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Effects of Zebra, Mussel, Dreissena Polymorpha Infestation on Lake Dardanelle Water Quality

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EFFECTS OF ZEBRA MUSSEL, *DREISSENA POLYMORPHA*, INFESTATION ON LAKE DARDANELLE WATER QUALITY

In requirement of USGS funded project
for the period July 1, 1995 through June 30, 1996

By

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Effects of Zebra Mussel, *Dreissena polymorpha*, Infestation on Lake Dardanelle Water Quality

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Research Project Technical Completion Report

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ABSTRACT

Zebra mussels recently invaded southern waterways including the Arkansas River. Large-scale filtration of suspended particulate matter by dense populations could alter reservoir ecosystem function. Furthermore, they attach to hard surfaces, thereby threatening normal operations of artificial structures. We designed this study to provide baseline data prior to establishment of high population levels of zebra mussels in Lake Dardanelle. The characterization of spatial and temporal variability in water quality, zooplankton, phytoplankton, and macrophytes will allow testing of several hypotheses. We sampled zebra mussel veliger and settling juvenile densities and zooplankton densities at four fixed sites and the key water quality variables at three of the sites biweekly from July 1995 through June 1996. Data from previous years regarding the above parameters is contained in other reports.

Production of zebra mussel veligers was approximately the same between the 1994-1995 and 1995-1996 sample seasons, but the number of adults increased dramatically. Veliger density frequently exceeded 20/L and the mean density of adults was > 4,000 m^2 during the 1995-1996 sample season. We observed substantial increases in ion concentrations, phosphate, conductivity, and Secchi disk visibility this sample season compared to the 1994-1995 sample season. Mean concentrations for calcium, magnesium, sulfate, chloride, and phosphate increased 43%, 42%, 42%, 48%, and 50%, respectively. Mean conductivity increased 44%, and four of the five highest Secchi disk readings taken the past three years were recorded in 1996. We observed substantial decreases in turbidity (31%), total dissolved solids (23%), and total phosphorous (13%). Densities of major zooplankton taxa were not substantially different this season compared with the 1994-1995 sample season. We observed slight increases in mean concentrations of chlorophylls *a*, *b*, and *c*, and a slight decrease in the mean percent coverage of rooted marcrophytes, but the values were not substantially different than those that we observed during the 1994-1995 sample season.

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ACKNOWLEDGEMENTS

We appreciate the assistance of ATU students Jason Phillips, Andy Dick, Lindsey Lewis, and Coburn Howell in the collection of field samples and entry of data. Portions of this project were funded by the U.S. Department of the Interior Geological Survey through the Arkansas Water Resources Center, Entergy Operations, Inc., and Arkansas Tech University.

INTRODUCTION

The zebra mussel, Dreissena polymorpha, was discovered in September 1992 in Lake Dardanelle, a 13,800 hectare impoundment on the Arkansas River. It could have a marked impact on the water quality and ecology of the reservoir. In western Lake Erie, adult zebra mussels increased 325% between 1988 and 1990, and the population of juvenile mussels increased greater than 900% (Leach 1993). Adults larger than 10 mm in length reached a mean density of 18,457/m^2 on reefs. Assuming an average filtration rate of 100 mL/h for typical (10 mm) zebra mussels (Kryger and Riisgard 1988), a population density of 18,457/m^2 would filter 1.8 m^3 of lake water per hour. Filtration rates this high would result in the filtration of the entire volume of a shallow reservoir like Lake Dardanelle over 20 times per day, which clearly would its water quality and biotic community.

Although, high densities of zebra mussels can alter the water quality, and subsequently, the ecology of infested waters, the effects of zebra mussels on water quality and ecology of Lake Dardanelle are difficult to predict, because it is a different system (i.e., has different water chemistry, thermal regimes, aquatic community structure, etc.) from those that have been previously studied.

This report primarily contains information on selected water quality and biotic parameters sampled during the 1995-1996 sample year. Additional water quality, zooplankton, and zebra mussel information can be found in Gagen and Stoeckel (1995) and Stoeckel and Gagen (1993, 1994, and 1995). Based on samples we have collected, the zebra mussel population is increasing dramatically, and it is likely to alter the water quality and ecology of Lake Dardanelle.

OBJECTIVES

This field-oriented study was designed to sample key aquatic variables at three fixed stations. The goal was to establish rigorous baseline data prior to establishment of a high density population of zebra mussels in Lake Dardanelle. The ongoing study is focused on spatial and temporal variability in water quality, zooplankton, phytoplankton (as a function of chlorophyll), and macrophytes. As zebra mussel populations increase over the next few years, we will be able to test several working hypotheses:

1) Water filtration by feeding zebra mussels will lead to decreases in phytoplankton and zooplankton densities

(and probably changes in species composition toward larger forms);

2) Water filtration by feeding zebra mussels will lead to decreased suspended solids and turbidity, and subsequently, to increased water clarity;

3) Total phosphorous will decrease, because it is largely associated with suspended material that is susceptible to filtration by zebra mussels; however, phosphate and other inorganic nutrients will increase during the exponential growth phase of the zebra mussel population, because uptake by phytoplankton will decrease;

4) Increased water clarity and availability of inorganic nutrients is expected to lead to proliferation of rooted macrophytes because Lake Dardanelle is shallow (mean depth of $\approx$ 4.3 m), furthermore, if a proliferation of rooted macrophytes does occur, the dominant substrate for zebra mussel attachment will shift from rocks to macrophytes;

5) The effects listed above will be most dominant at times and places least influenced by Arkansas River flow (e.g., summer, and in the Illinois Bayou Bay of Lake Dardanelle).

RELATED RESEARCH

In 1991, Strayer hypothesized that Arkansas was near the southern limit for zebra mussel colonization based on the range of temperatures tolerated in Europe. However, we hypothesized that their high degree of adaptability would allow them to proliferate in shallow southern reservoirs dominated by fine substrate.

In 1993, we initiated a study to document any changes in the abundance and distribution of zebra mussels in lake Dardanelle. Since that time, we have documented rapid proliferation of zebra mussels in Lake Dardanelle. Larval, juvenile, and adult zebra mussel samples have been collected in Lake Dardanelle since July, 1993 as part of a separate, but related study funded by Entergy Operations (operations management of Arkansas Nuclear One). The larval and juvenile stages were sampled at four, fixed sites (Figure 1) which correspond to zooplankton and water chemistry sample sites in the present study. Adults were sampled at random sites along the shoreline. In 1996, we switched from measuring abundance of adults as number observed per man-hour of snorkeling, to number counted in 0.25 m^2 quadrat samplers, because number of adults had increased dramatically. Larval zebra mussels were collected in a 64-micron mesh Nitex net towed vertically from a depth of three meters to the surface and by pumping water from a depth of three meters through the net. Except during periods of equipment malfunction, both techniques were used and samples were enumerated separately. Larval zebra mussels were identified and counted in these samples under polarized

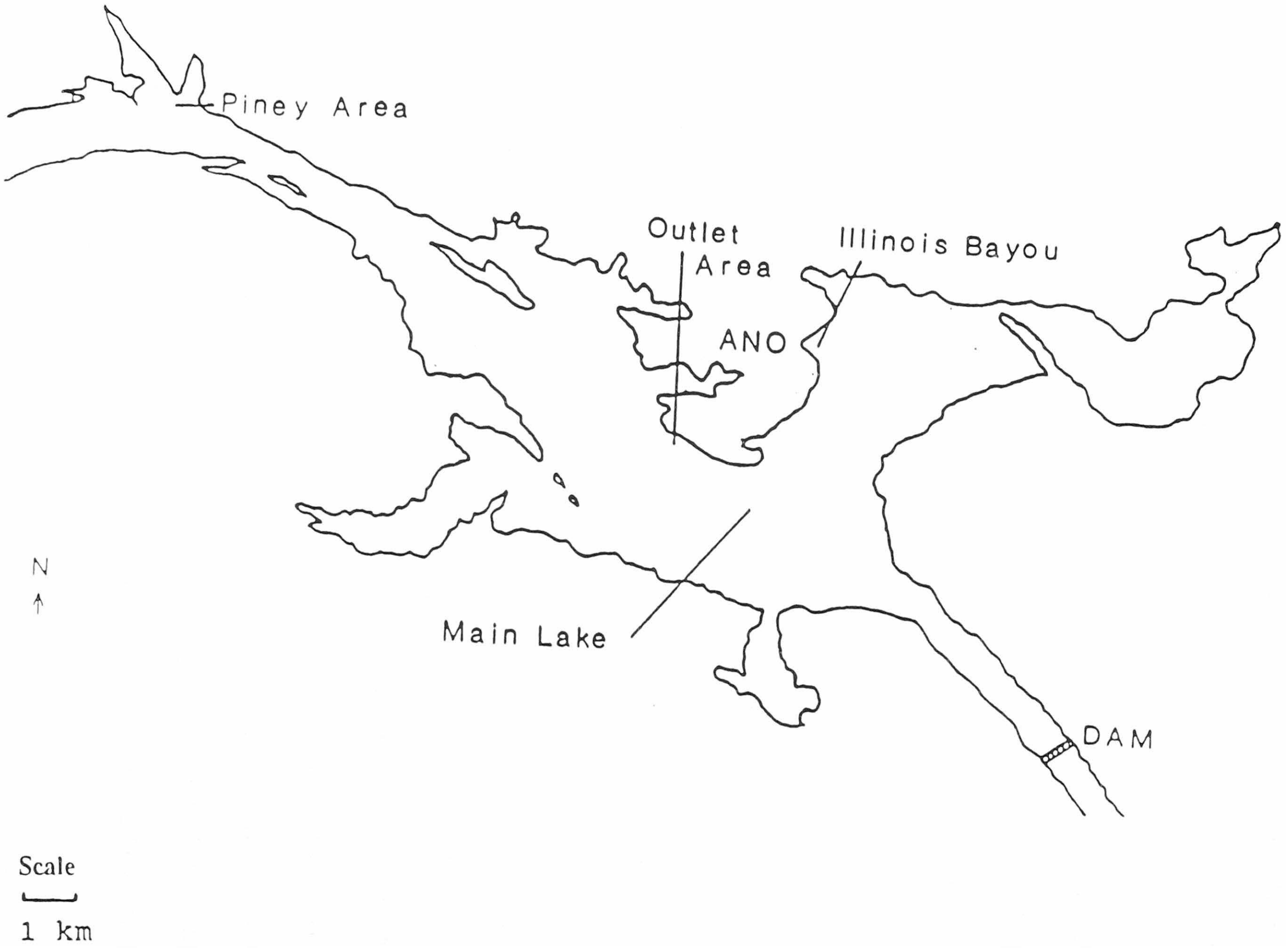

Figure 1. Map of Illinois Bayou, river channel, Big Piney, and outlet area sampling locations on Lake Dardanelle, AR. Only zooplankton, zebra mussels, and associated data were collected at the outlet area.

light. PVC-plate samplers with attached glass slides (Marsden, 1992) were used to sample settling juvenile zebra mussels.

Another related and long-standing research project sampled larval fish at night biweekly. Unfortunately, this project ended in 1994, and we are currently looking for funding to sample post-zebra mussel infestation impacts on larval fish production.

Zebra mussel densities have increased substantially since they were first found in Lake Dardanelle by Charlie Adams (Entergy Operations) in September, 1992. For example, in 1993 ≤ 45 , in 1994 ≤ 58, and in 1995 ≤ 140 adult zebra mussels were found per hour of effort. In the quantitative survey in 1996, we collected an average of $> 4,000$ adults/m^2 at 16 sites (Figure 2). In April 1996, we observed thousands of adult zebra mussels/m^2 on spillway gates at the Dardanelle lock and dam, and boat owners began reporting zebra mussel biofouling at local marinas. The maximum mean settling rates (mean for two, 15-cm^2 plates) of juvenile zebra mussels increased from $0/m^2$ in 1993 to $> 10,000$ m^2 in 1995. Mean density of larval zebra mussels in 1993 was always less than 0.1/L, whereas, it exceeded 20/L five times during the 1994-1995 sample year and five times during the 1995-1996 sample year (Figure 3).

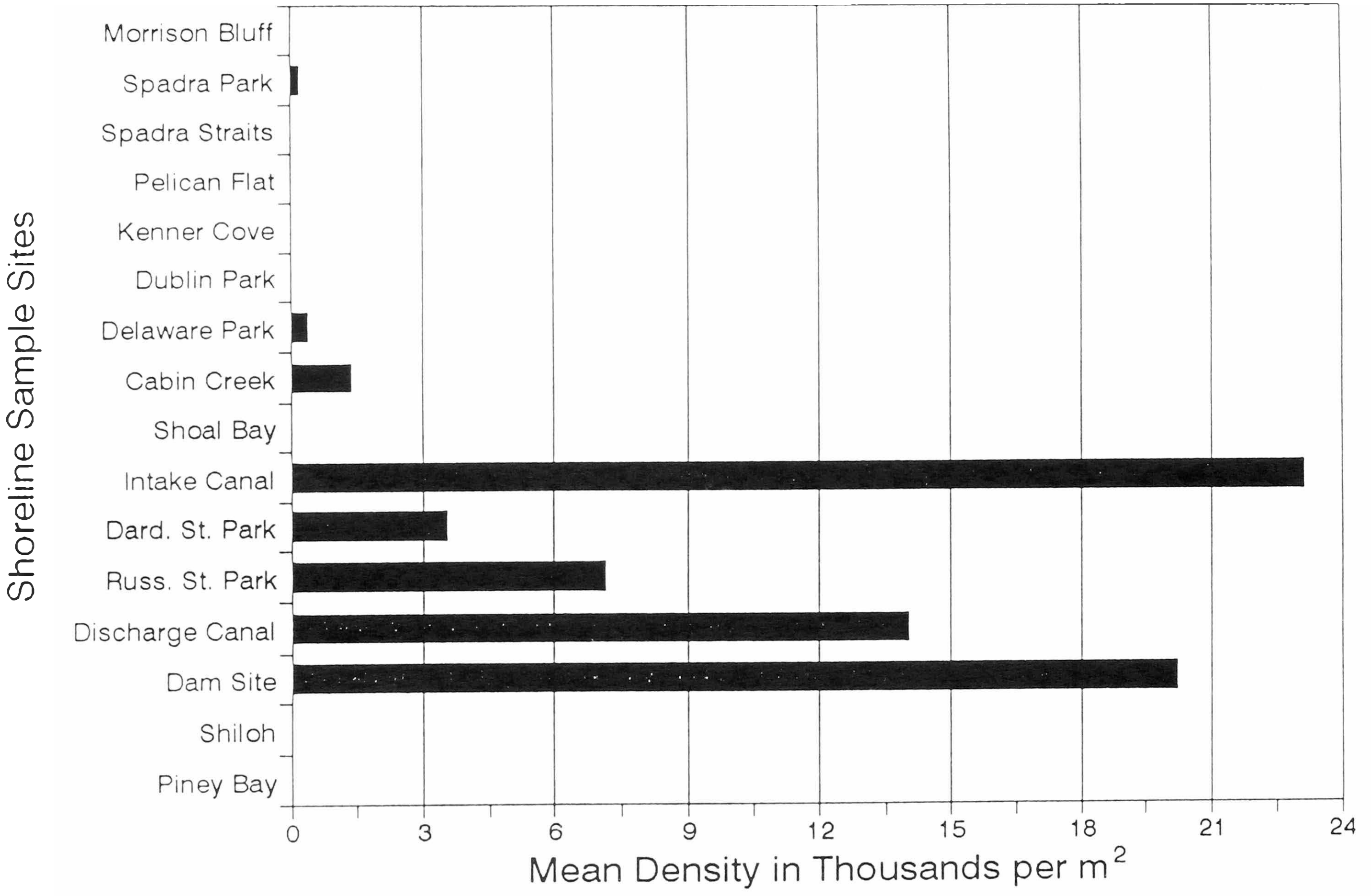

Figure 2. Densities of zebra mussel ≥ 4 mm at selected sites along the shoreline of Lake Dardanelle, AR.

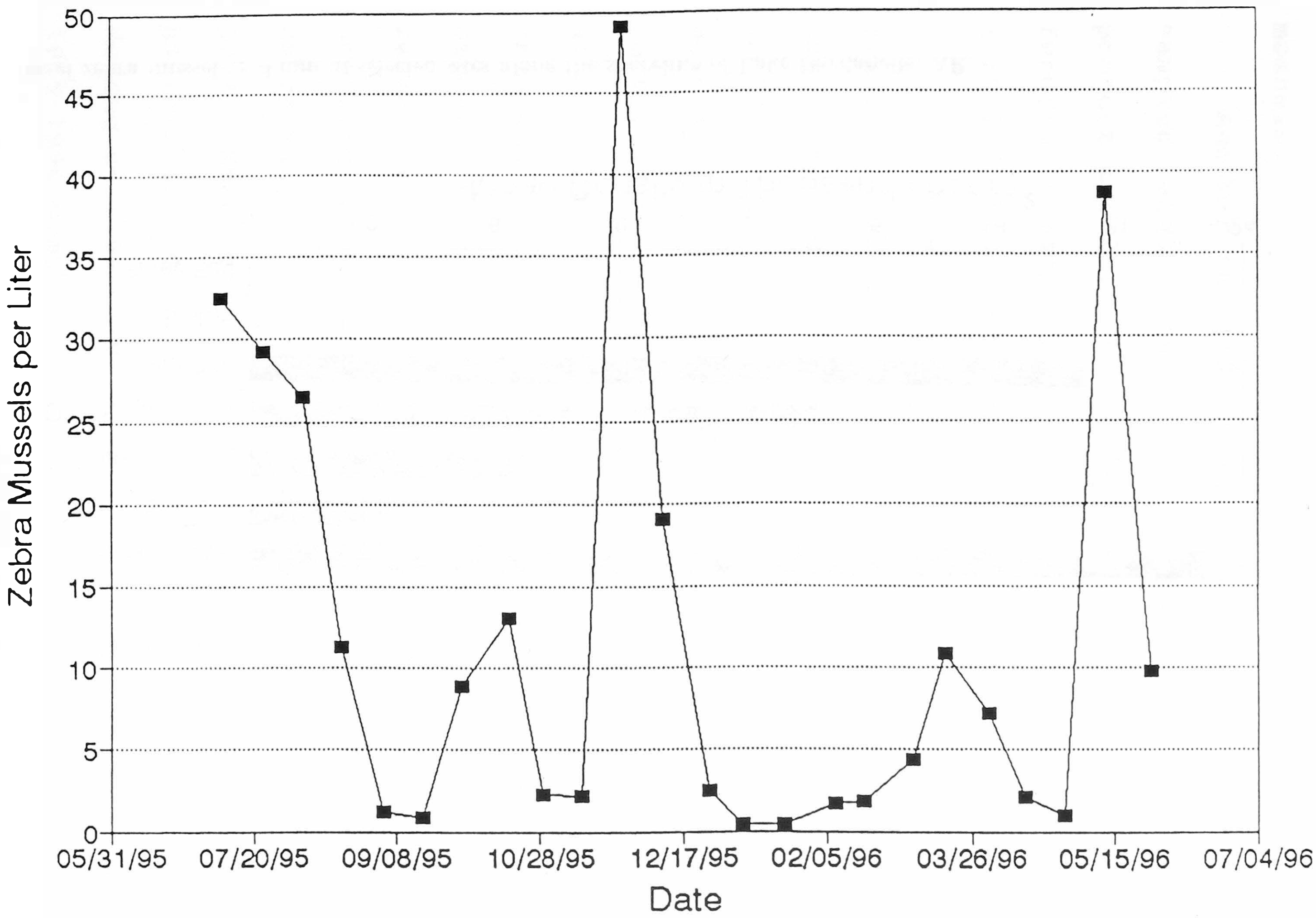

Figure 3. Changes in density of zebra mussels in the plankton of Lake Dardanelle, AR, since July 9, 1995. The value for each date is the mean density of zebra mussels collected in pump and vertical tow samples (unless only one type was taken) averaged across four sample areas.

MATERIALS AND METHODS

We collected water biweekly from a depth of 1 m in a polycarbonate sampler to analyze selected water chemistry parameters and chlorophyll levels at three sites in Lake Dardanelle (Figure 1). Lake Dardanelle does not stratify for an extended period in summer, therefore, stratified sampling was unnecessary. Secchi disk depth and dissolved oxygen and temperature profiles were also recorded when water samples were collected. Refrigerated water samples were transported to the Arkansas Water Resources Center Water Quality Laboratory for analysis by EPA accepted methods. Analyses included: total phosphorous, chlorophylls *a*, *b*, *c*, ammonia, nitrate, chloride, calcium, magnesium, phosphate, pH, nitrite, sulfate, turbidity, conductivity, and suspended solids. All 16 parameters were measured for half the sample dates; whereas, only the first six were measured for the other half (Table 1).

The percentage of bottom area covered by submerged and emergent macrophytes in 100 m by 25 m areas near each of the three sample sites (Illinois Bayou, river channel, and Piney Bay) was estimated visually with the aid of a rake and SCUBA. The river channel site was located in an area just north of this open water site. These samples were collected seasonally in water $\leq$ 2 m deep and within 25 m of shore.

Zooplankton and larval zebra mussels were collected

Table 1. Water chemistry parameters tested and sampling dates. An X denotes the that parameters were sampled on the corresponding date.

Sample Dates September 1994 - June 1995	Ca, Cl, NH$_4$-N, NO$_3$-N, Total P, Chlorophylls *a*, *b*, and *c*	Mg, NO$_2$-N, pH, PO$_4$-P, SO$_4$, TSS, Turbidity, Conductivity	Sample Dates July 1995 - June 1996	Ca, Cl, NH$_4$-N, NO$_3$-N, Total P, Chlorophylls *a*, *b*, and *c*	Mg, NO$_2$-N, pH, PO$_4$-P, SO$_4$, TSS, Turbidity, Conductivity
			7/9/95	X	X
			7/24/95	X	
			8/6/95	X	X
			8/20/95	X	
9/3/94	X	X	9/4/95	X	X
9/18/94	X		9/17/95	X	
10/2/94	X	X	10/1/95	X	X
10/16/94	X		10/17/95	X	
10/30/94	X	X	10/29/95	X	X
11/13/93	X		11/12/95	X	
11/27/94	X	X	11/26/95	X	X
12/11/94	X		12/10/95	X	
12/26/94	X	X	12/26/95	X	X
1/9/95	X		1/7/96	X	
1/22/95	X	X	1/21/96	X	X
2/6/95	X		2/8/96	X	
2/19/95	X	X	2/18/96	X	X
3/5/95	X		3/6/96	X	
3/19/95	X	X	3/17/96	X	X
4/4/95	X		4/1/96	X	
4/16/95	X	X	4/14/96	X	X
4/30/95	X		4/28/96	X	
5/14/95	X	X	5/12/96	X	X
5/29/95	X		5/28/96	X	
6/11/95	X	X	6/10/96	X	X
6/27/95	X		6/24/96	X	

biweekly at four sites (Figure 1) by pulling a 64 μm mesh Nitex net vertically from a depth of 3 m to the surface or by pumping water from a depth of 3 m through the net (Marsden, 1992). The samples were preserved in Lugol's solution, and analyzed following the methodology of Wetzel and Likens (1991). For each zooplankton sample, the density of individuals in each major group, Copepoda, Cladocera, Ostracoda, nauplii, Rotifera, and other, was determined. The additional, concurrent, zebra mussel data reviewed in this paper, was collected in a different, funded study; therefore methods are detailed in appropriate cited literature.

