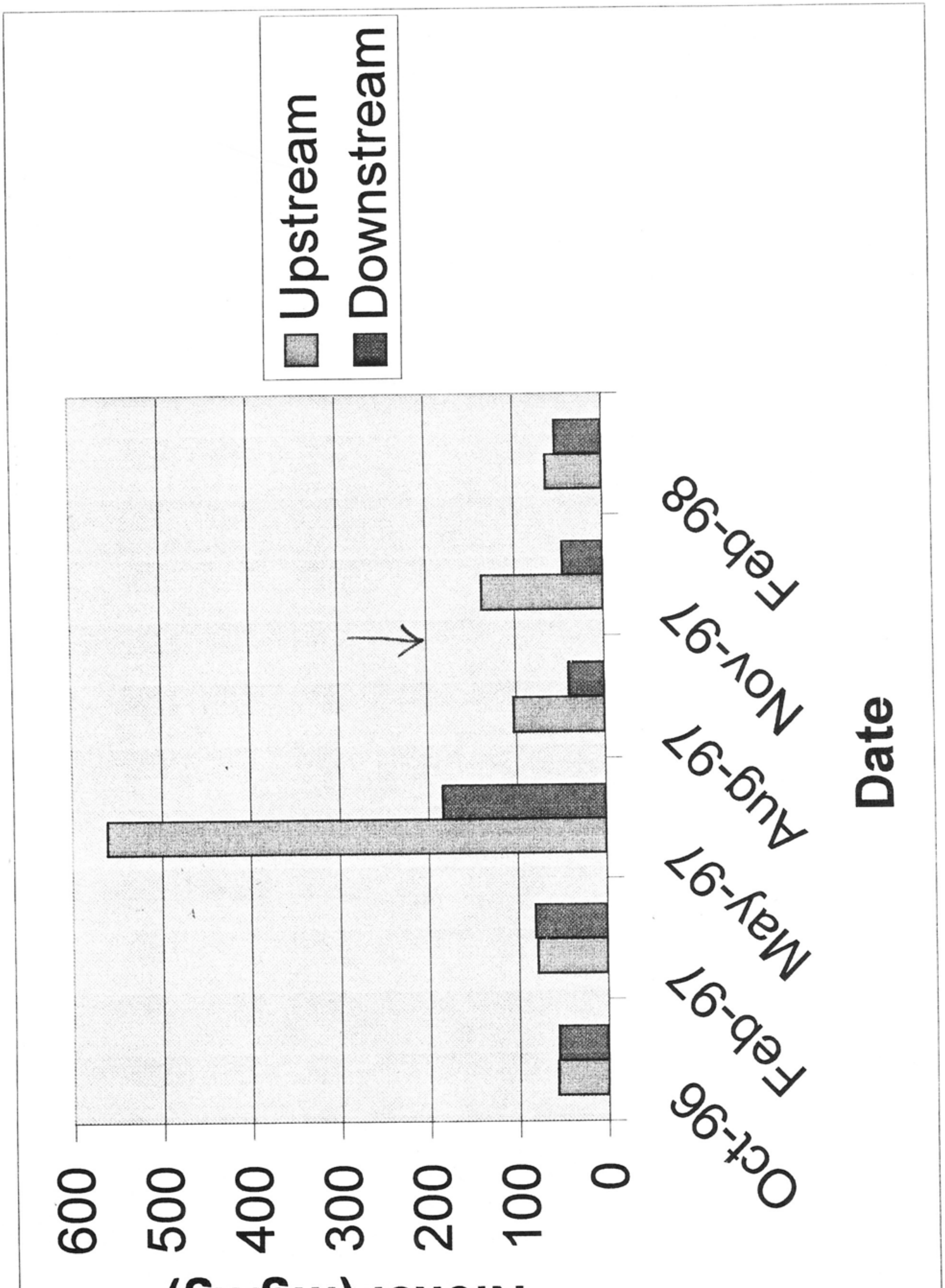

Nickel (mg/kg)
600
500
400
300
200
100
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 14

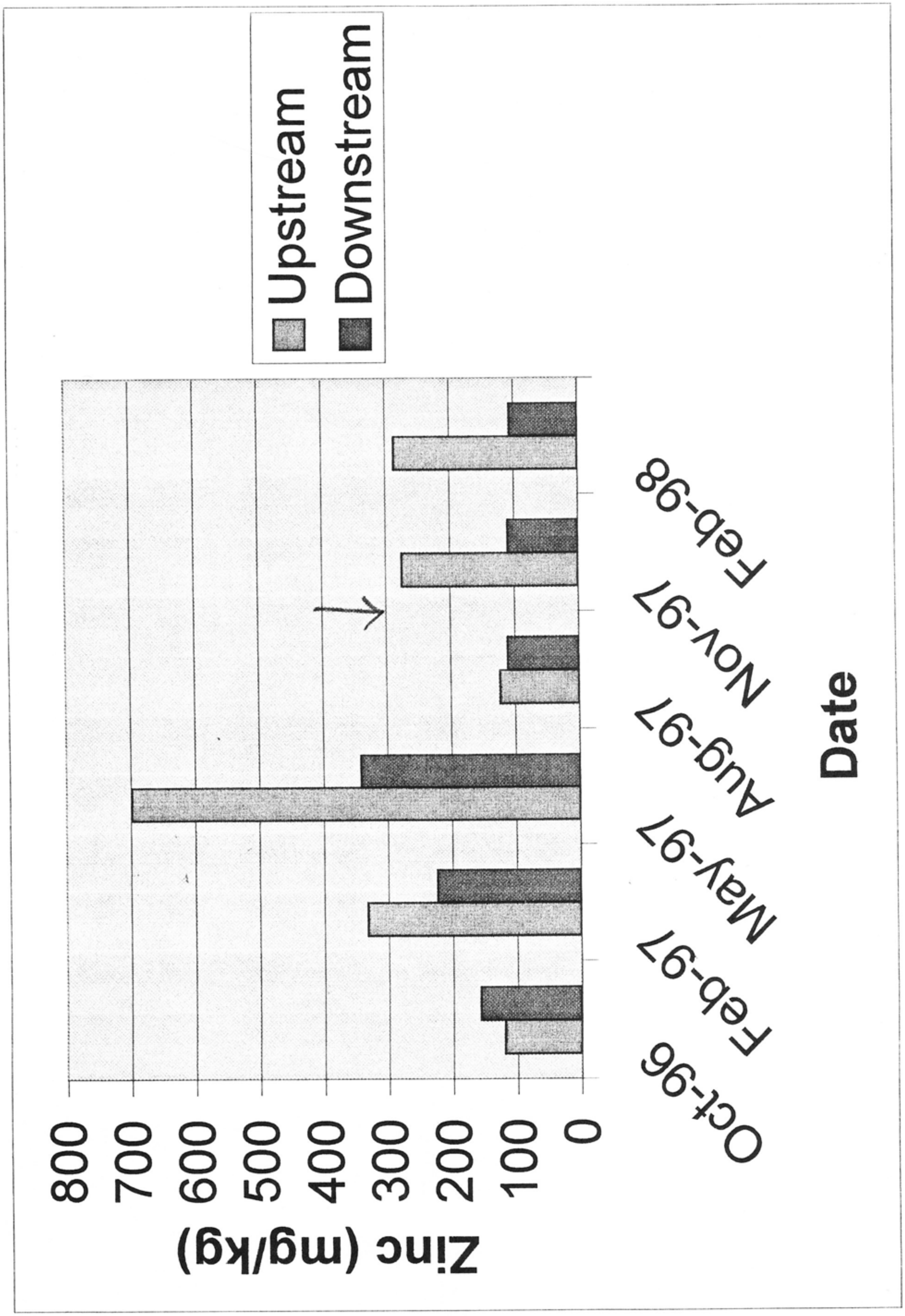