RESULTS

Turbidity levels were notably higher at the river channel site compared to the Illinois Bayou and Big Piney sites, and Secchi disk readings were usually lower at the river channel site compared to the other two sites (Figures 4 and 5). There was a decrease in mean turbidity between sample years at all sites (Tables 2, 3, and 4). The mean turbidity value was 31% lower for the 1995-1996 sample year compared to the 1994-1995 sample year (Table 5). Most of the chlorophyll was chlorophyll *a* (mean of 16.3 μg/L) which was lowest in winter when water temperatures and solar infiltration were the lowest (Figure 6). There was a slight increase in all mean chlorophyll values between years; the mean respective values for the 1994-1995 and 1995-1996

Table 2. Lake Dardanelle Water Quality (mean ± S.E.) at the Piney Bay site from September 1994 through June 1995, and from July 1995 to June 1996. The units of measurement for all variables is mg/L except for pH, turbidity (NTU), conductivity (μS/cm), and the chlorophylls (μg/L).

Variable	N	1994-1995	N	1995-1996
Ca	22	19.6 ± 2.6	25	28.4 ± 2.5
Cl	22	47.0 ± 8.8	26	63.7 ± 7.3
Mg	11	5.1 ± 1.0	12	6.7 ± 1.0
NH_4-N	22	0.030 ± 0.003	26	0.054 ± 0.006
NO_3-N	22	0.26 ± 0.05	26	0.16 ± 0.02
NO_2-N	11	0.008 ± 0.002	13	0.005 ± 0.000
pH	11	7.60 ± 0.19	12	7.91 ± 0.13
PO_4-P	11	0.034 ± 0.010	13	0.037 ± 0.009
Total P	21	0.079 ± 0.009	26	0.070 ± 0.008
SO_4	11	25.4 ± 5.1	13	33.1 ± 4.8
Suspended Solids	11	17.3 ± 5.9	13	11.1 ± 2.3
Turbidity	11	22.2 ± 5.9	12	12.0 ± 2.3
Conductivity	11	326 ± 65	12	419 ± 64
Chlorophyll *a*	22	15.2 ± 2.6	26	14.0 ± 2.0
Chlorophyll *b*	22	0.5 ± 0.1	26	0.6 ± 0.2
Chlorophyll *c*	22	1.8 ± 0.4	26	1.8 ± 0.3

Table 3. Lake Dardanelle Water Quality (mean ± S.E.) at the river channel site from September 1994 through June 1995, and from July 1995 to June 1996. The units of measurement for all variables is mg/L except for pH, turbidity (NTU), conductivity ($\mu S/cm$), and the chlorophylls ($\mu g/L$).

Variable	N	1994-1995	N	1995-1996
Ca	22	27.9 ± 1.6	25	36.9 ± 1.4
Cl	22	60.9 ± 6.5	26	86.7 ± 6.8
Mg	11	7.0 ± 0.5	12	8.9 ± 0.8
NH_4-N	22	0.031 ± 0.003	26	0.046 ± 0.005
NO_3-N	22	0.30 ± 0.04	26	0.20 ± 0.02
NO_2-N	11	0.007 ± 0.001	13	0.007 ± 0.001
pH	11	7.91 ± 0.12	12	8.03 ± 0.12
PO_4-P	11	0.060 ± 0.013	13	0.082 ± 0.021
Total P	22	0.097 ± 0.010	26	0.082 ± 0.008
SO_4	11	32.4 ± 3.4	13	42.0 ± 3.7
Suspended	11	23.4 ± 6.5	13	18.0 ± 4.5
Turbidity	11	29.0 ± 6.5	11	21.9 ± 4.8
Conductivity	11	420 ± 46	12	570 ± 38
Chlorophyll *a*	22	15.3 ± 2.4	26	16.6 ± 2.1
Chlorophyll *b*	22	0.4 ± 0.1	26	0.5 ± 0.2
Chlorophyll *c*	22	1.7 ± 0.2	26	2.3 ± 0.3

Table 4. Lake Dardanelle Water Quality (mean ± S.E.) at the Illinois Bayou site from September 1994 through June 1995, and from July 1995 to June 1996. The units of measurement for all variables is mg/L except for pH, turbidity (NTU), conductivity (µS/cm), and the chlorophylls (µg/L).

Variable	N	1994-1995	N	1995-1996
Ca	22	21.2 ± 2.1	25	33.3 ± 2.1
Cl	22	51.5 ± 7.0	26	85.1 ± 6.1
Mg	11	5.1 ± 0.8	12	8.7 ± 1.0
NH_4-N	22	0.056 ± 0.024	26	0.045 ± 0.004
NO_3-N	22	0.29 ± 0.06	26	0.15 ± 0.02
NO_2-N	11	0.008 ± 0.002	13	0.007 ± 0.002
pH	11	7.86 ± 0.17	12	8.04 ± 0.13
PO_4-P	11	0.028 ± 0.005	13	0.083 ± 0.039
Total P	22	0.078 ± 0.008	26	0.069 ± 0.005
SO_4	11	27.2 ± 4.3	13	45.5 ± 2.9
Suspended	11	9.2 ± 1.2	13	9.3 ± 1.5
Turbidity	11	16.3 ± 2.8	12	12.7 ± 2.4
Conductivity	11	310 ± 58	12	534 ± 42
Chlorophyll *a*	22	16.8 ± 2.5	26	18.2 ± 2.0
Chlorophyll *b*	22	0.4 ± 0.1	26	0.6 ± 0.2
Chlorophyll *c*	22	1.9 ± 0.4	26	2.2 ± 0.3

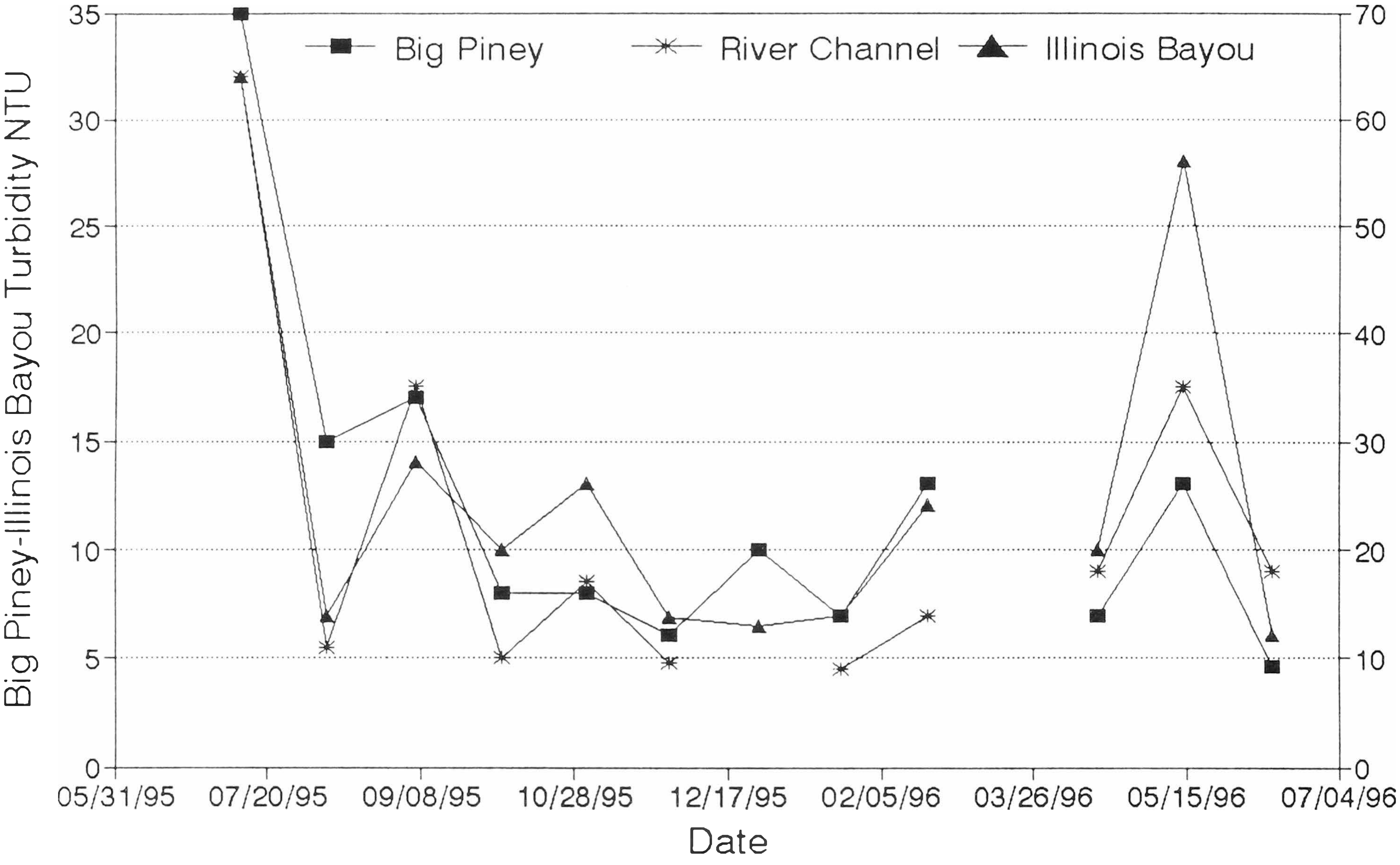

Figure 4. Comparison of turbidity among sample areas and dates.

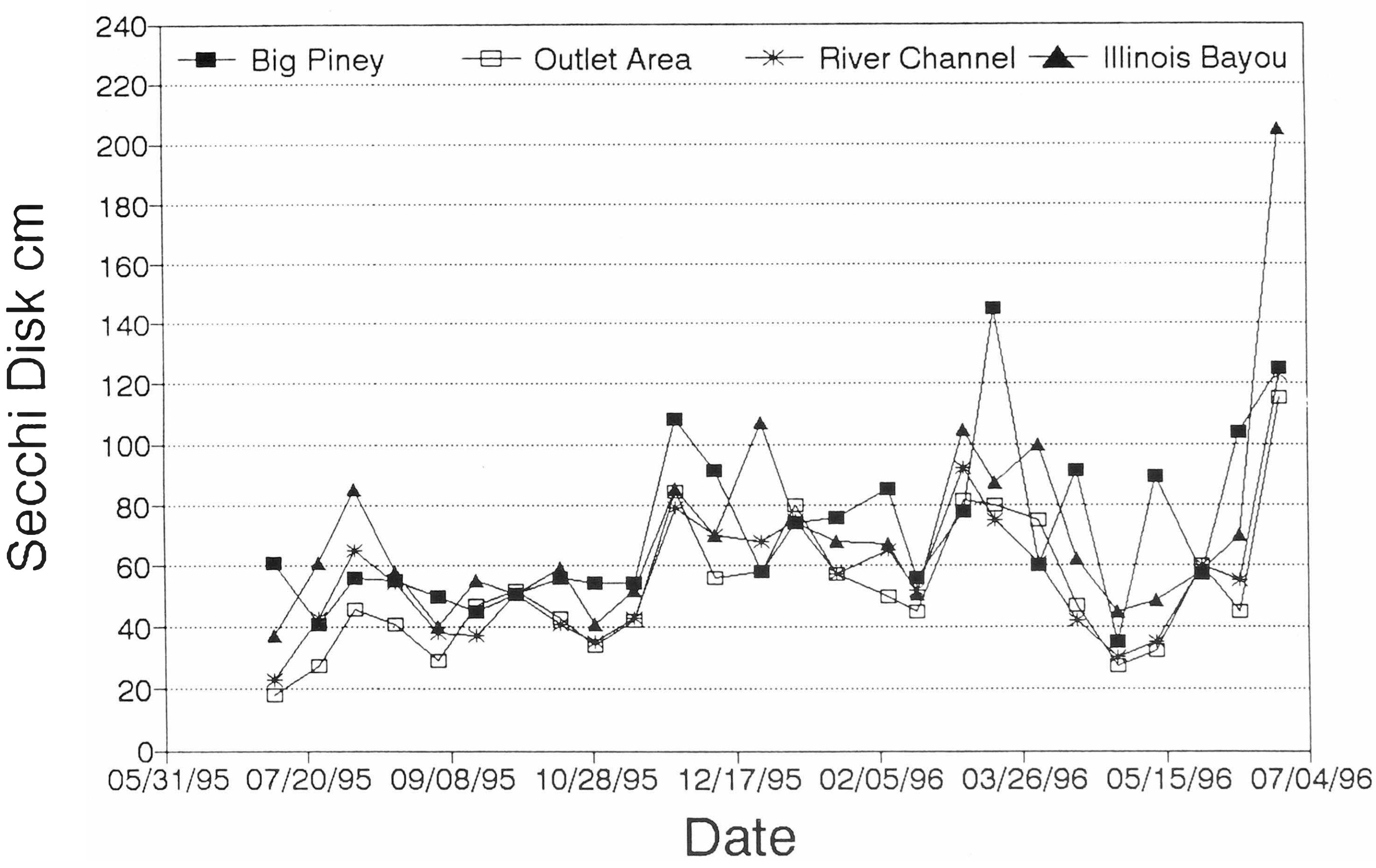

Figure 5. Comparison of Secchi disk visibility among sample areas and dates.

Table 5. Lake Dardanelle Water Quality (mean values of all sites) from September 1994 through June 1995, and from July 1995 to June 1996. The units of measurement for all variables is mg/L except for pH, turbidity (NTU), conductivity (μS/cm), and the chlorophylls (μg/L).

Variable	1994-1995	1995-1996
Ca	22.9	32.9
Cl	53.1	78.5
Mg	5.7	8.1
NH_4-N	0.039	0.048
NO_3-N	0.28	0.17
NO_2-N	0.007	0.006
pH	7.79	7.99
PO_4-P	0.037	0.067
Total P	0.084	0.074
SO_4	28.4	40.2
Suspended	16.7	12.8
Turbidity	22.5	15.5
Conductivity	352	508
Chlorophyll *a*	15.7	16.3
Chlorophyll *b*	0.4	0.6
Chlorophyll *c*	1.8	2.1

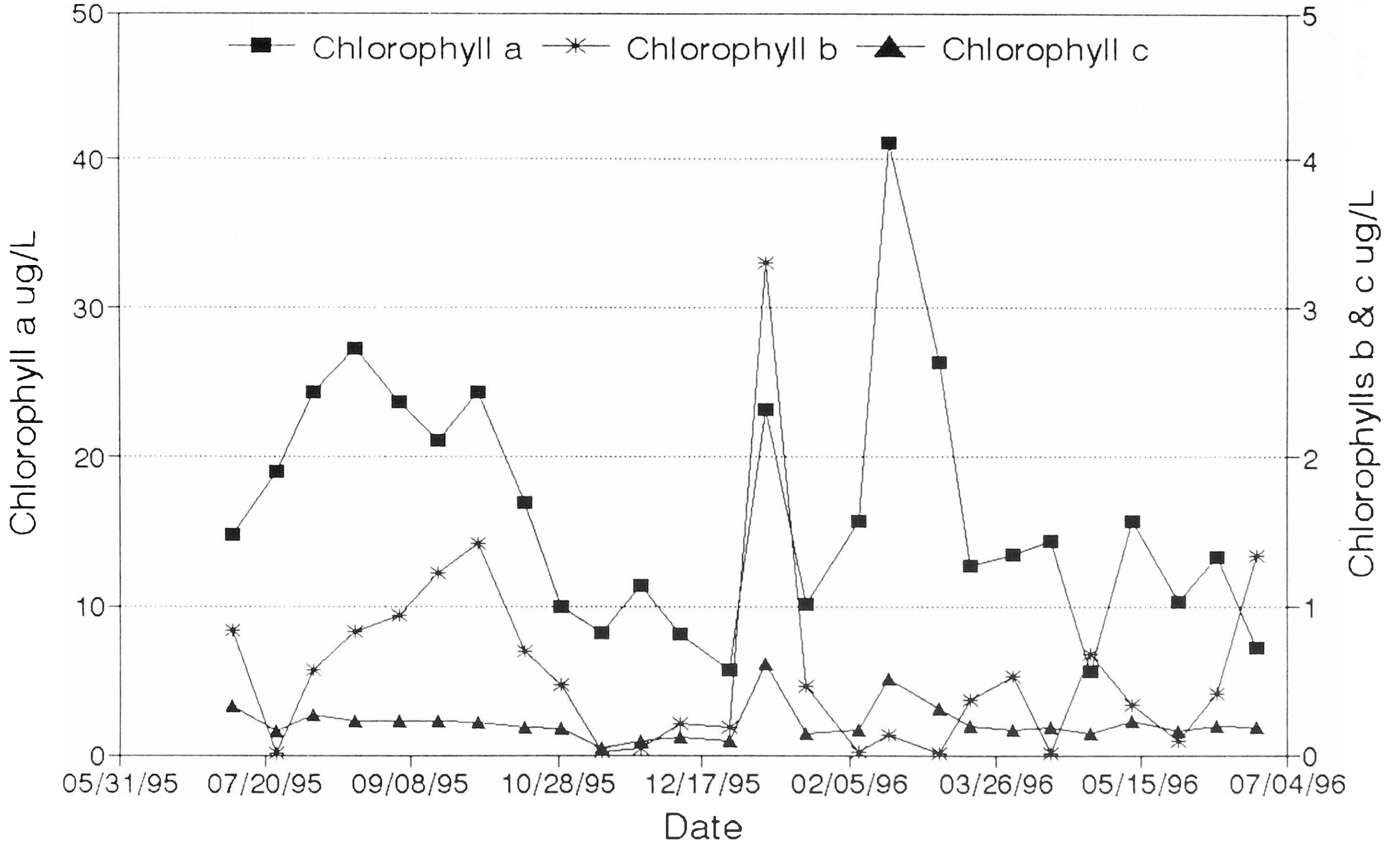

Figure 6. Comparison of chlorophylls *a*, *b*, and *c* among dates. Values are averaged across three sample areas.

sample years were 15.7 vs. 16.3 μg/L for chlorophyll *a*, 0.4 vs. 0.6 μg/L for chlorophyll *b*, and 1.8 vs. 2.1 for 1.8 μg/L for chlorophyll *c* (Table 5). Total suspended solids averaged 12.8 mg/L and followed the same pattern as turbidity (Figure 7). The mean total suspended solid value was 23% lower for the 1995-1996 sample year compared to the 1994-1995 sample year (Table 2). Mean soluble reactive phosphorus concentration increased 50%, whereas mean total phosphorous concentration decreased 13% between sample years. Nitrogen levels were generally higher at the Big Piney site, whereas Nitrate levels were generally higher at the river channel site (Figures 8 and 9). None of the nitrogen compounds (NH_4, NO_3, or NO_2) exhibited a significant change in their mean values between sample years. Mean concentrations of all major cations and anions were substantially higher for the 1995-1996 sample year compared to the 1994-1995 sample year, calcium increased 43%, magnesium increased 42%, sulfate increased 42%, and chloride increased 48% (Table 5). Conductivity tended to be lower at the Big Piney site compared to the other sites (Figure 10). Mean conductivity, for all sites combined, increased 44%; approximately the same proportion as the major ions (Table 5). Dissolved oxygen and temperature were similar among sample areas and followed normal seasonal patterns with the highest dissolved oxygen and lowest temperatures in the winter months (Figures 11 and 12, respectively). Additional

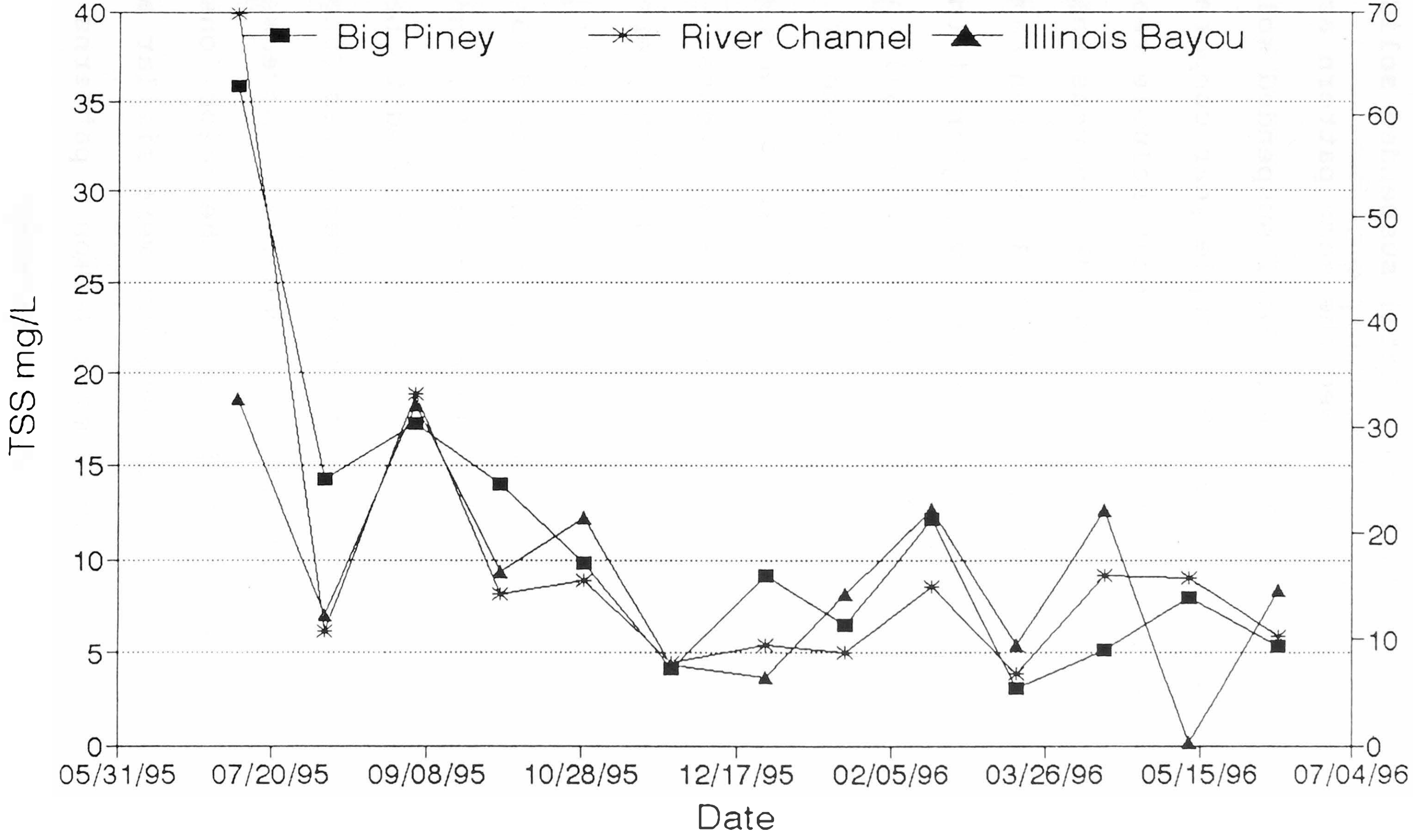

Figure 7. Comparison of total suspended solids among sample areas and dates.

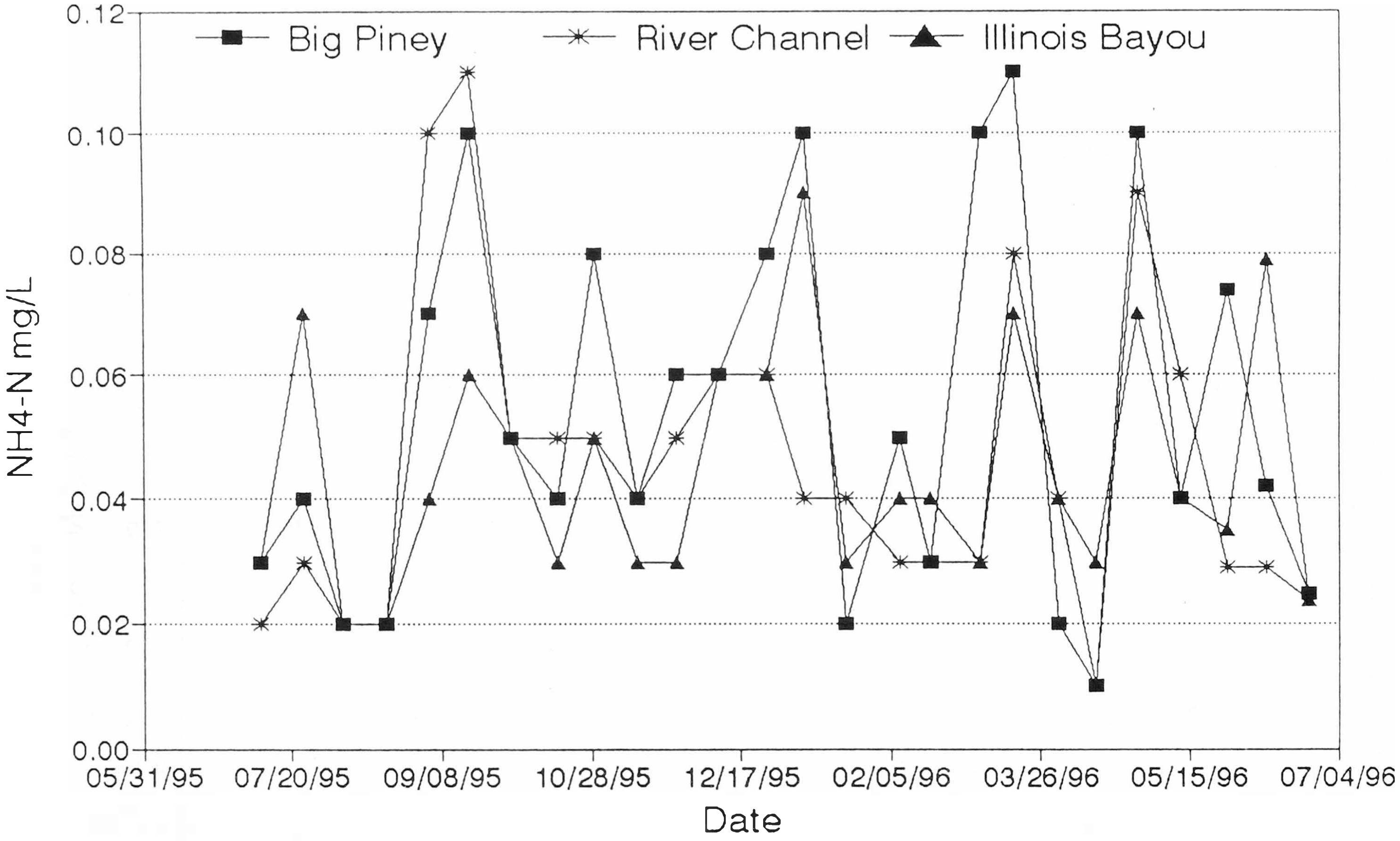

Figure 8. Comparison of ammonia-N among sample areas and dates.

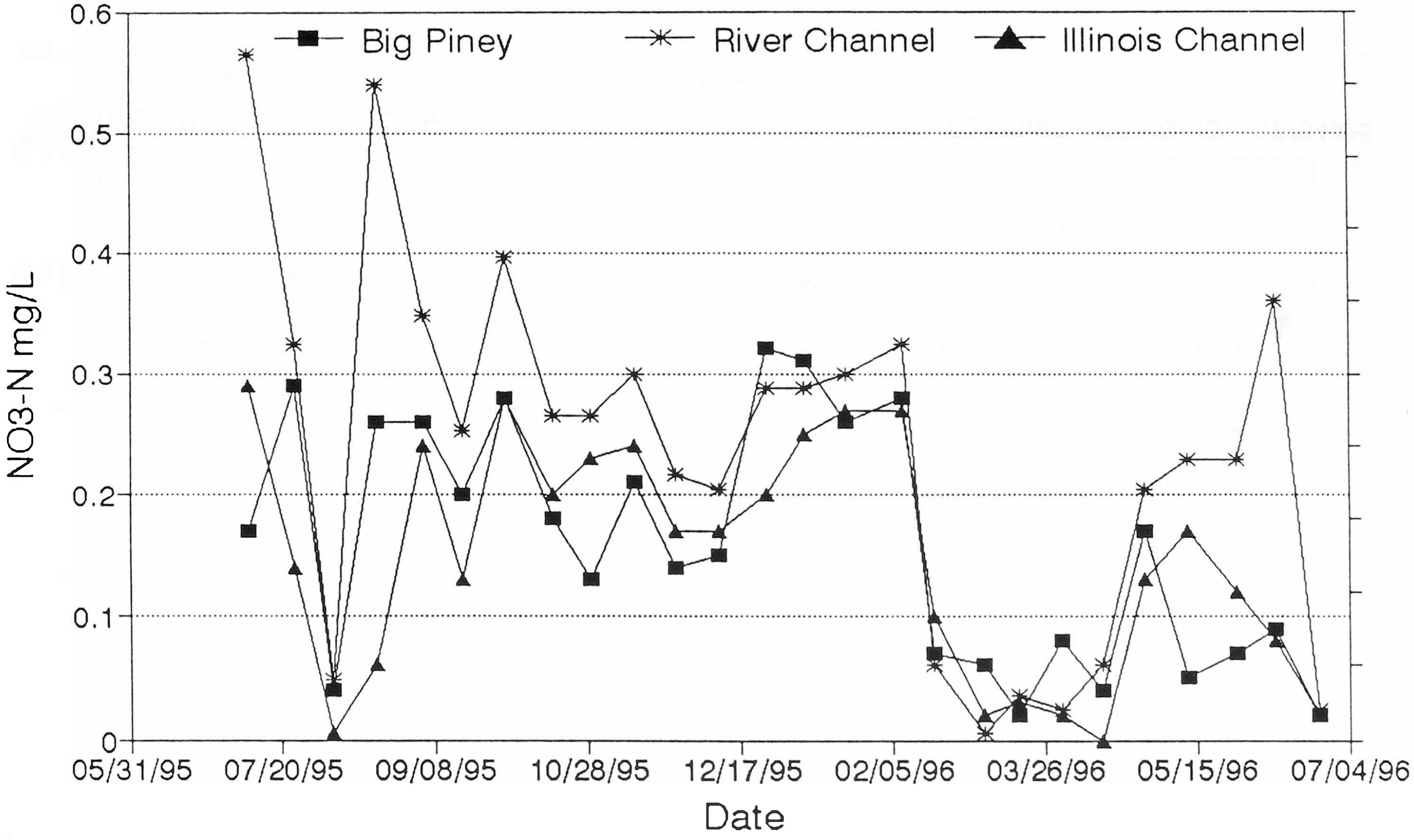

Figure 9. Comparison of nitrate-N among sample areas and dates.

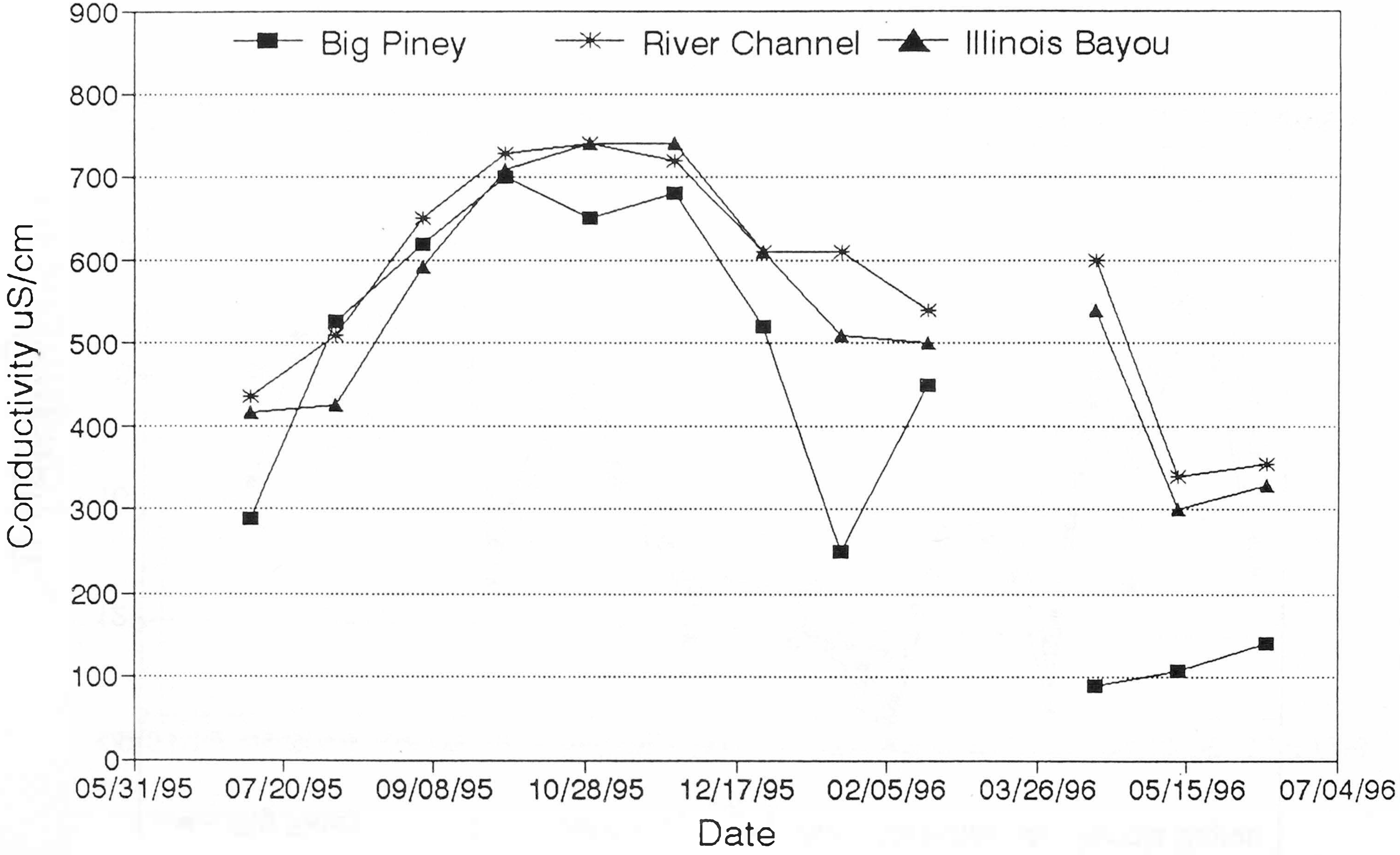

Figure 10. Comparison of conductivity among sample areas and dates.

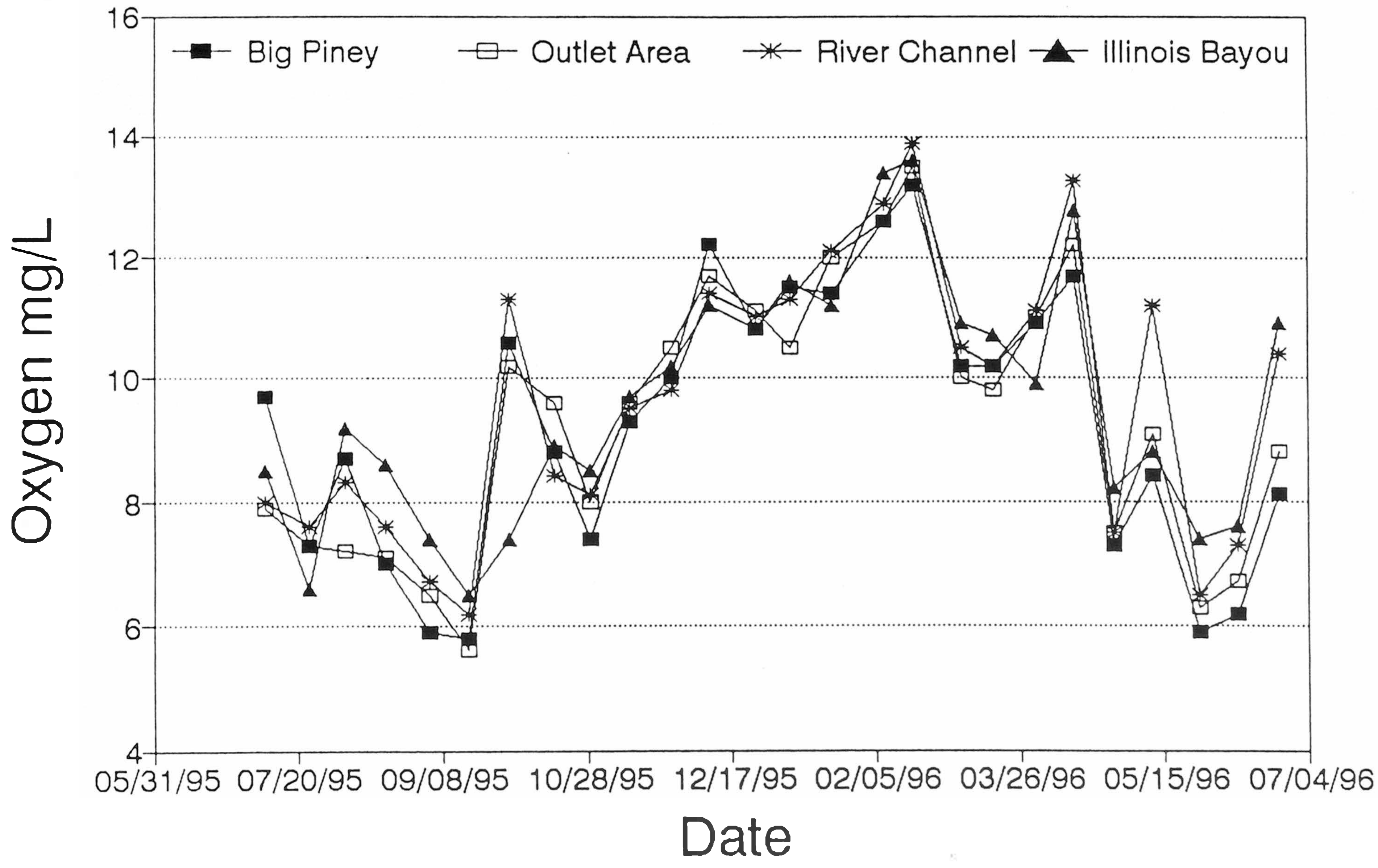

Figure 11. Comparison of dissolved oxygen among sample areas and dates.

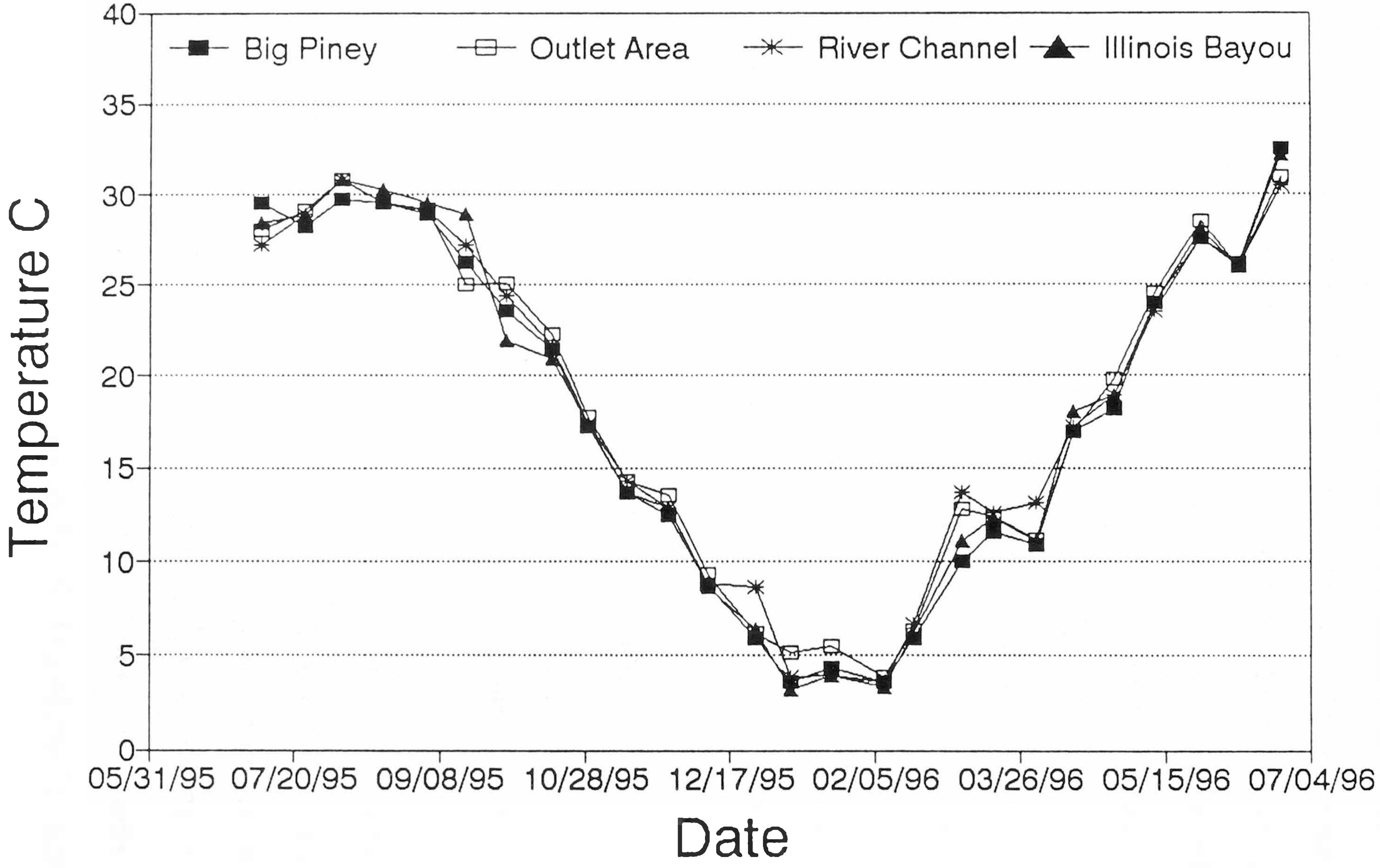

Figure 12. Comparison of temperature at a depth of 1 m among sample areas and dates.

water chemistry patterns are contained in Appendix A.

The zooplankton community in Lake Dardanelle was numerically dominated by rotifers (Figure 13). Their density was similar among sites and often exceeded 80/L in vertical tow samples (Figure 14). Rotifer density was lowest in winter as expected. Zebra mussel veligers, nauplii, copepods, and cladocerans composed substantial proportions of the total zooplankton (Figures 15, 16, 17, and 18). Ostracods and "other zooplankton" never constituted a large proportion of the total zooplankton. Separate area graphs for each site showing community composition for each taxa are presented in Appendix B.

Although we did not find any submergent vegetation at our sample sites, we did observe some small patches at various sites around the reservoir. The emergent vegetation coverage ranged from ≈ 1 to 41% depending on site and season (Figure 19). Mean percent coverage was lowest at the river channel site and highest at the Illinois Bayou site. A large portion of the weed bed at the river channel site was lost during high water in Spring 1995. There was a slight decrease in the mean coverage at our sites between the 1994-1995 and 1995-1996 sample years (Figure 20). Virtually all of the aquatic vegetation in sample areas was water willow, <u>Dianthera</u> (<u>Justicia</u>) <u>americana</u>.

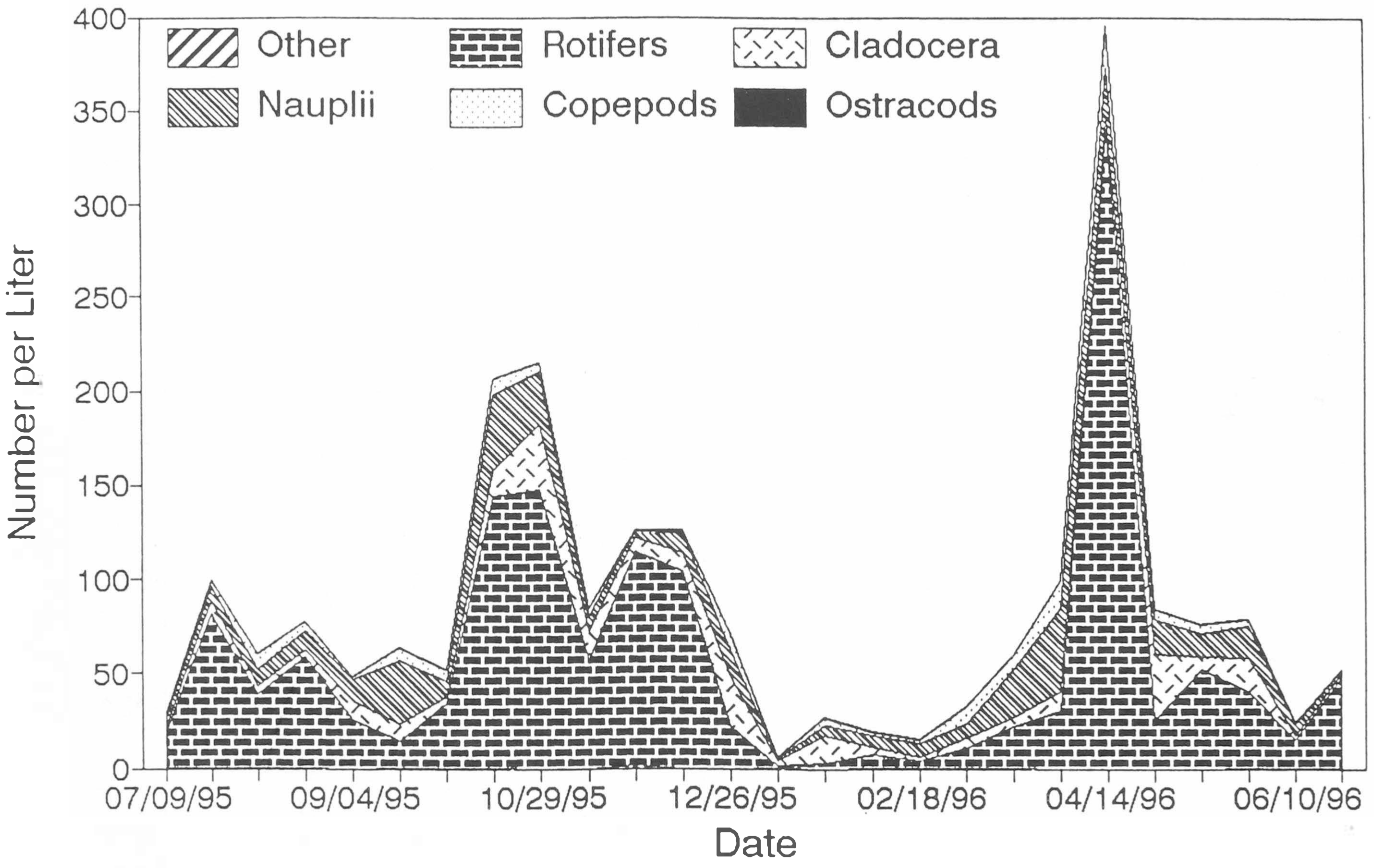

Figure 13. Changes in density of zooplankton (exclusive of zebra mussels) in the plankton of Lake Dardanelle, AR, since July 9, 1995. The value for each date is the mean density of zooplankton collected in pump and vertical tow samples (unless only one type was taken) averaged across four sample areas.