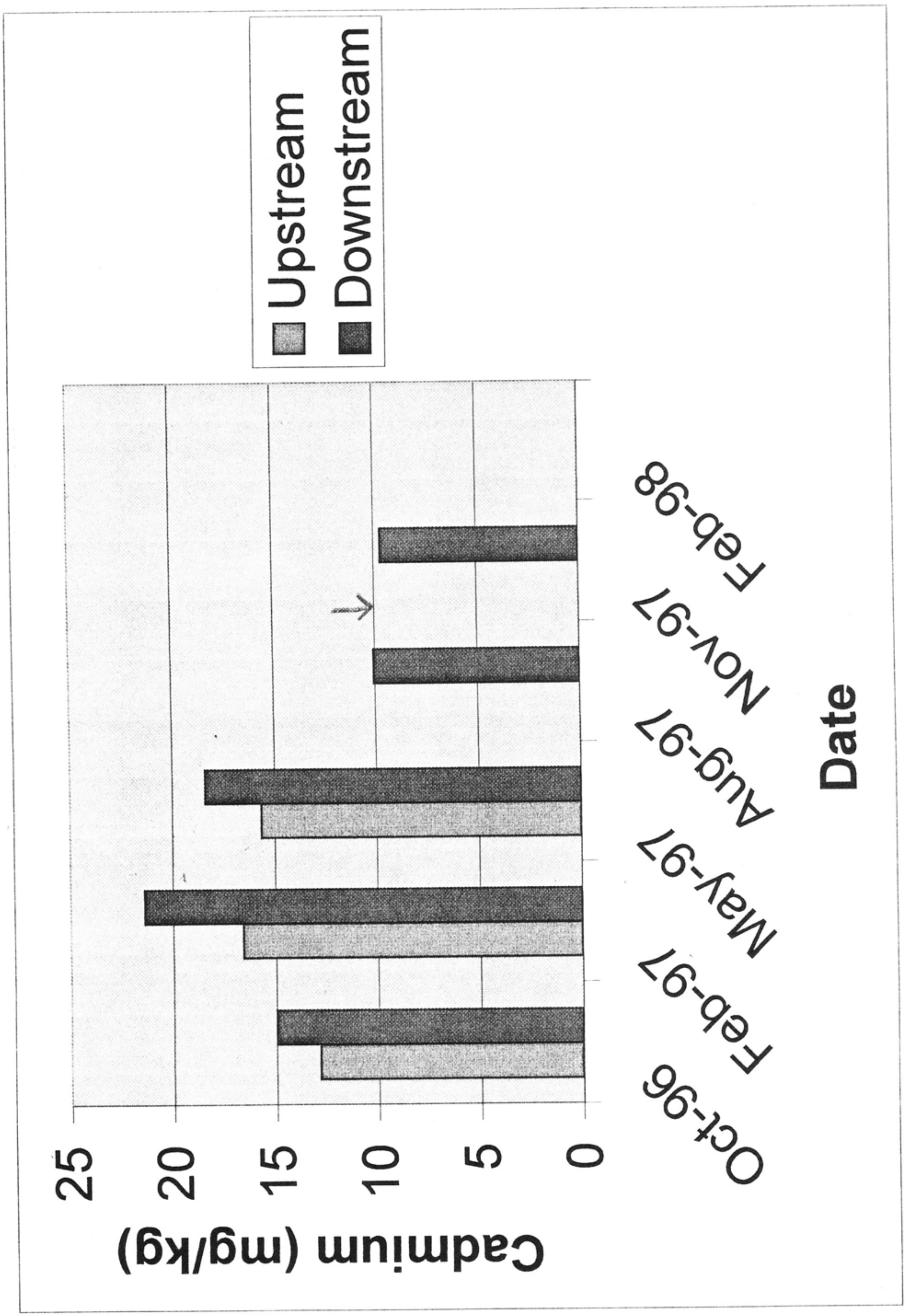