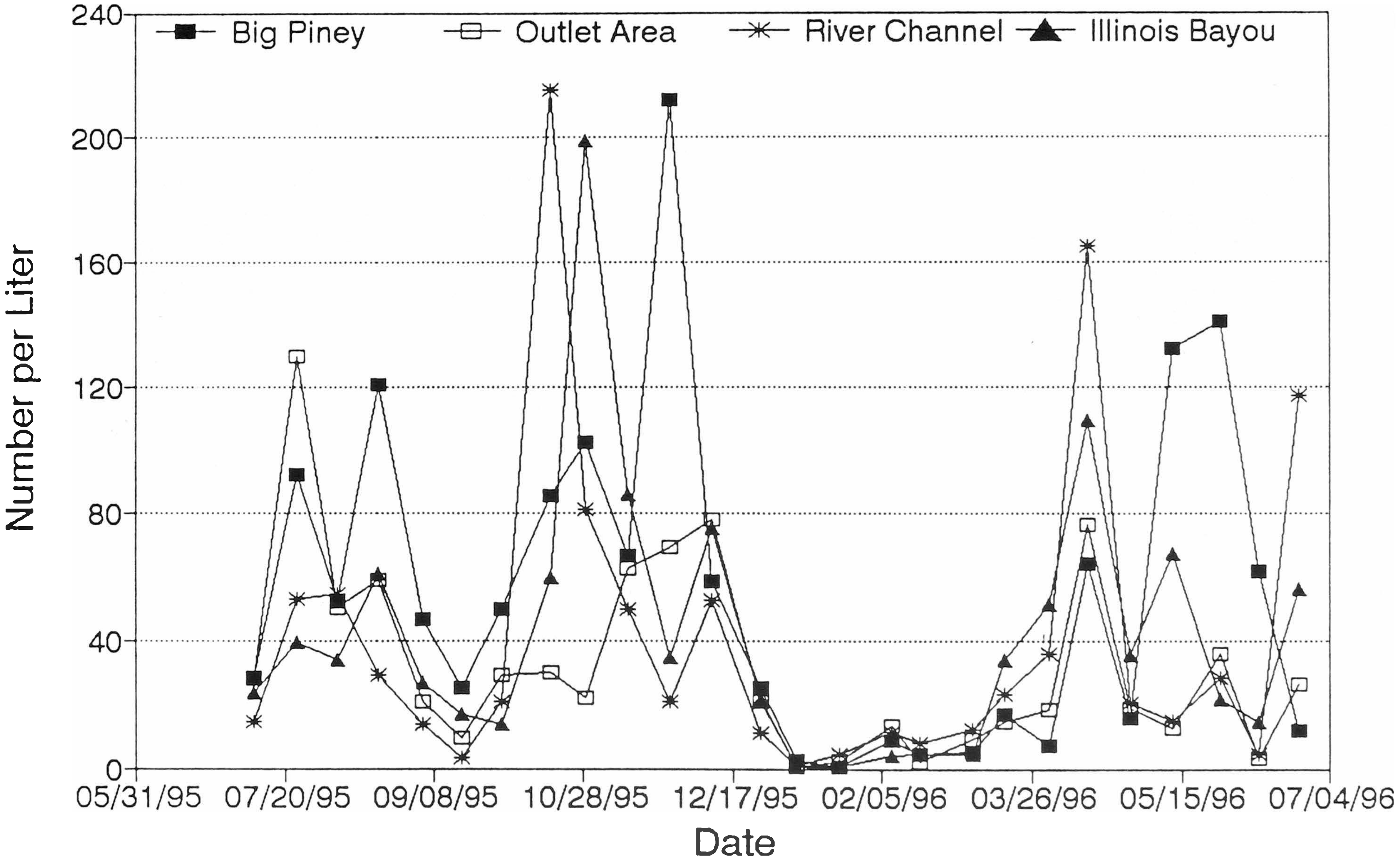

Figure 14. Changes in densities of rotifers collected in vertical tow samples among sample areas and dates.

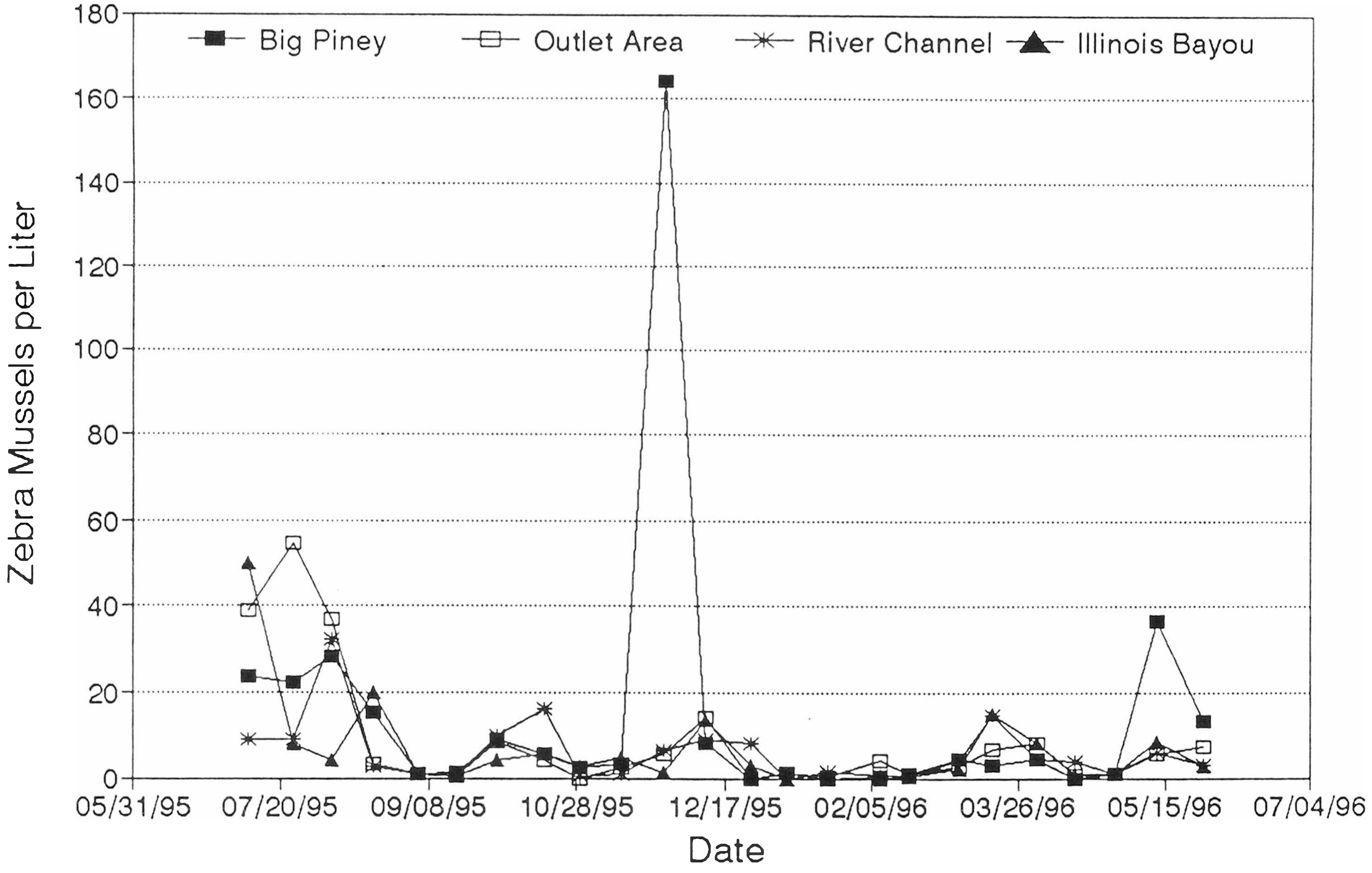

Figure 15. Changes in densities of zebra mussels collected in vertical tow samples among sample areas and dates.

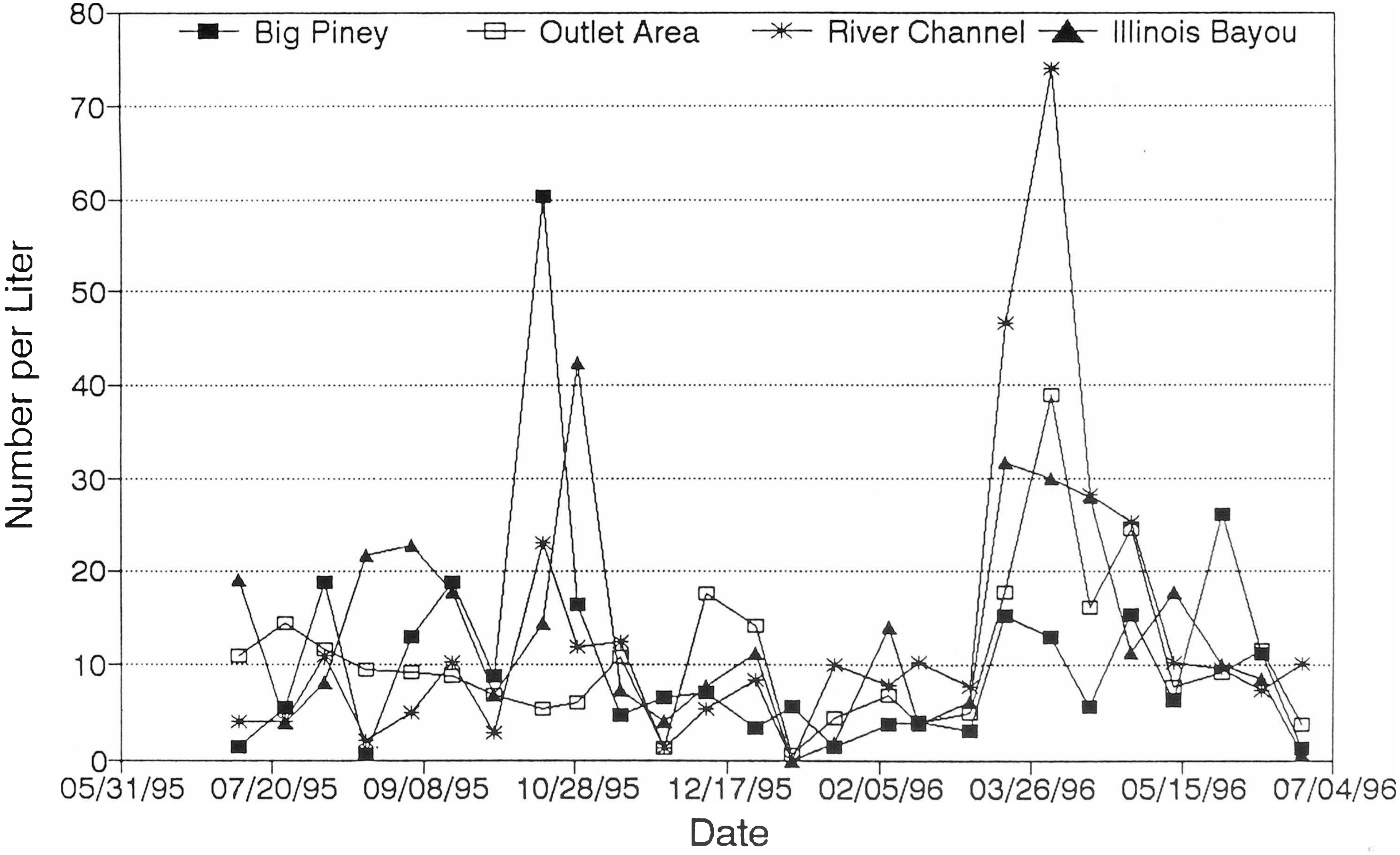

Figure 16. Changes in densities of nauplii collected in vertical tow samples among sample areas and dates.

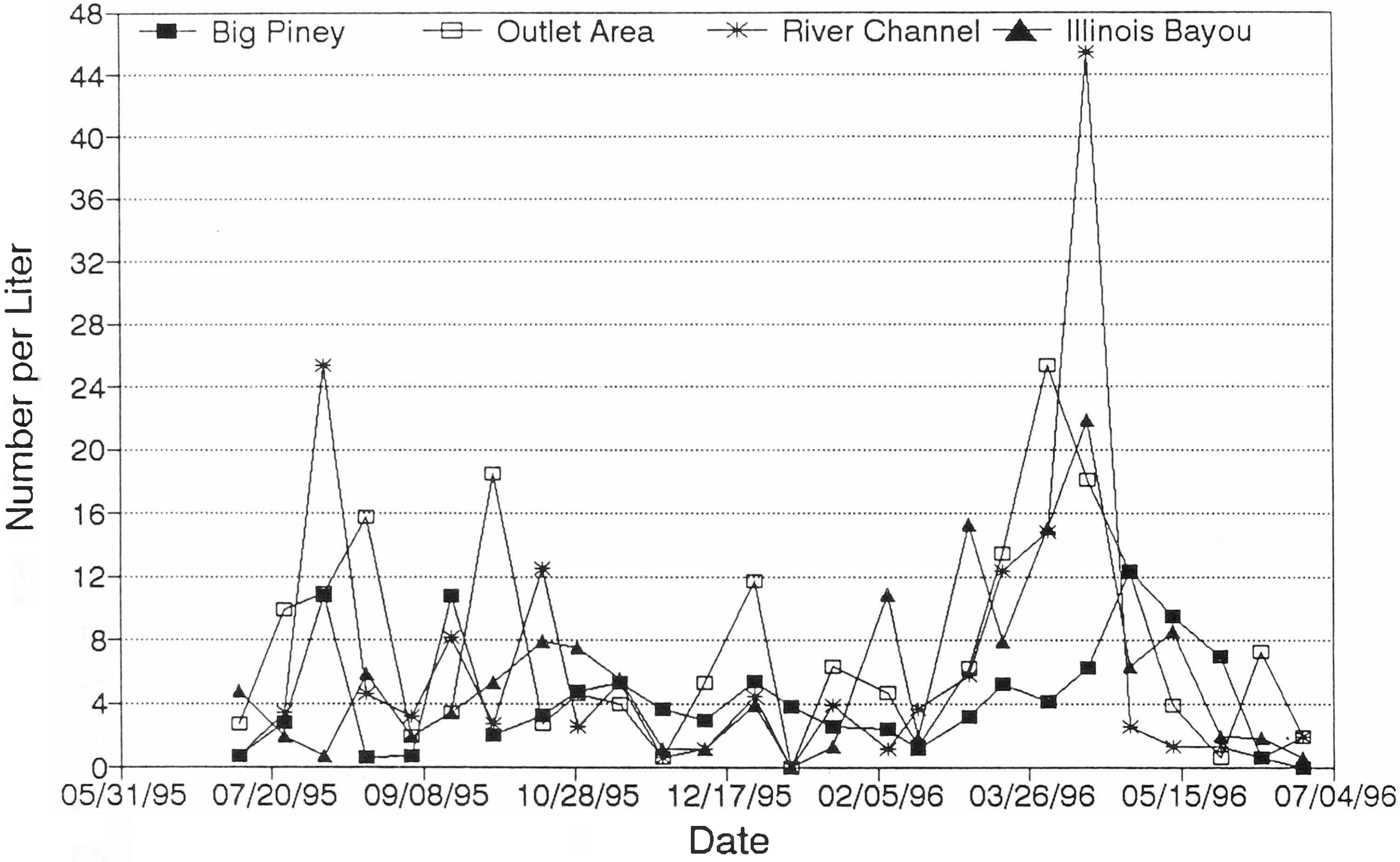

Figure 17. Changes in densities of copepods collected in vertical tow samples among sample areas and dates.

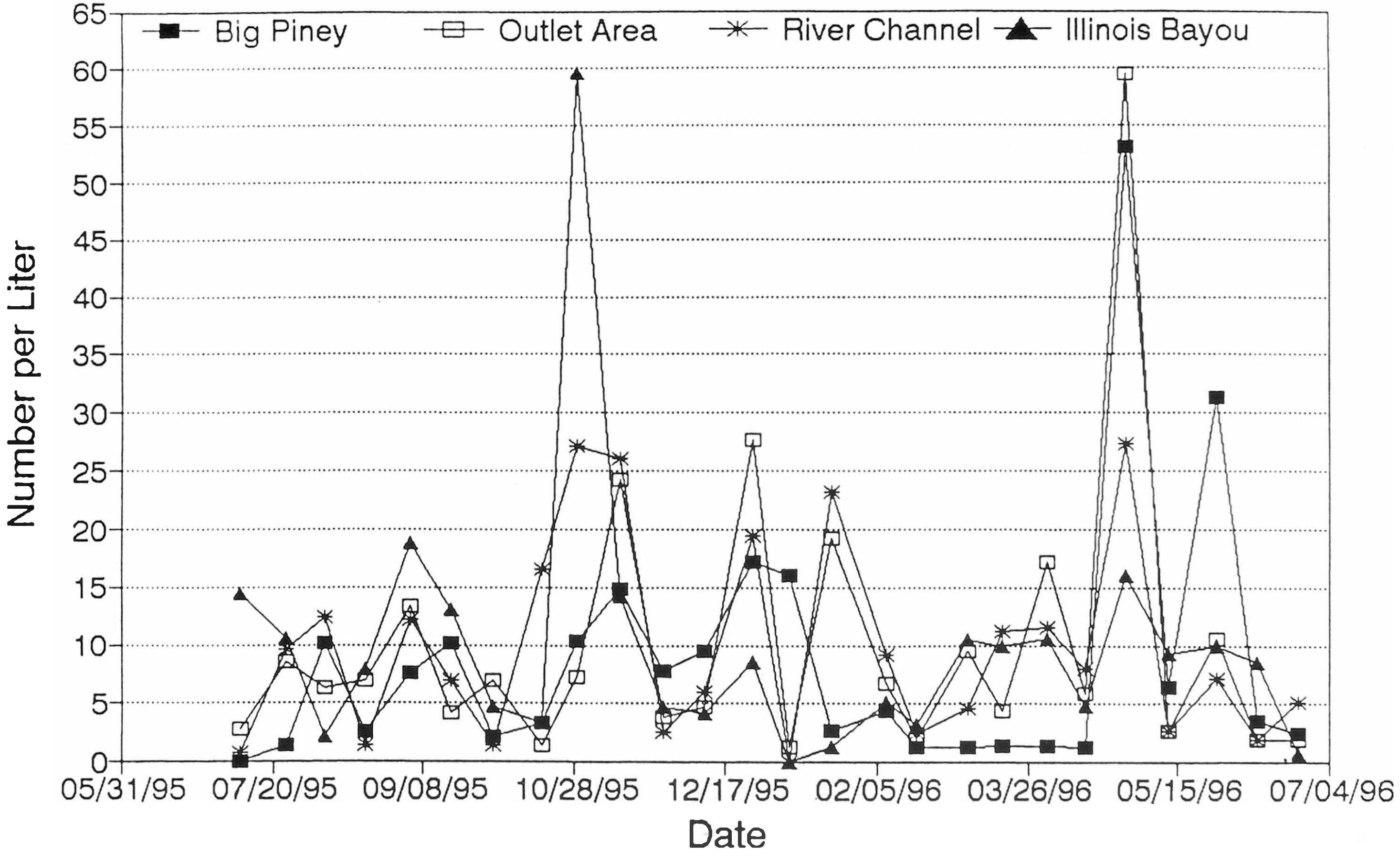

Figure 18. Changes in densities of cladocerans collected in vertical tow samples among sample areas and dates.

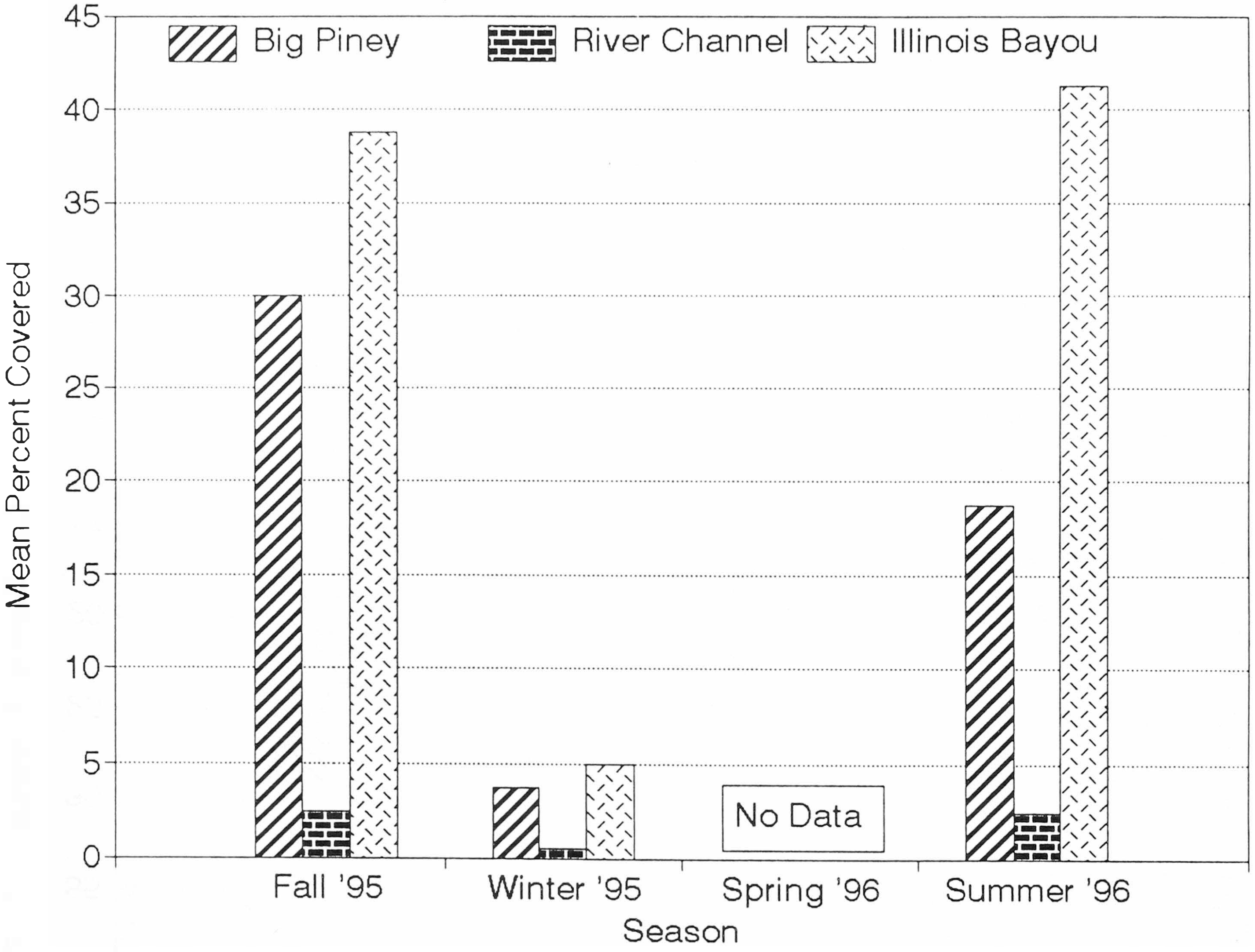

Figure 19. Seasonal changes in percent surface area coverage of submergent and emergent vegetation among sample areas.