Upstream
Downstream
Zinc (mg/kg)
800
700
600
500
400
300
200
100
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date

Figure 15



Cadmium (mg/kg)
25
20
15
10
5
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 16

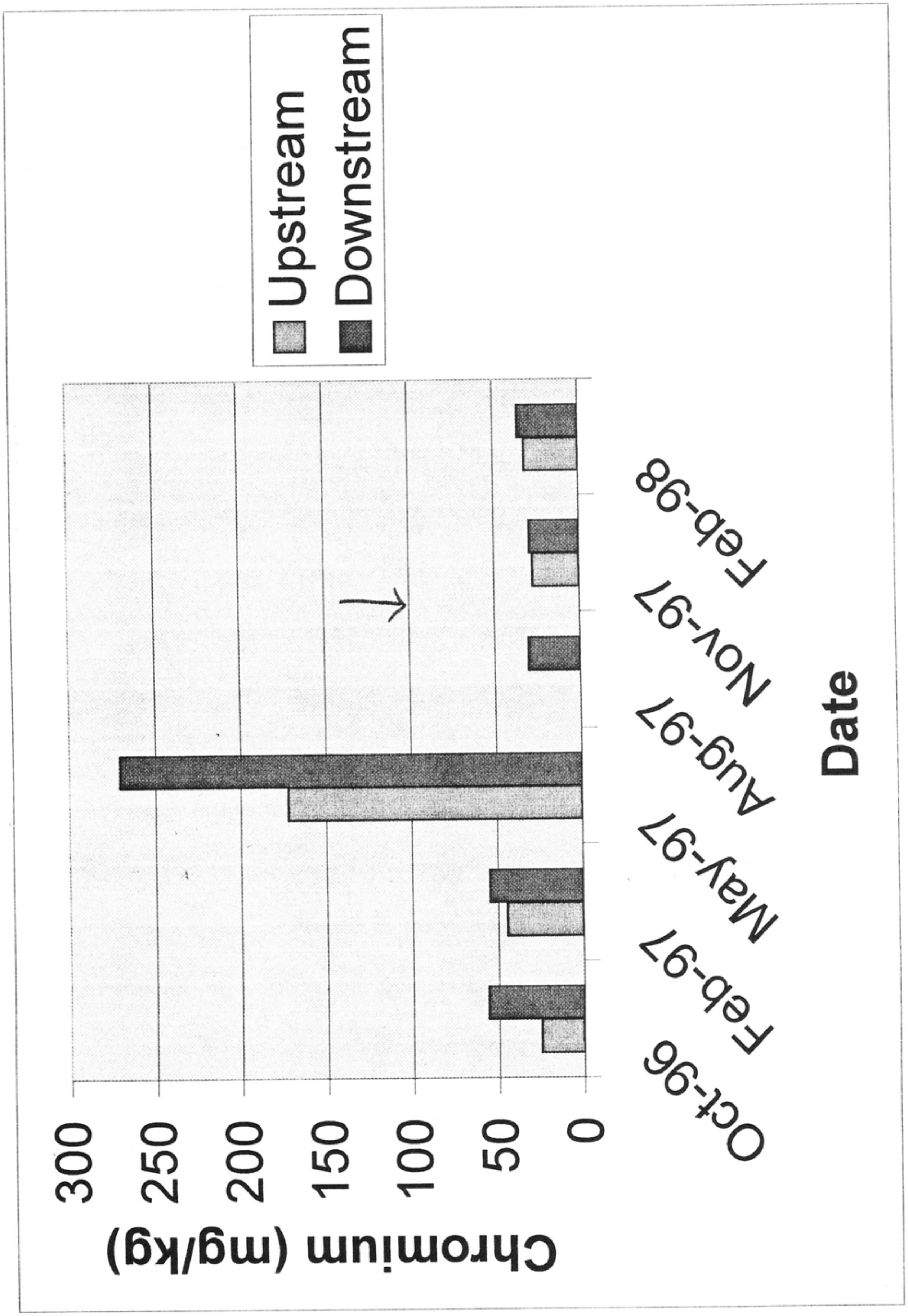
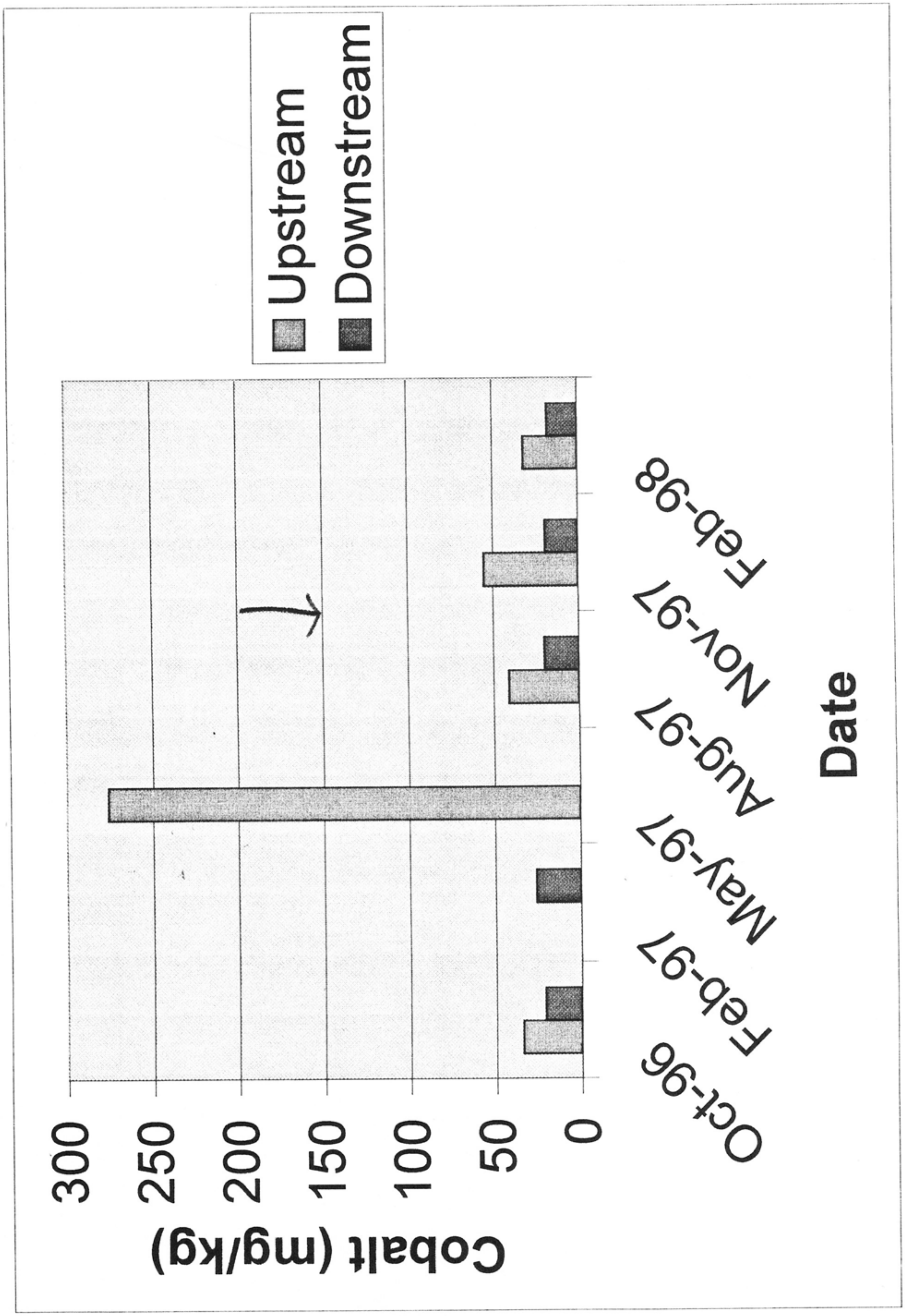