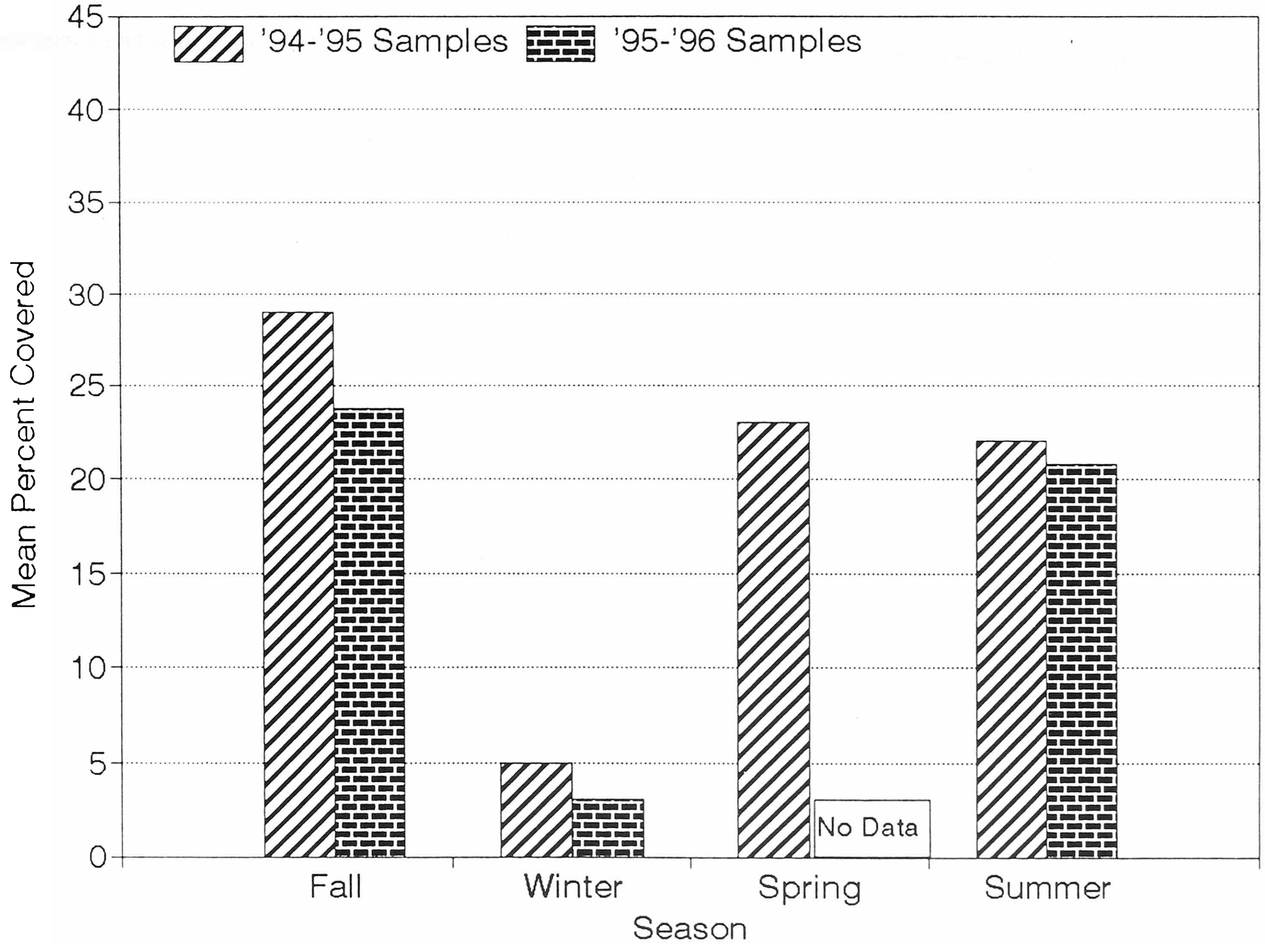

Figure 20. Comparison of seasonal changes in percent area coverage of submergent and emergent vegetation between sample years.

CONCLUSIONS

Lake Dardanelle is highly influenced by the Arkansas River which flows through it. The reservoir is very shallow (mean depth $\approx$ 4.3 m), yet the littoral zone is narrow due to high levels of suspended solids during most of the year. During 1995-1996 the photic zone increased substantially compared to the 1994-1995 sample season. Four of the five highest average Secchi disk readings during the past three years were recorded in 1996. Lower than normal river flow rate in summer may have contributed to this pattern, however, it is probably due largely to filtration of suspended particulate matter by the zebra mussels. At the average density of adults recorded in 1996, zebra mussels have the capacity to filter the entire volume of the reservoir approximately twice daily. Small patches of submergent macrophytes have already become established, and if water clarity continues to increase, we expect that submergent vegetation will increase substantially within the next few years. The concentration of total suspended solids was positively correlated with turbidity indicating that suspended solids, in addition to zebra mussel filtration, continues to have a significant influence on turbidity (Figure 21). In 1995-1996 we also noted a moderately strong correlation between suspended solids and total phosphorous (Figure 22). The observation that the main lake (river channel site) had higher turbidity readings is consistent with our hypothesis

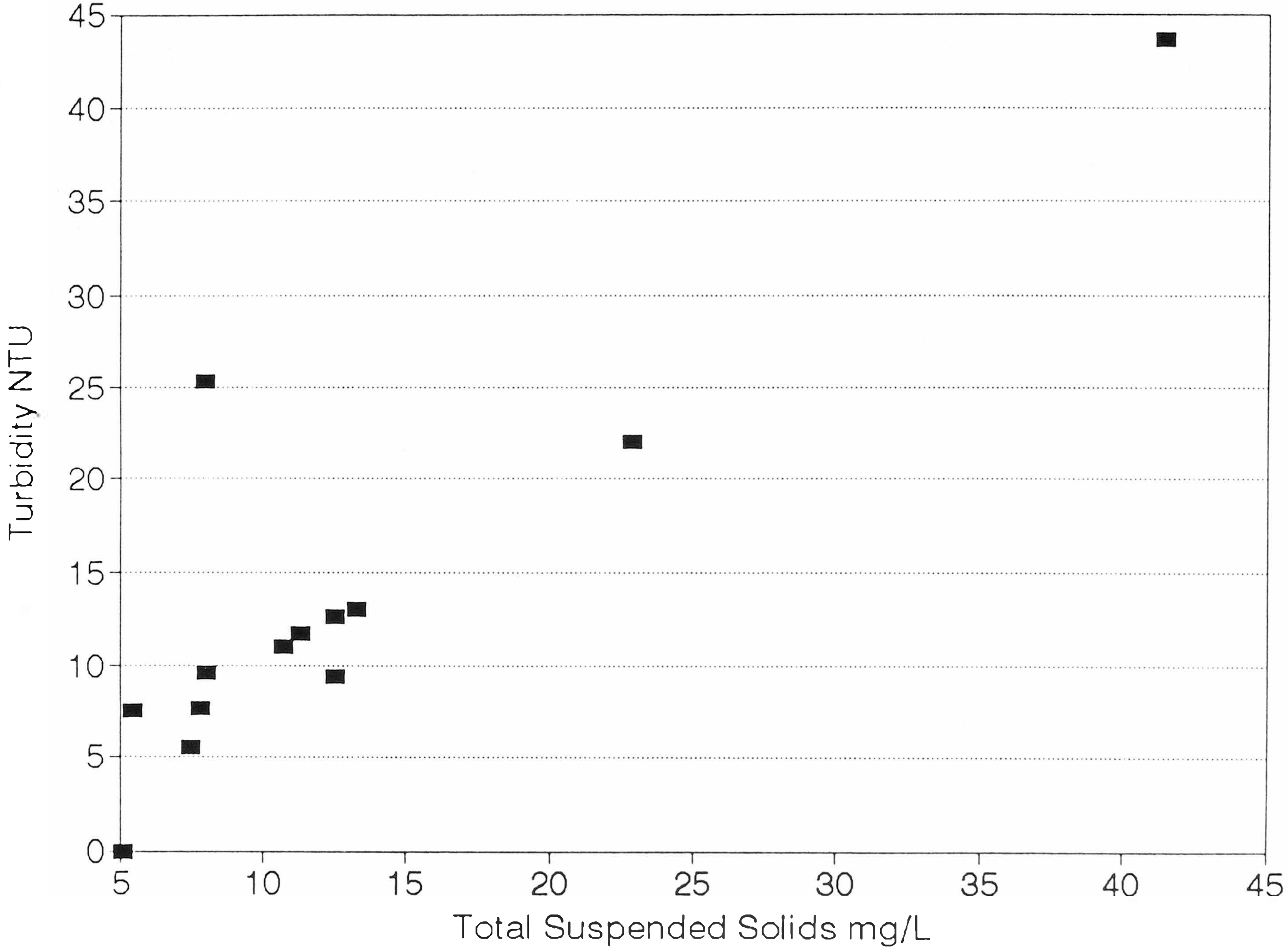

Figure 21. Scatter plot of turbidity versus total suspended solids for all sample areas and dates combined.

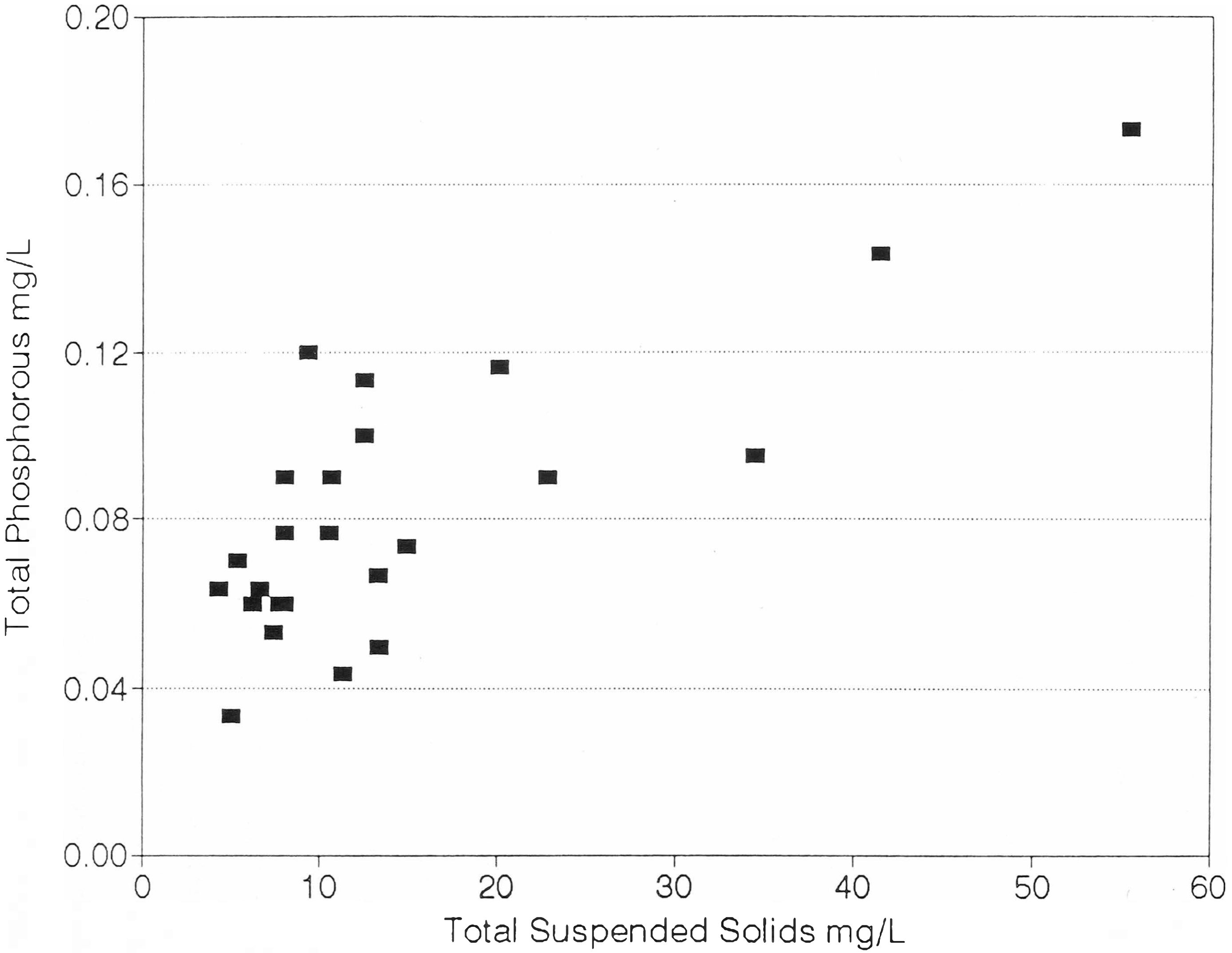

Figure 22. Scatter plot of total phosphorous versus total suspended solids for all sample areas and dates combined.

that large bays are more vulnerable to high filtration rates of dense mussel communities.

Our preliminary observations indicate that in 1996, adult zebra mussels will be very abundant and concentrated in areas dominated by hard substrate (rather than the more common silt and sand substrate). Because the population of adult zebra mussels has remained low until now, we consider the data in this report to constitute a baseline for comparison of changes as the population increases.

If water clarity increases as a result of zebra mussel filtration, we expect zooplankton communities to avoid sight-feeding predators by moving deeper into the water column during daylight hours. If zebra mussels establish a substantial population and selectively remove larger zooplankton, then copepods and cladocerans would comprise even smaller proportions of future samples. Furthermore, it is possible that larval fish productivity could decline due to competition for the larger zooplankton.

High nutrient availability and suitable substrate in Lake Dardanelle could support dense stands of aquatic macrophytes; however, light penetration is limiting as is typical of other reservoirs on the Arkansas River. Increased light penetration could result in establishment of dense beds of emergent and submergent vegetation, which could drastically influence fish population dynamics and negatively impact boating. We have made substantial progress toward characterizing key water quality and biotic parameters of Lake Dardanelle, and upon completion of this study we should be able to test critical hypotheses relative to zebra mussel invasion of shallow southern reservoirs. The trends thus far, support hypotheses 2, 3, and 5, but we have not yet observed substantial changes in the parameters addressed in hypotheses 1 and 4.

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APPENDIX A
ADDITIONAL WATER QUALITY PATTERNS

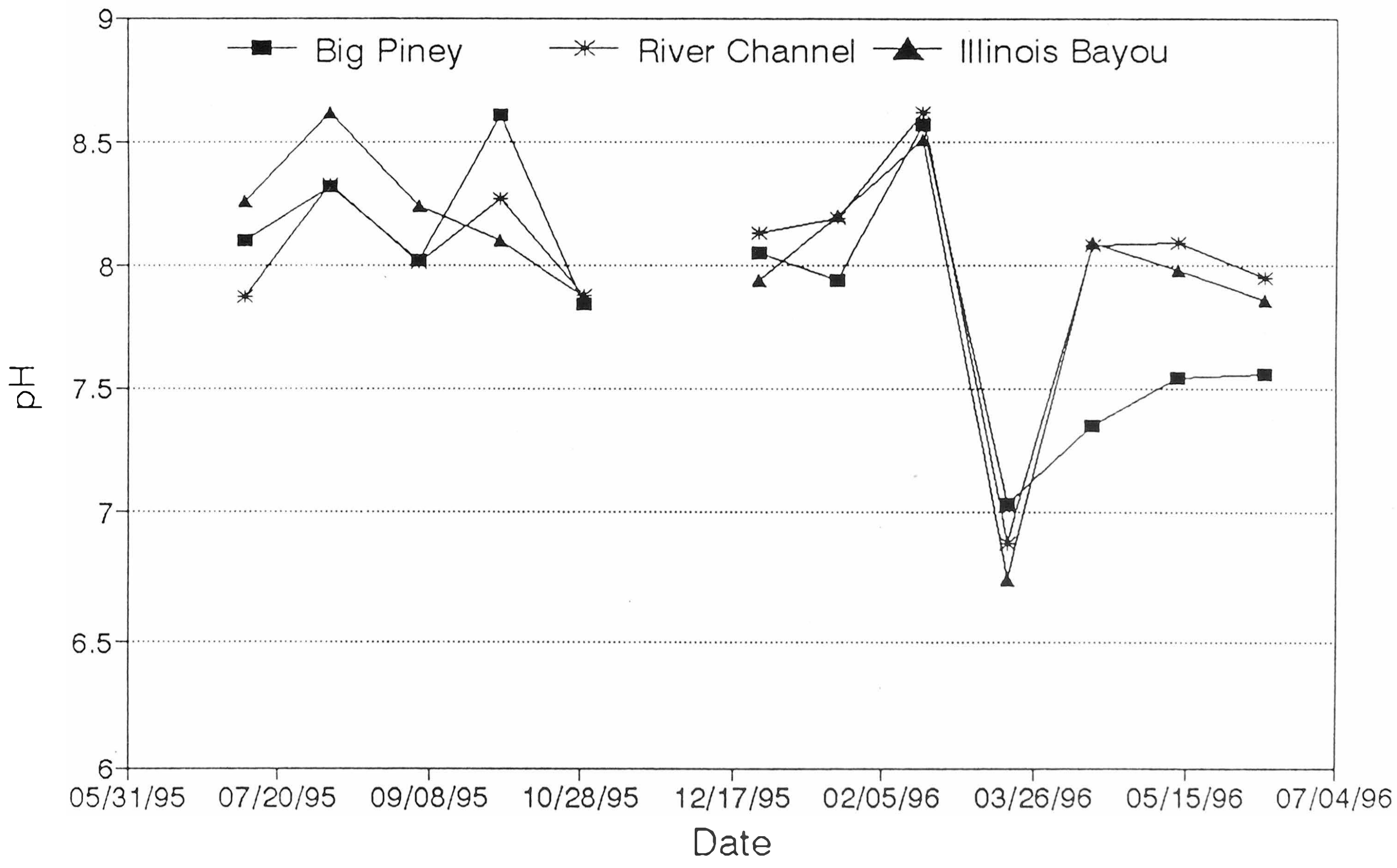

Figure 23. Comparison of pH values among sample areas and dates.

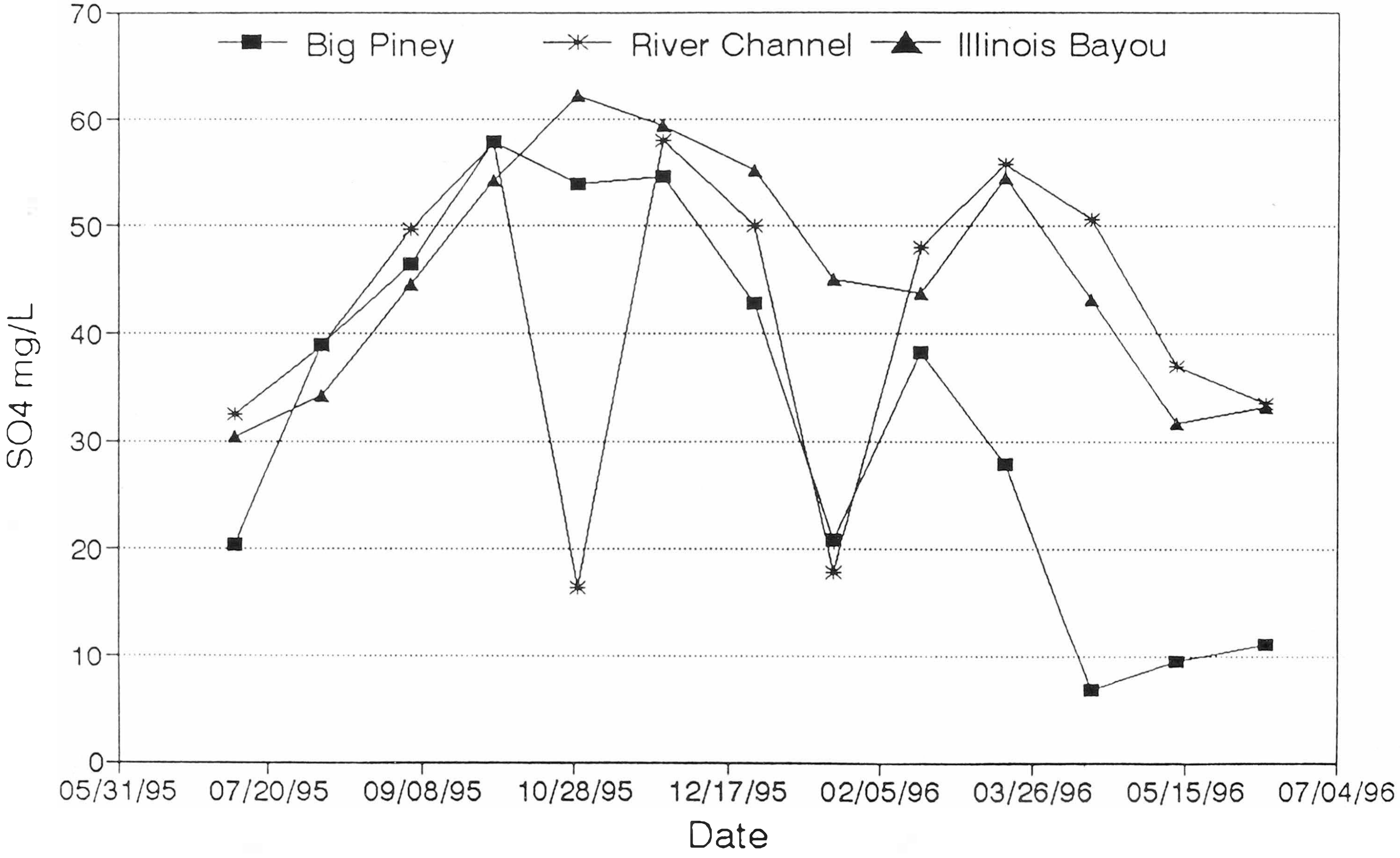

Figure 24. Comparison of sulfate concentrations among sample areas and dates.

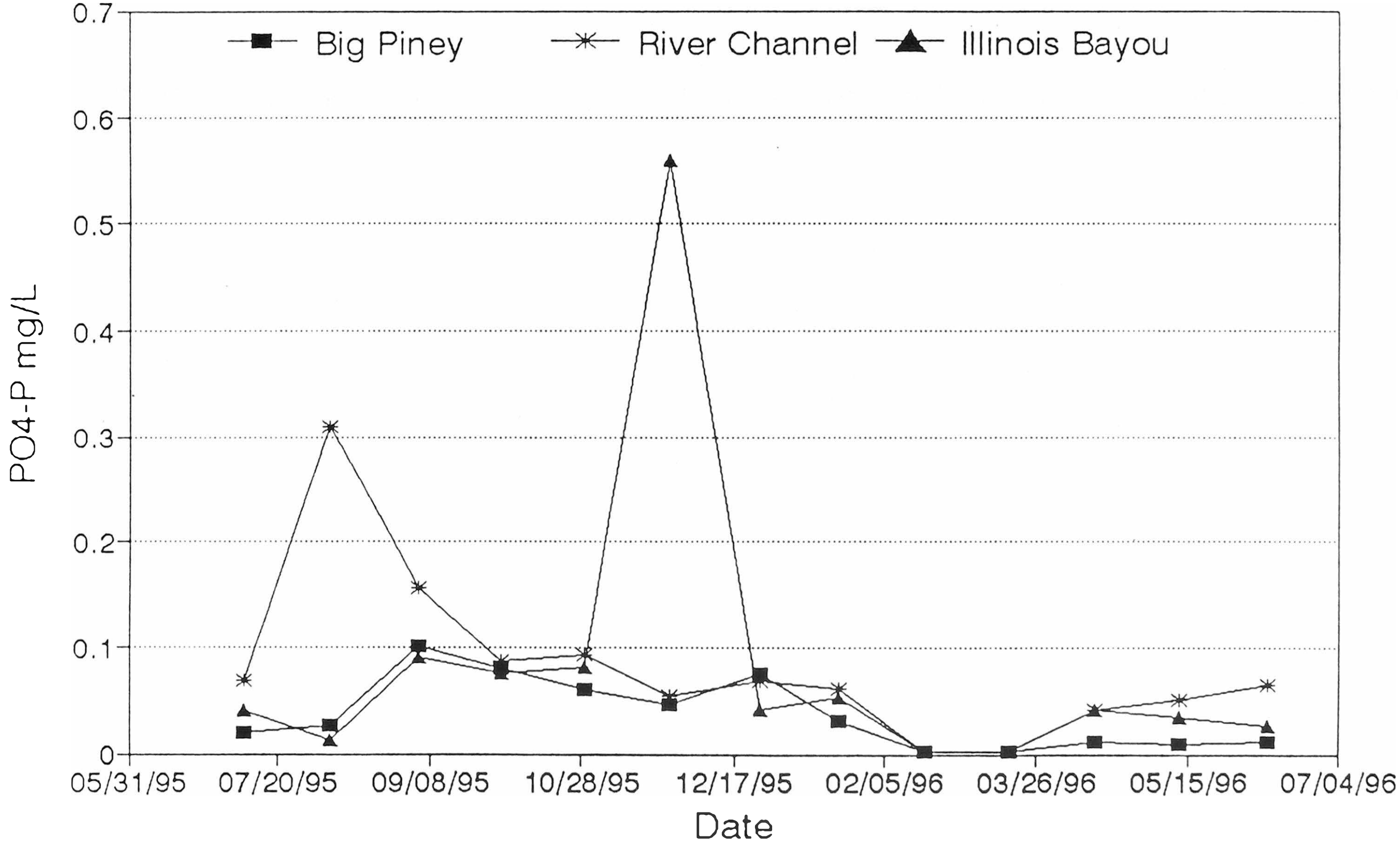

Figure 25. Comparison of phosphate-P concentrations among sample areas and dates.