Chromium (mg/kg)
300
250
200
150
100
50
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 17



Cobalt (mg/kg)
300
250
200
150
100
50
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 18

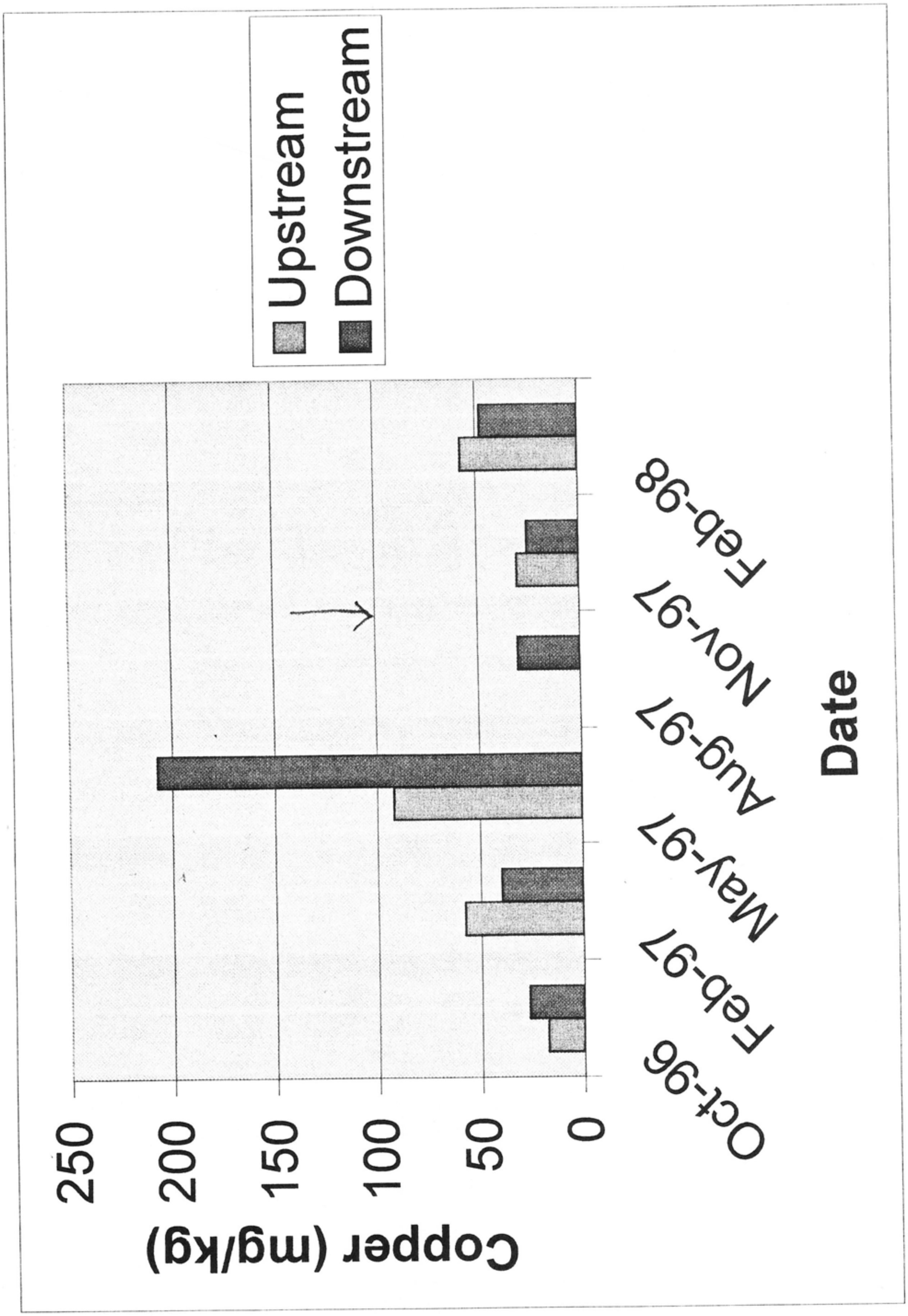
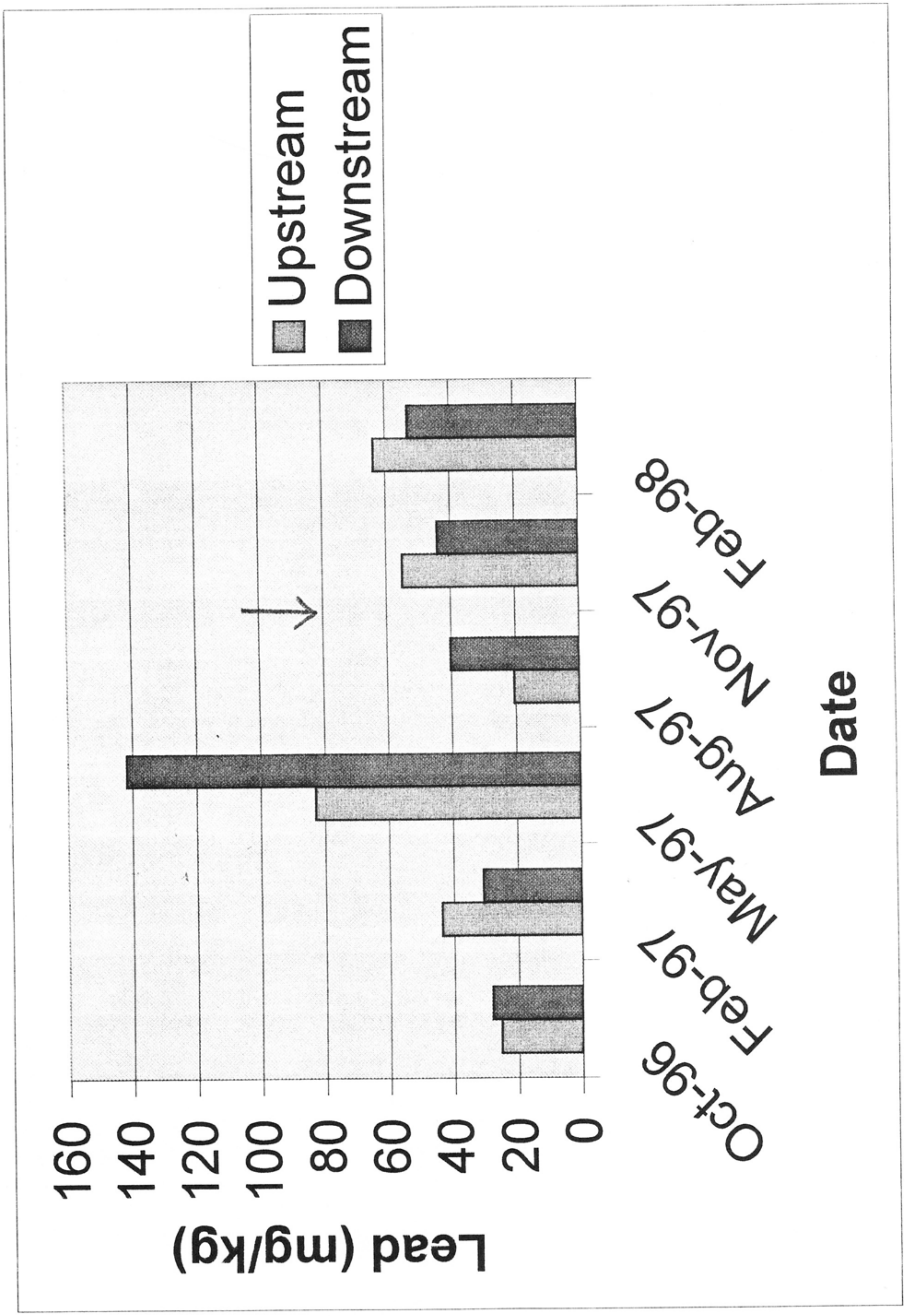