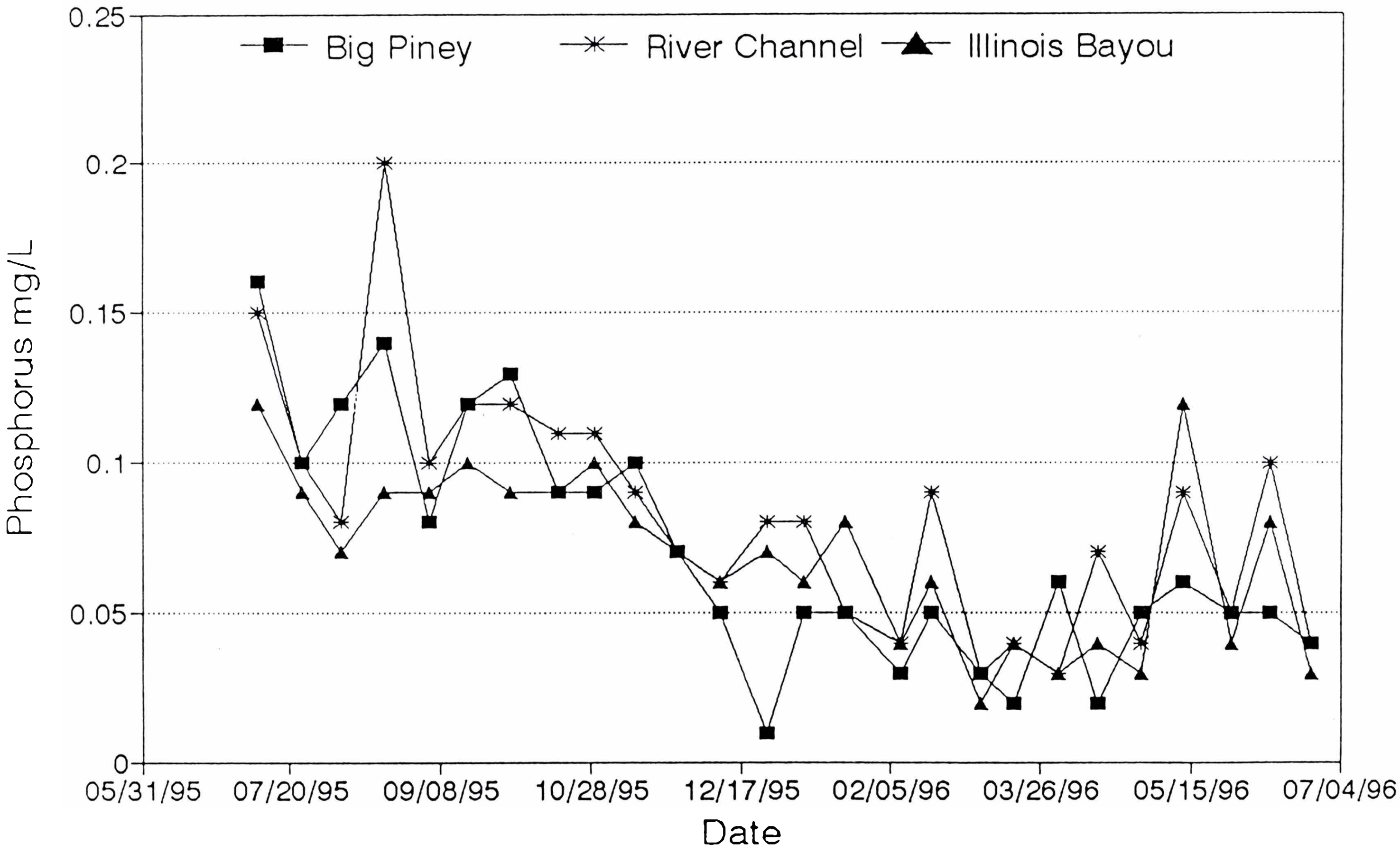

Figure 26. Comparison of total phosphorous concentrations among sample areas and dates.

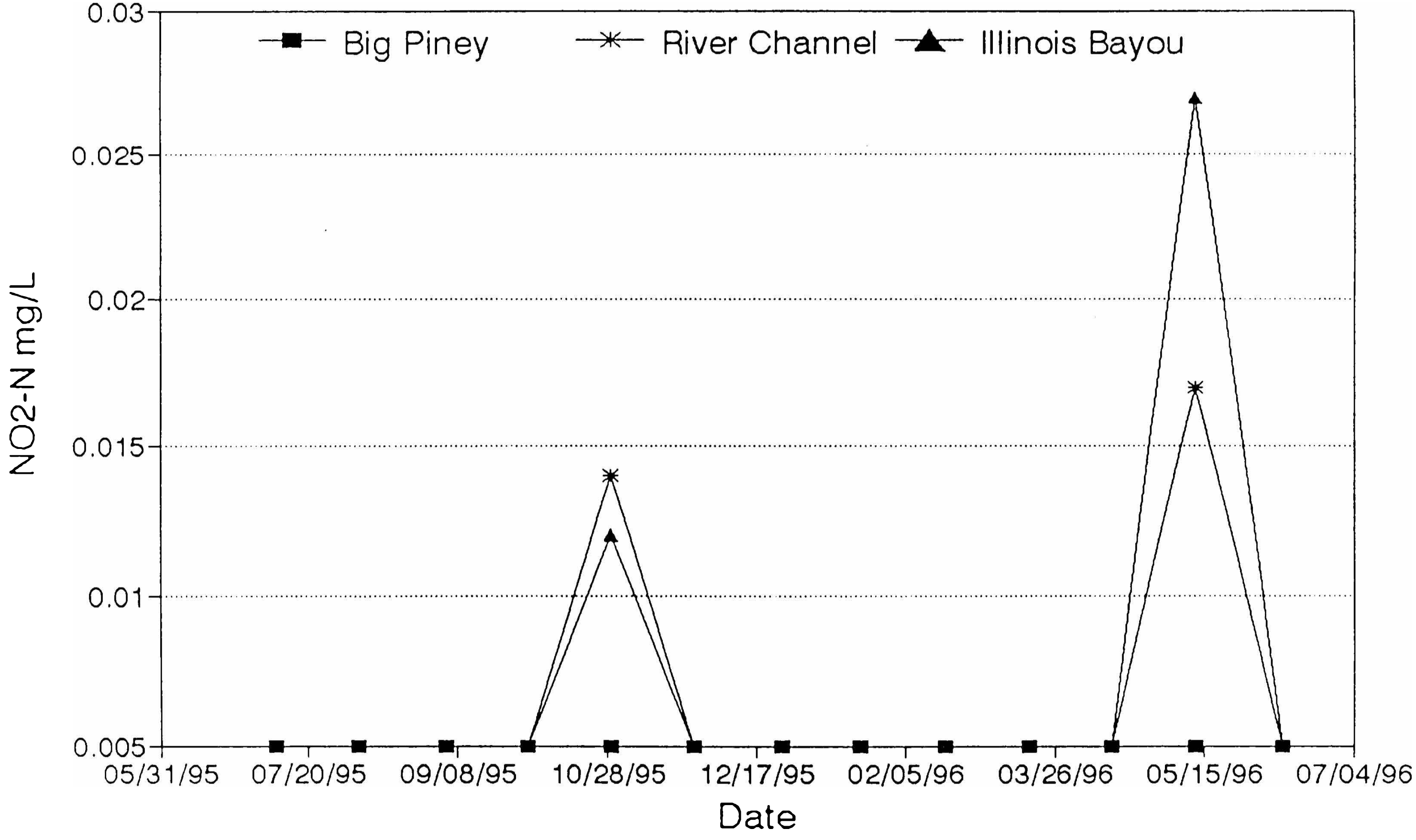

Figure 27. Comparison of nitrite-N concentrations among sample areas and dates.

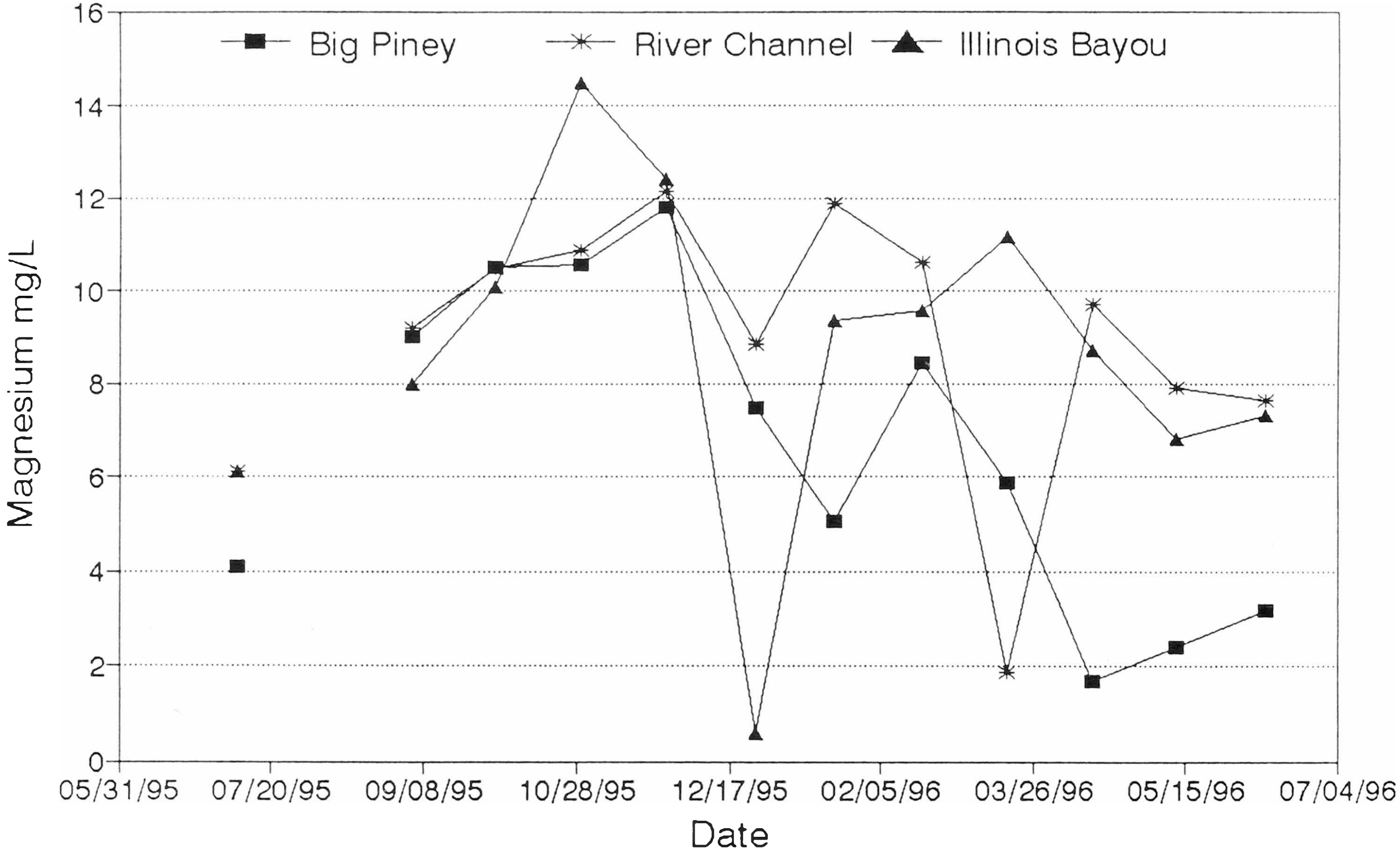

Figure 28. Comparison of magnesium concentrations among sample areas and dates.

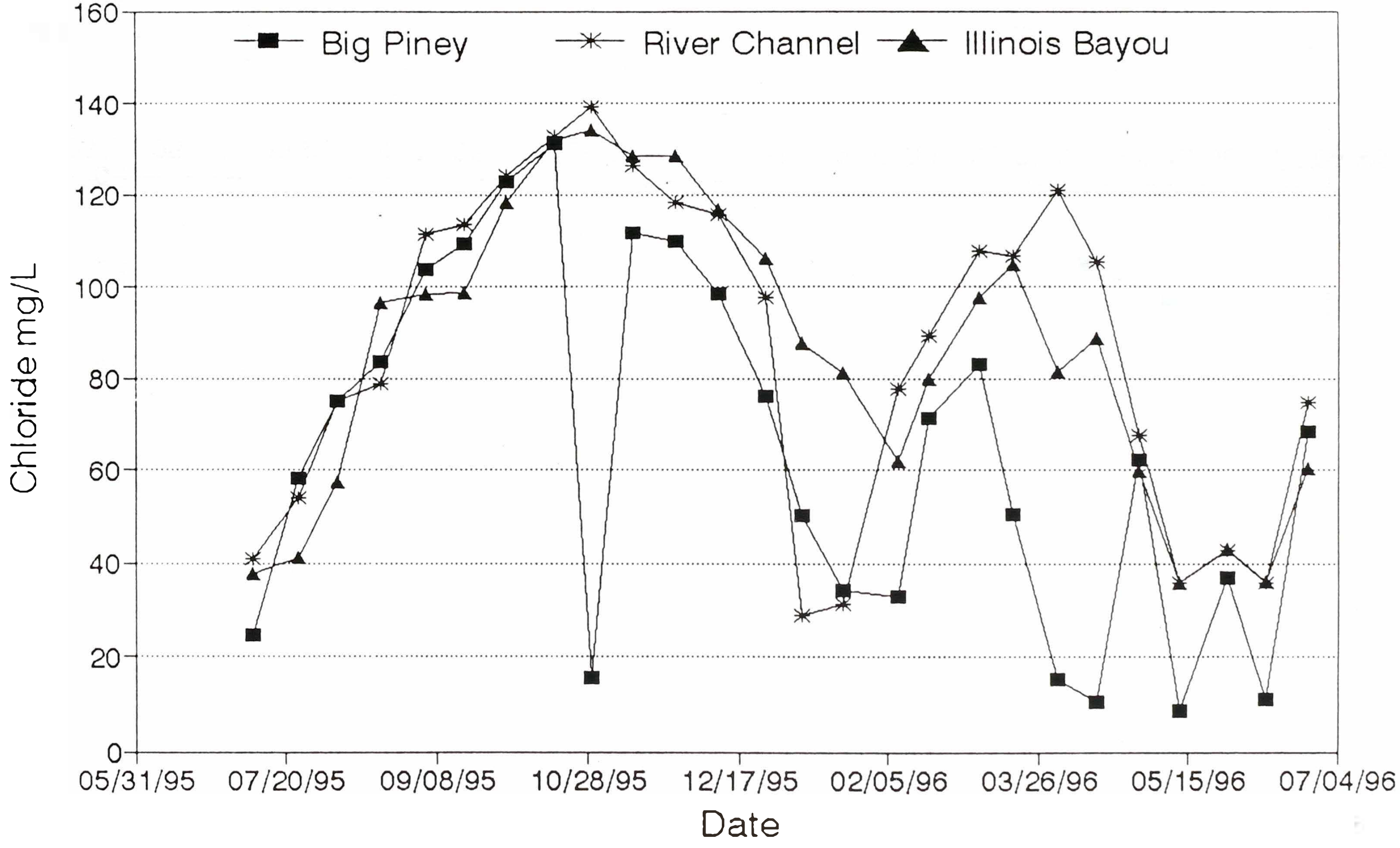

Figure 29. Comparison of chloride concentrations among sample areas and dates.

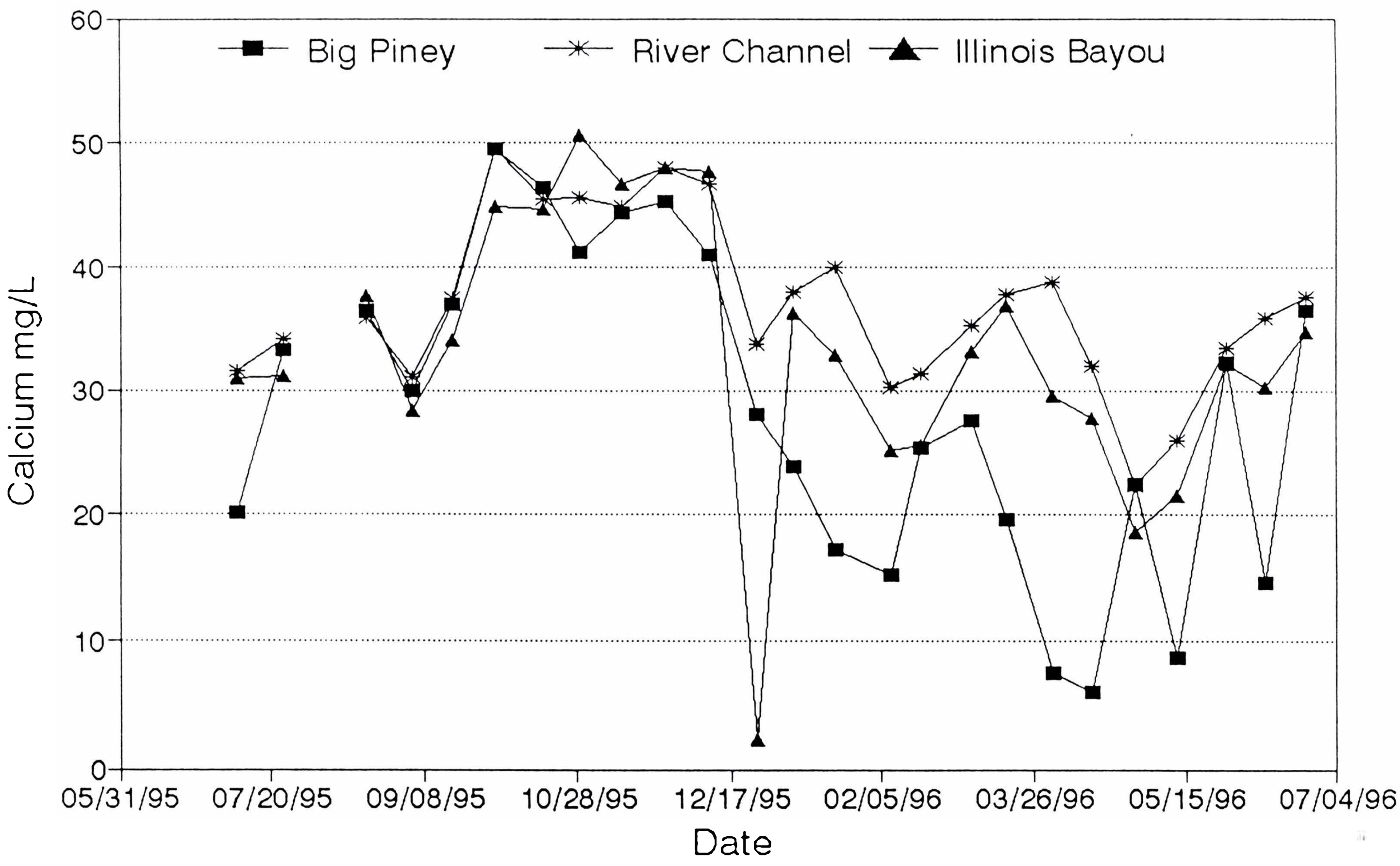

Figure 30. Comparison of calcium concentrations among sample areas and dates.

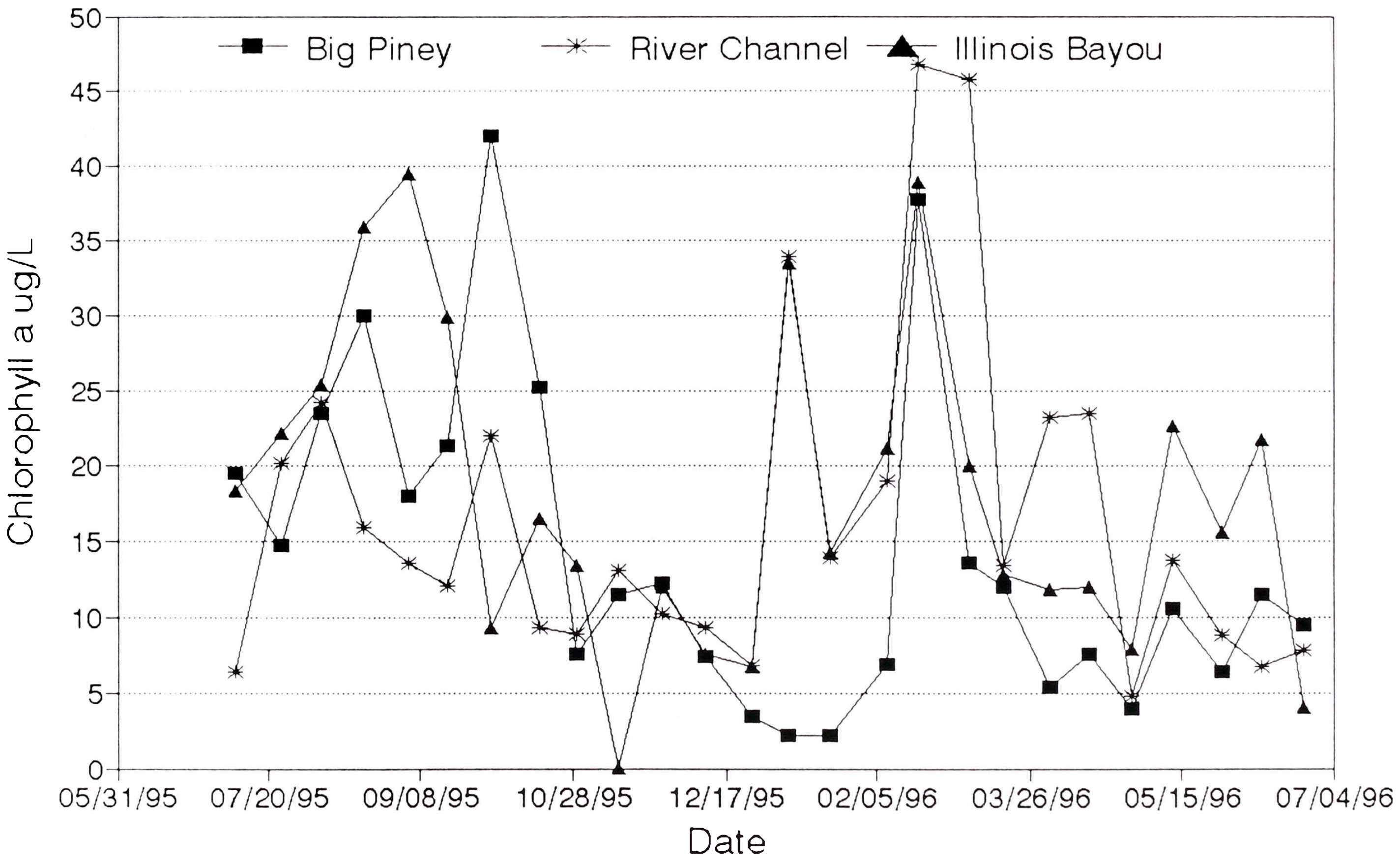

Figure 31. Comparison of chlorophyll *a* concentrations among sample areas and dates.

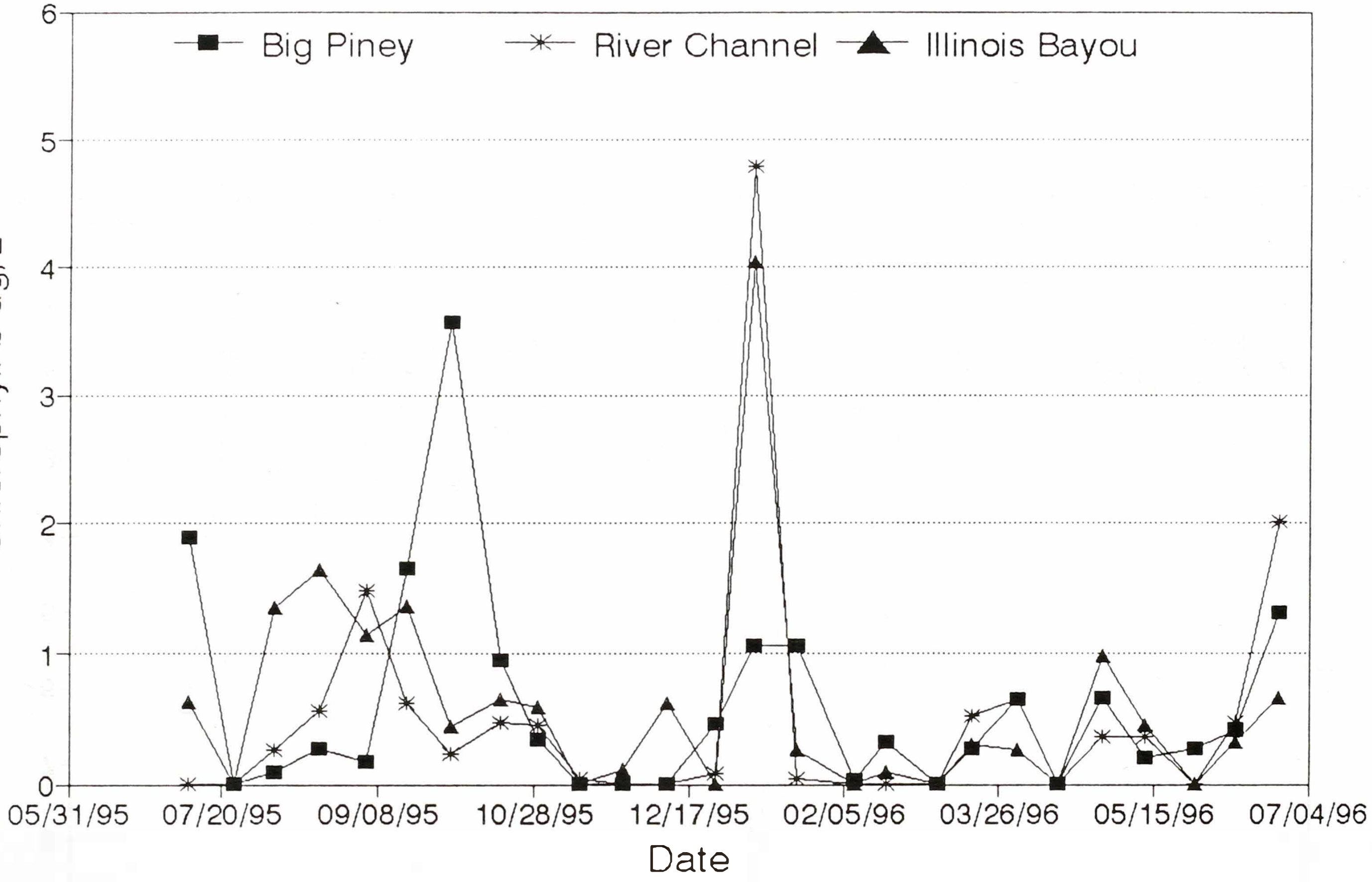

Figure 32. Comparison of chlorophyll *b* concentrations among sample areas and dates.

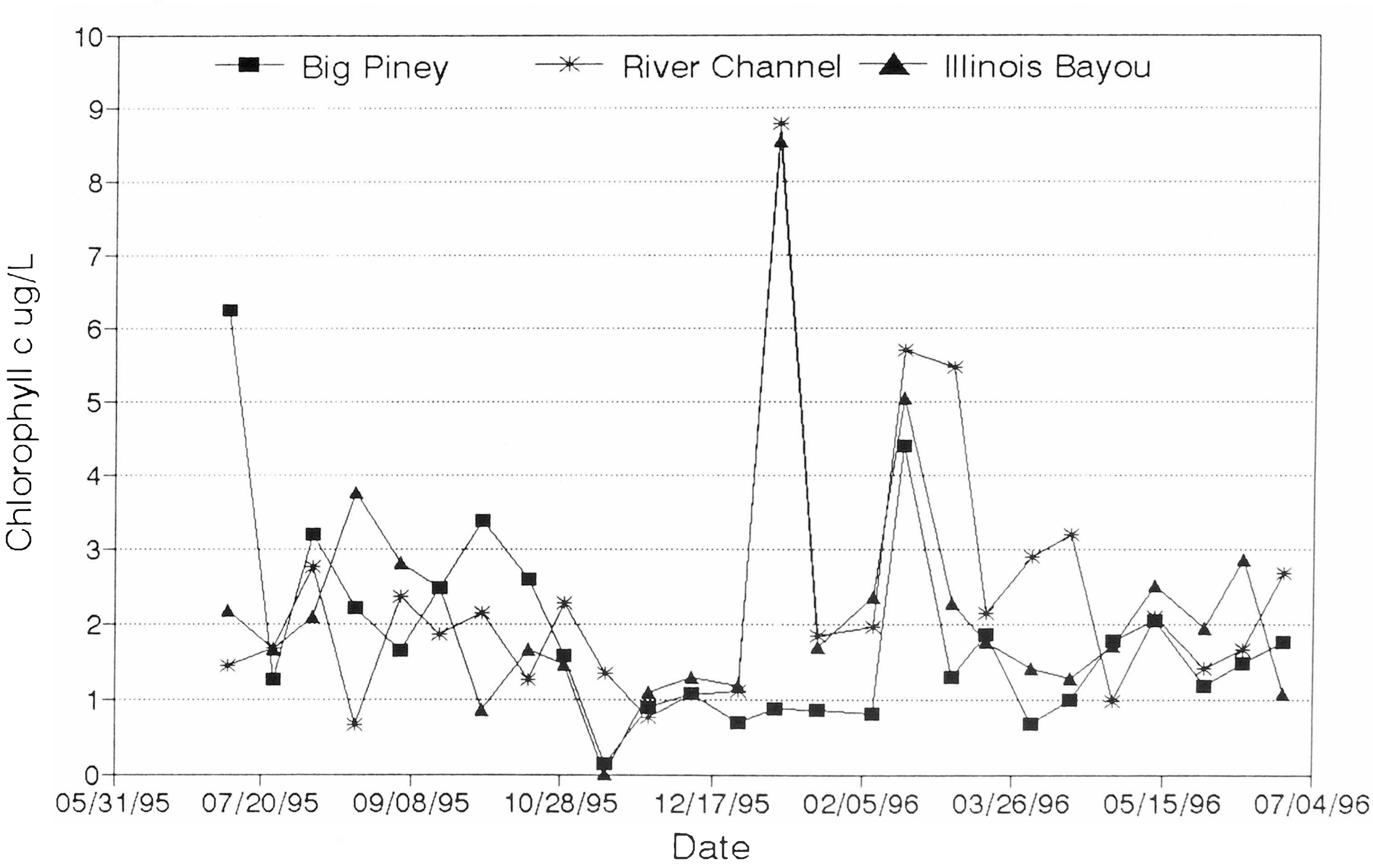

Figure 33. Comparison of chlorophyll *c* concentrations among sample areas and dates.

APPENDIX B
ADDITIONAL ZOOPLANKTON PATTERNS

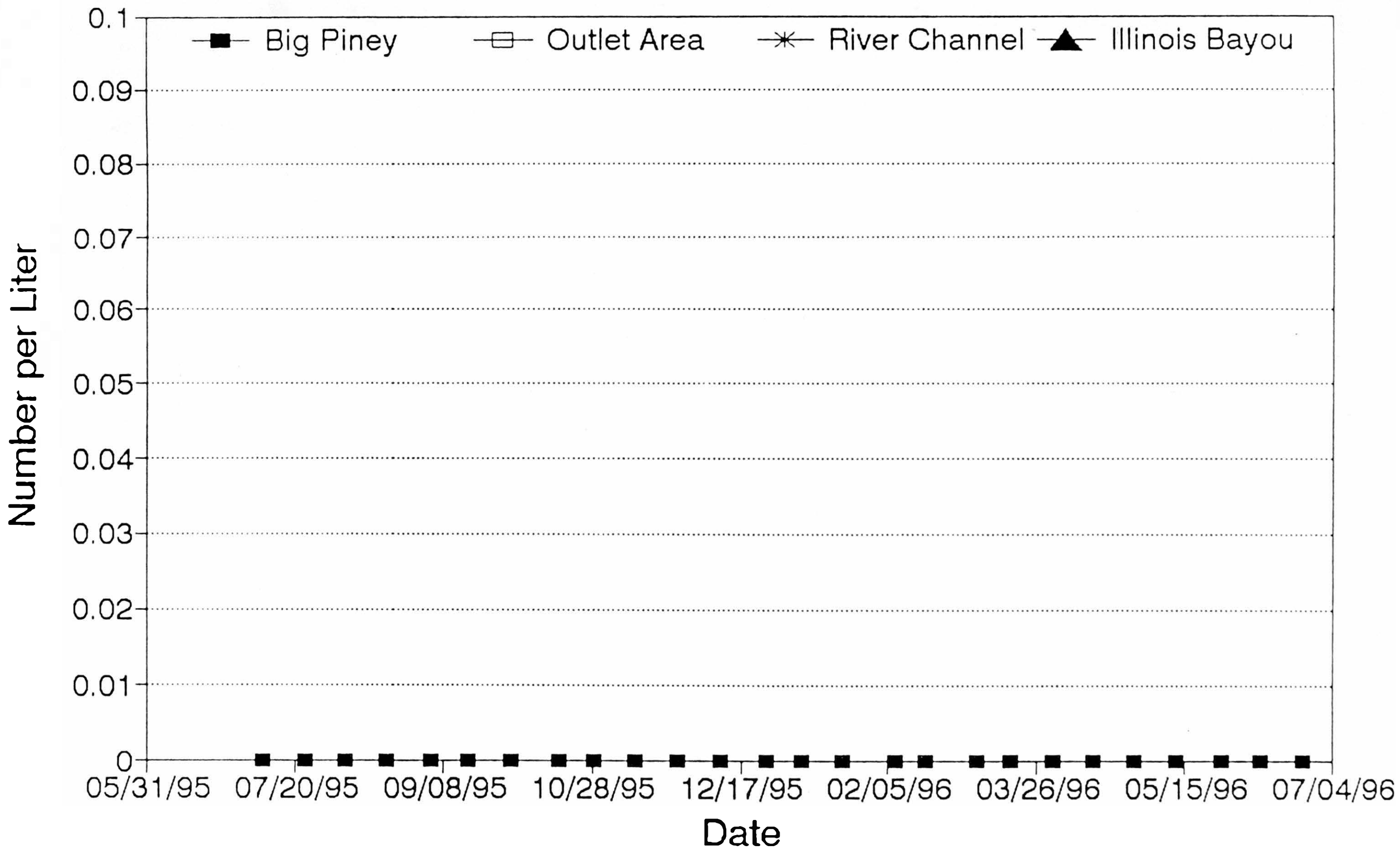

Figure 34. Changes in densities of ostracods collected in vertical tow samples among sample areas and dates.

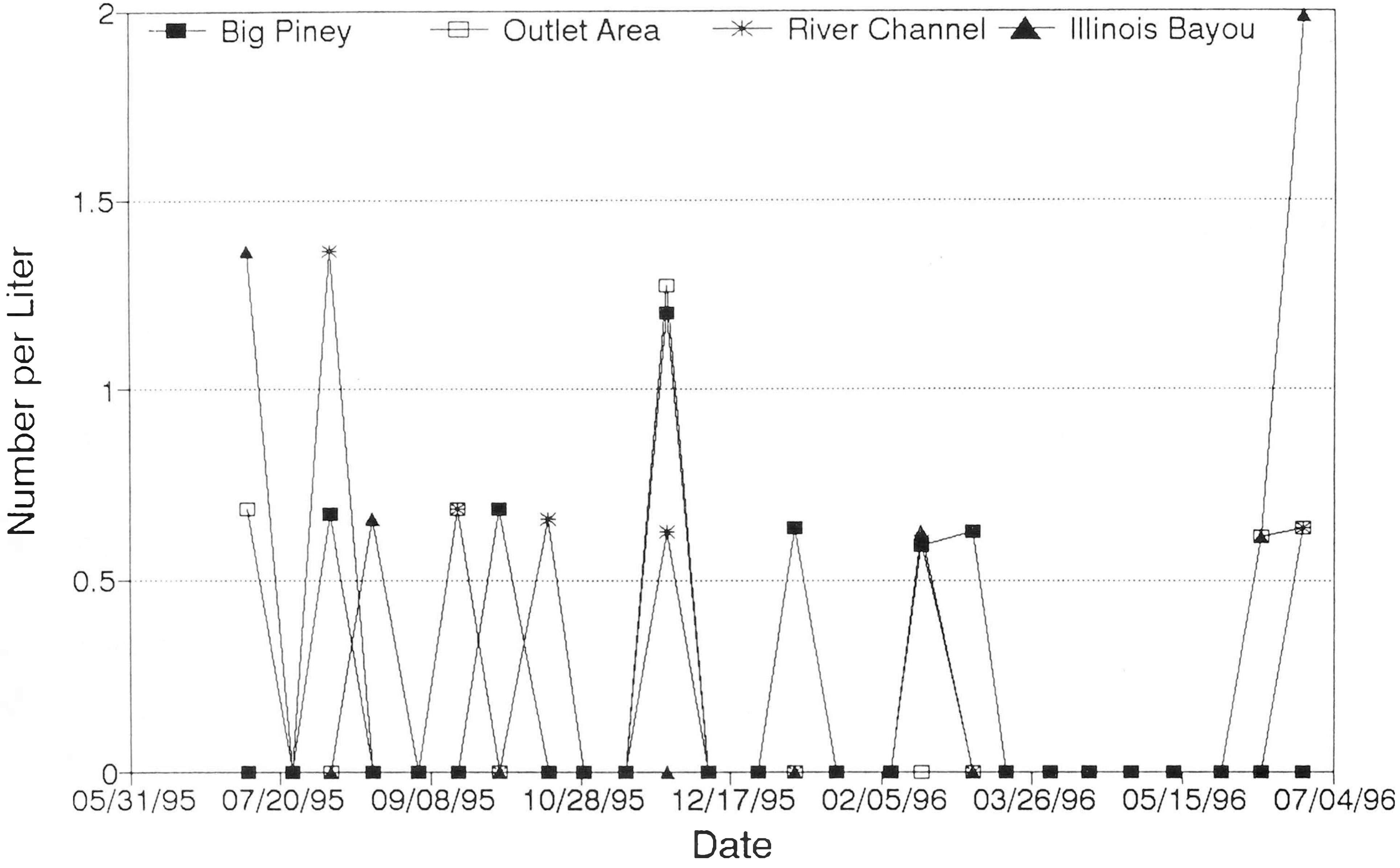

Figure 35. Changes in densities of other zooplankton collected in vertical tow samples among sample areas and dates.

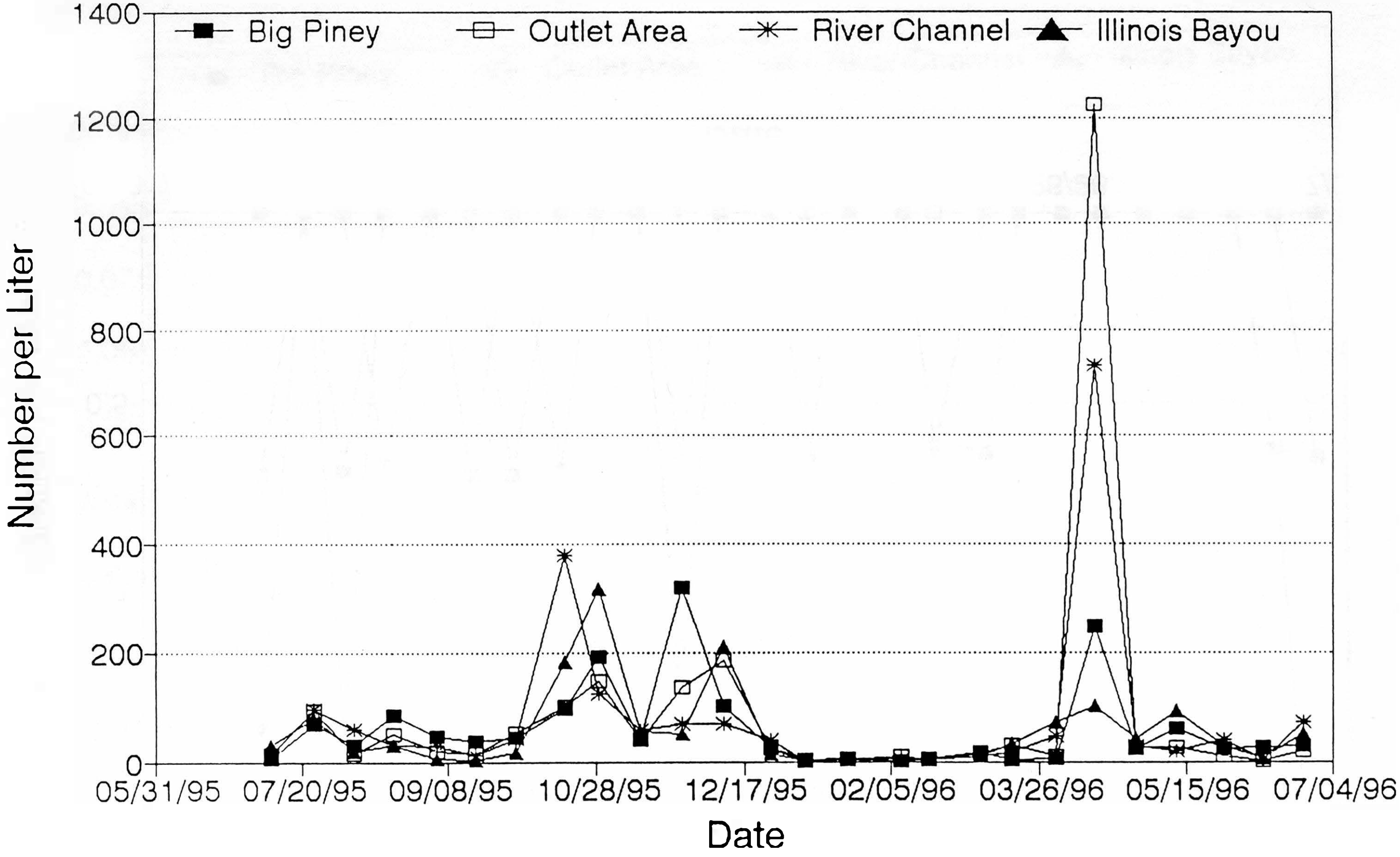

Figure 36. Changes in densities of rotifers collected in pump samples among sample areas and dates.

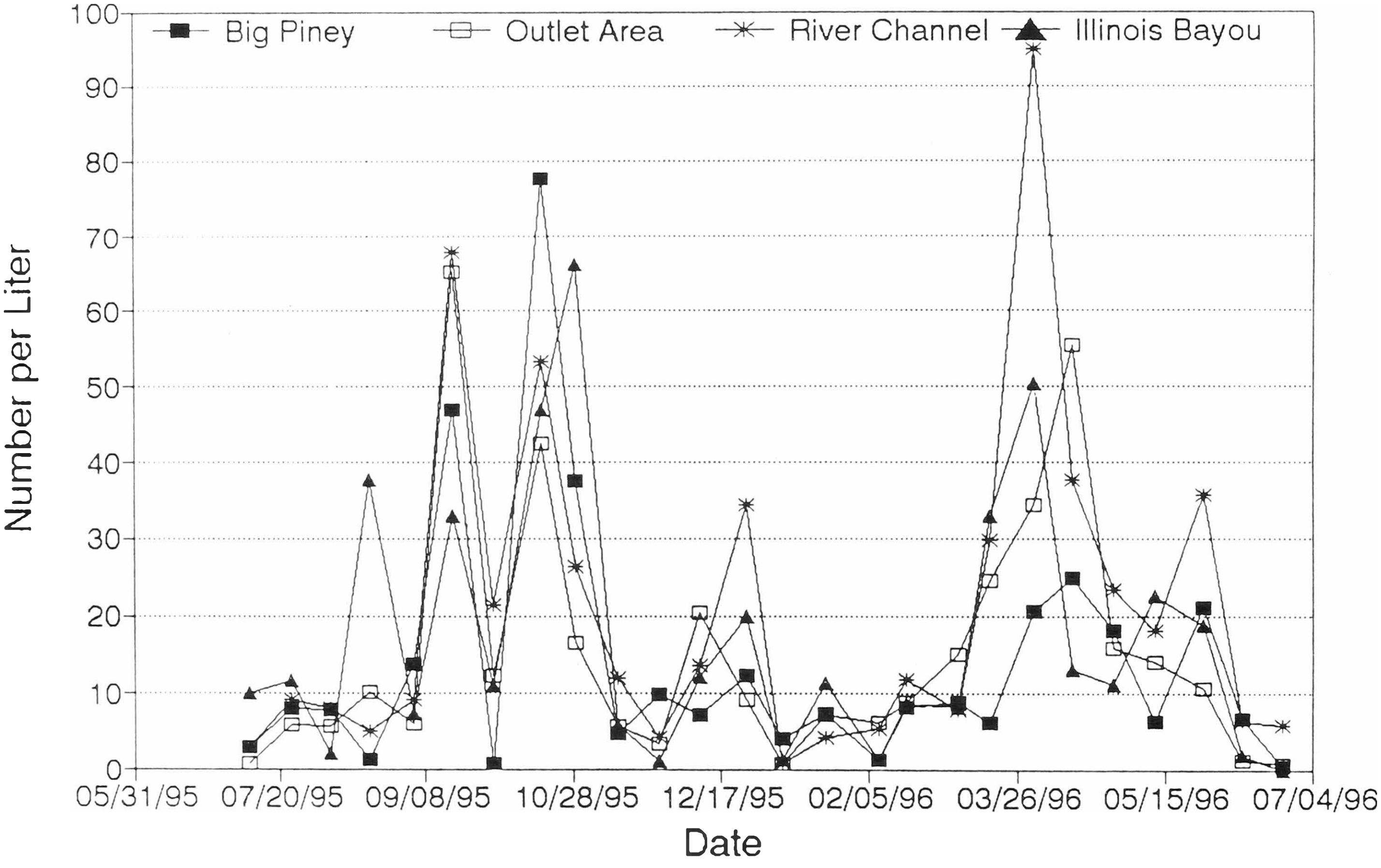

Figure 37. Changes in densities of nauplii collected in pump samples among sample areas and dates.