Copper (mg/kg)
250
200
150
100
50
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 19



Lead (mg/kg)
160
140
120
100
80
60
40
20
0
Oct-96
Feb-97
May-97
Aug-97
Nov-97
Feb-98
Date
Upstream
Downstream

Figure 20

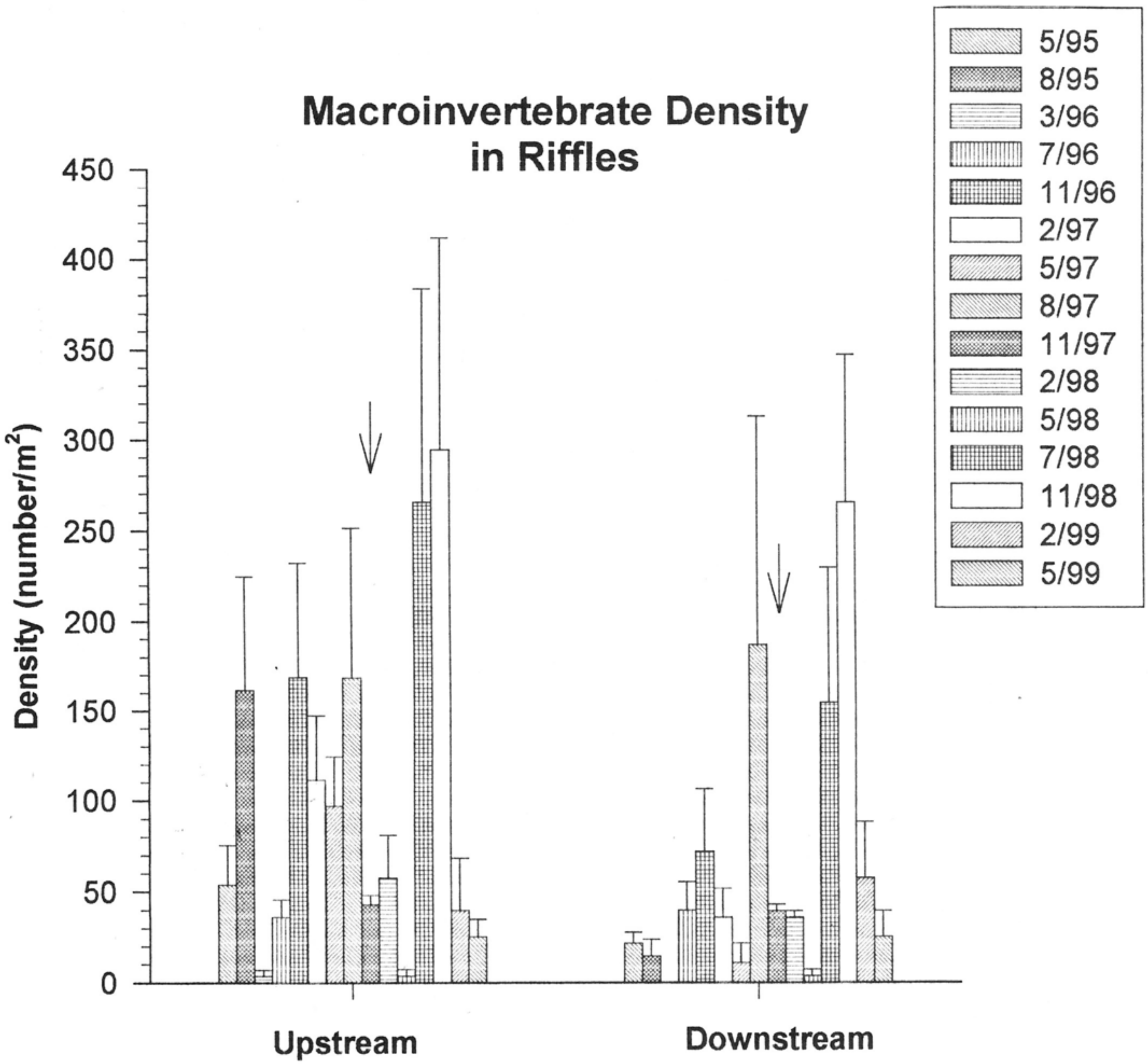

Macroinvertebrate Density
in Riffles
Density (number/m²)
450
400
350
300
250
200
150
100
50
0
Upstream
Downstream
5/95
8/95
3/96
7/96
11/96
2/97
5/97
8/97
11/97
2/98
5/98
7/98
11/98
2/99
5/99

Figure 21