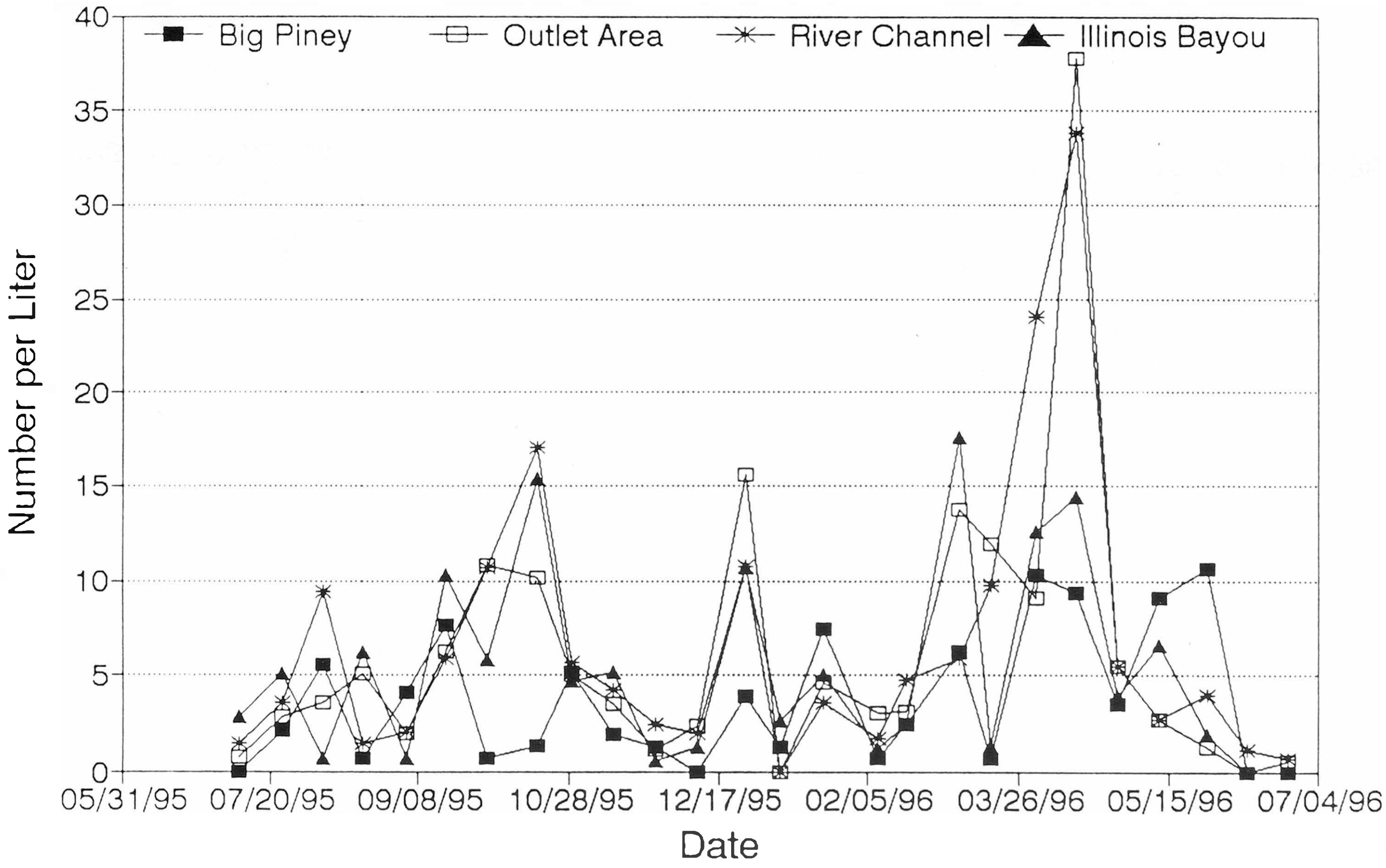

Figure 38. Changes in densities of copepods collected in pump samples among sample areas and dates.

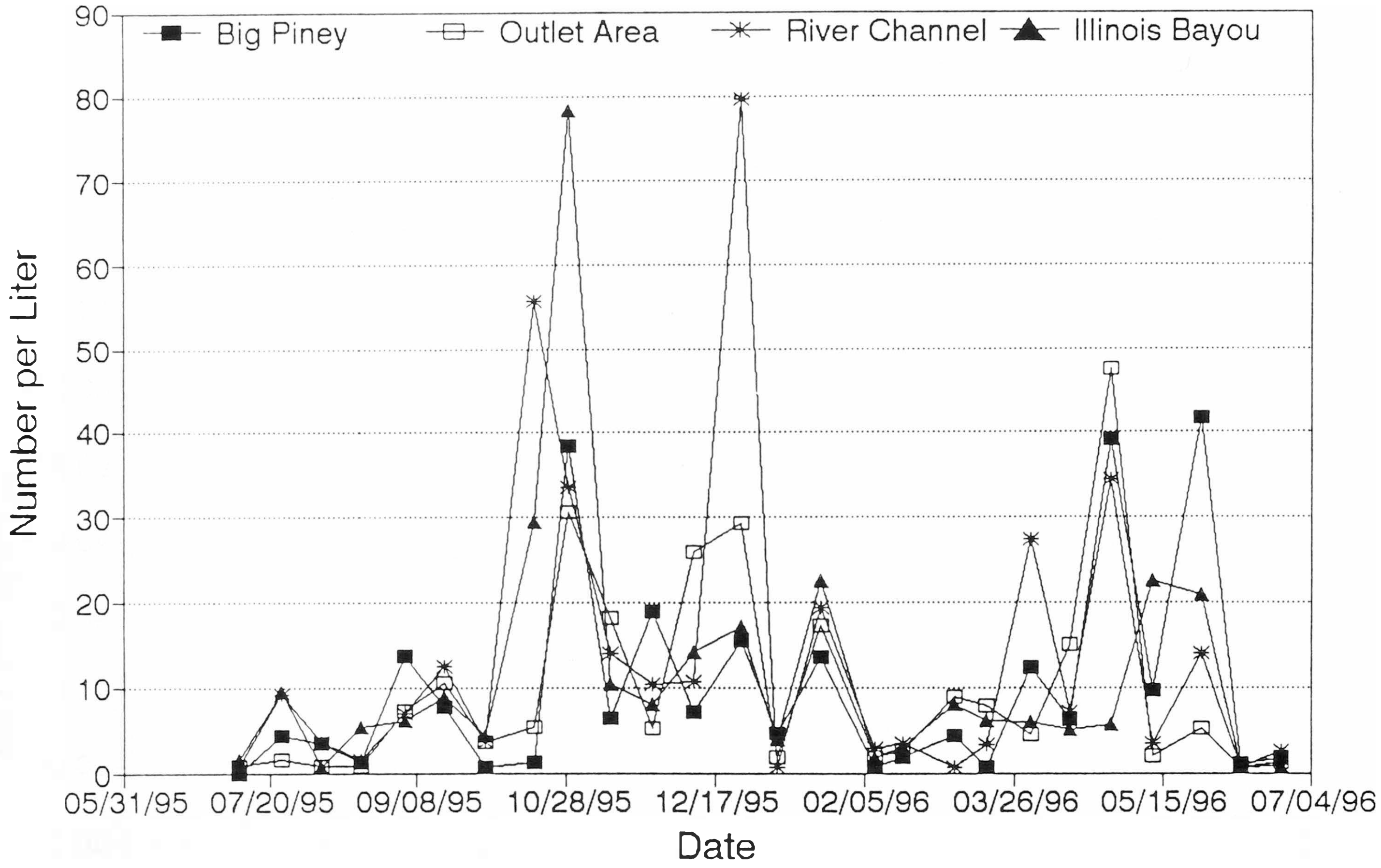

Figure 39. Changes in densities of cladocerans collected in pump samples among sample areas and dates.

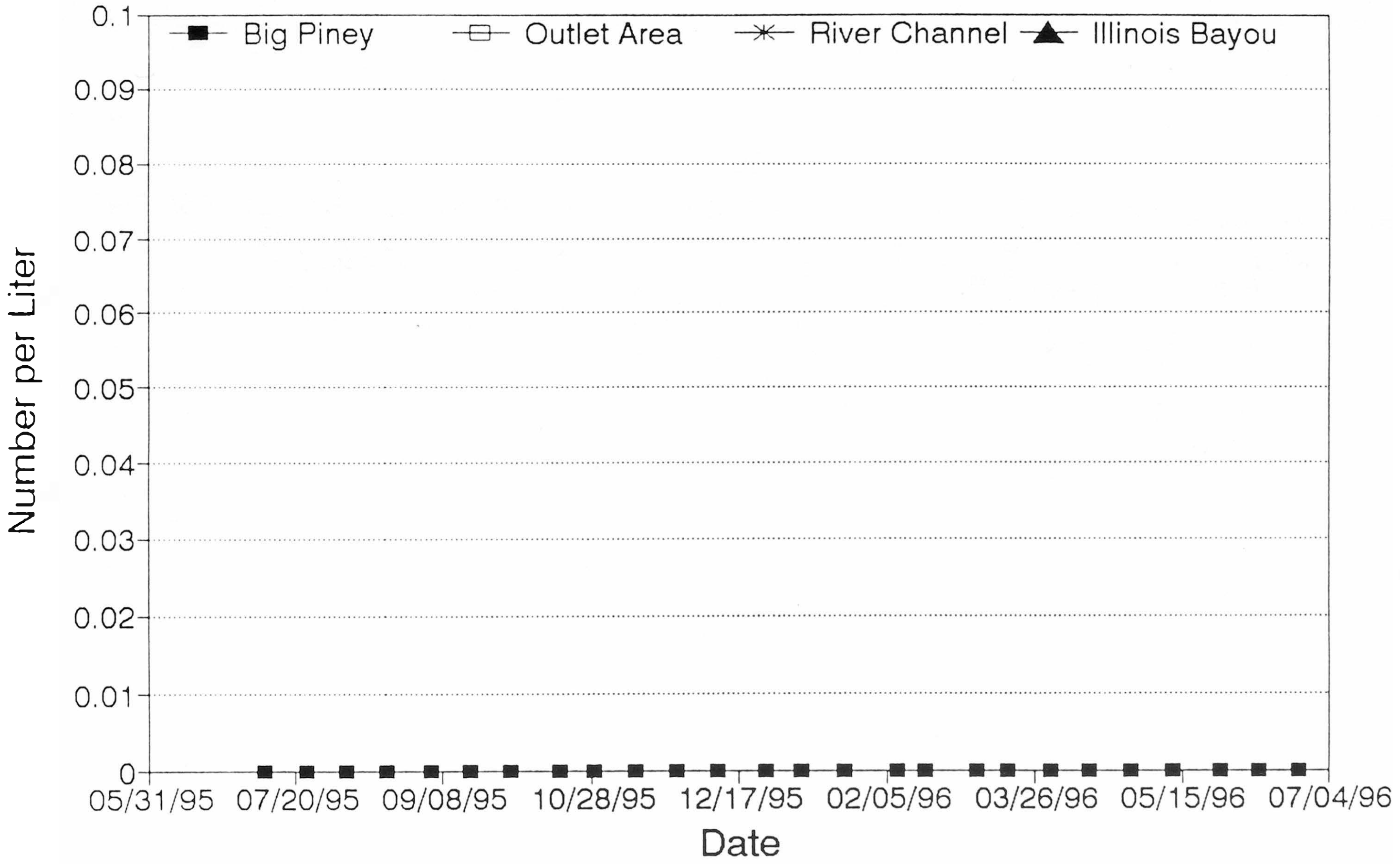

Figure 40. Changes in densities of ostracods collected in pump samples among sample areas and dates.

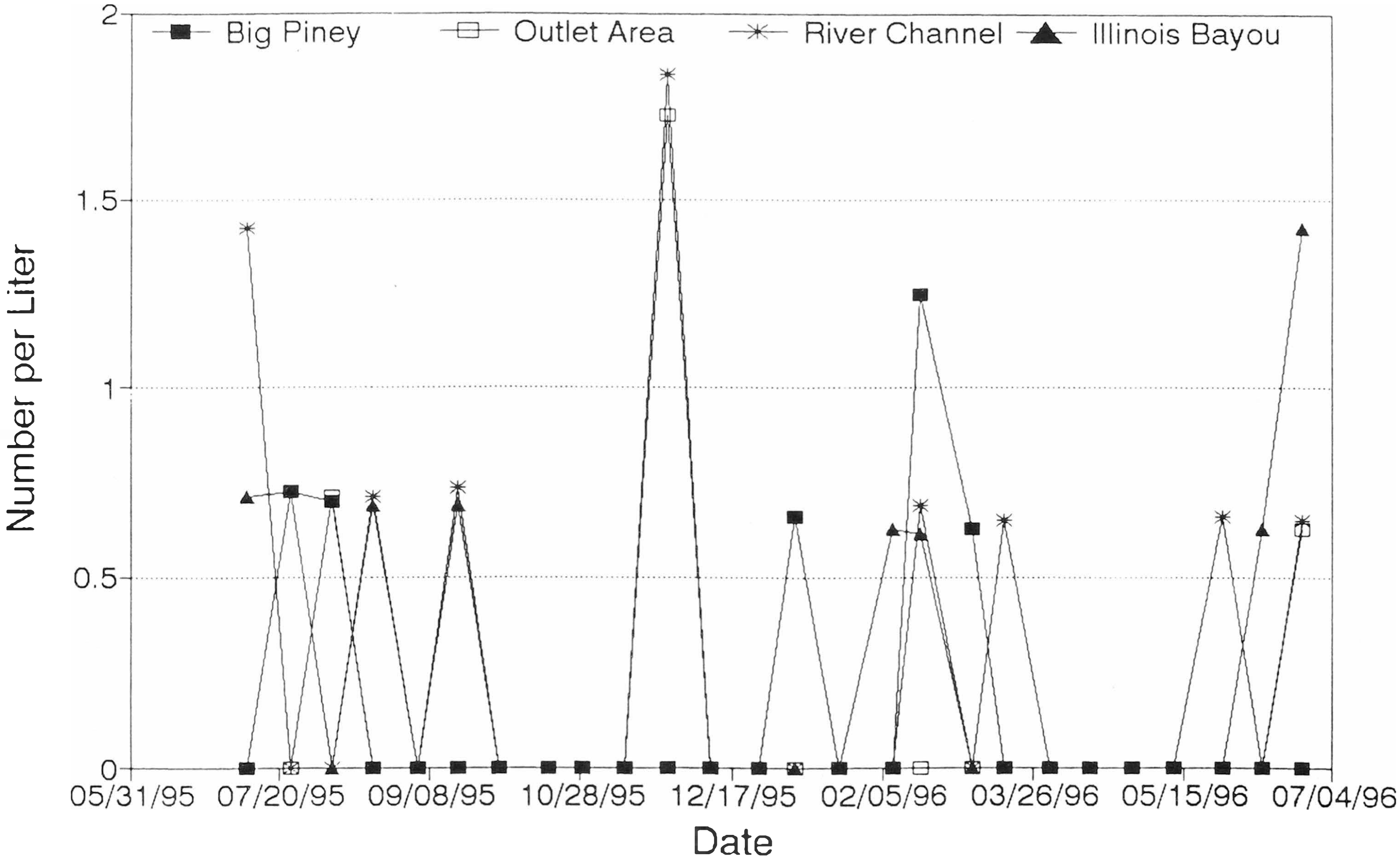

Figure 41. Changes in densities of other zooplankton collected in pump samples among sample areas and dates.

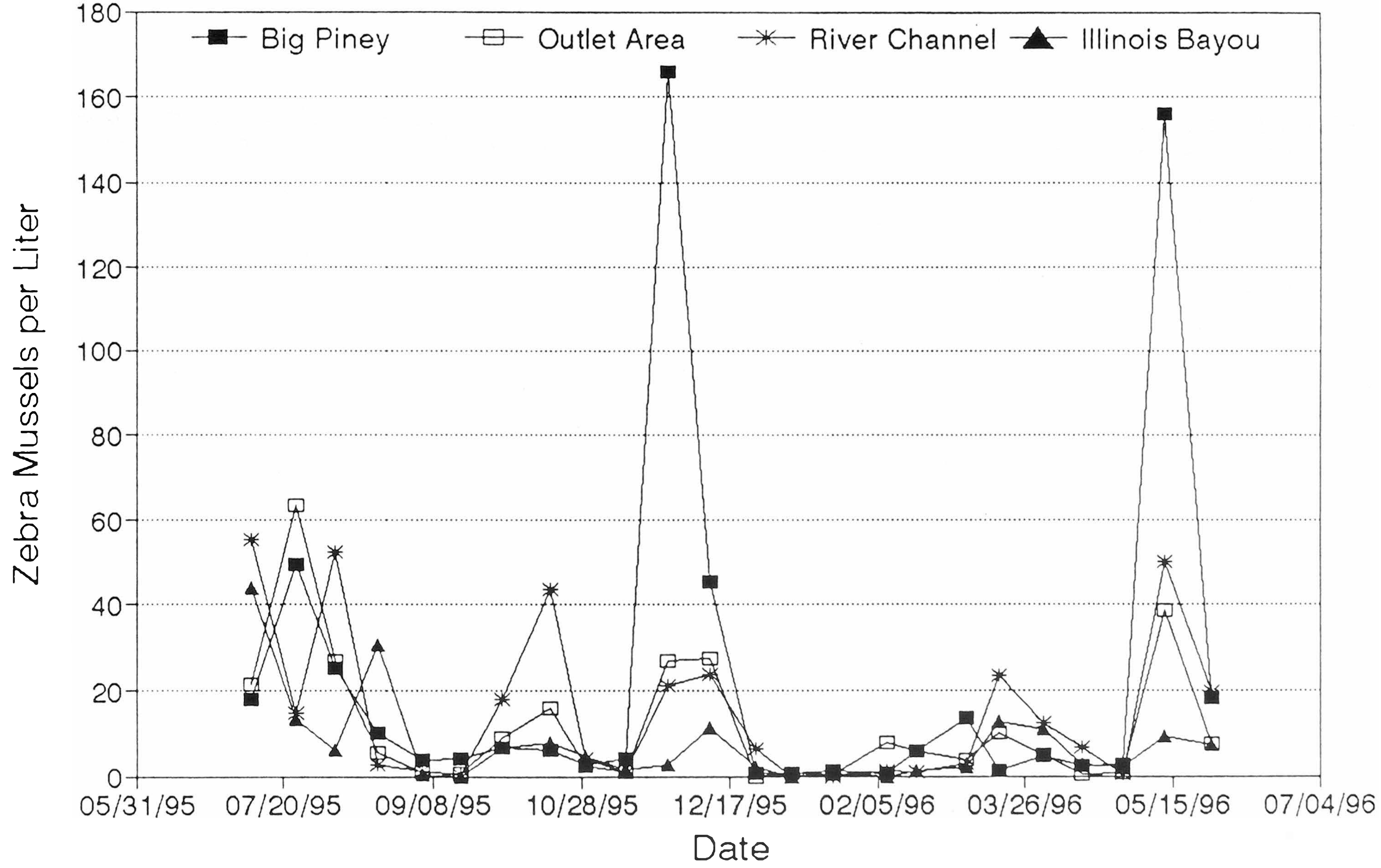

Figure 42. Changes in densities of zebra mussels collected in pump samples among sample areas and dates.

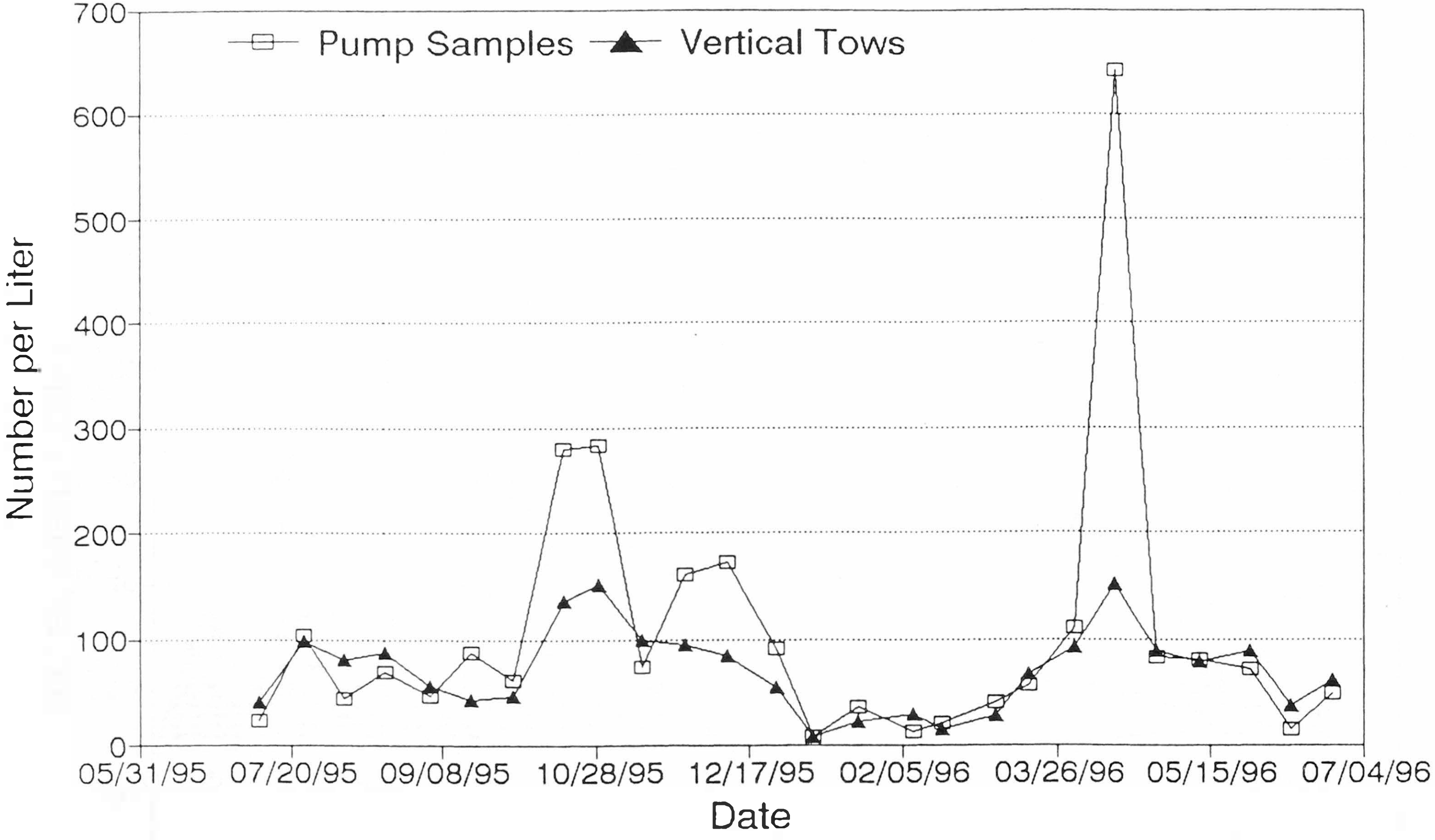

Figure 43. Comparison of densities of zooplankton collected in pump samples and densities of zooplankton collected in pull samples among dates. Values for each date are averaged across four sample areas.

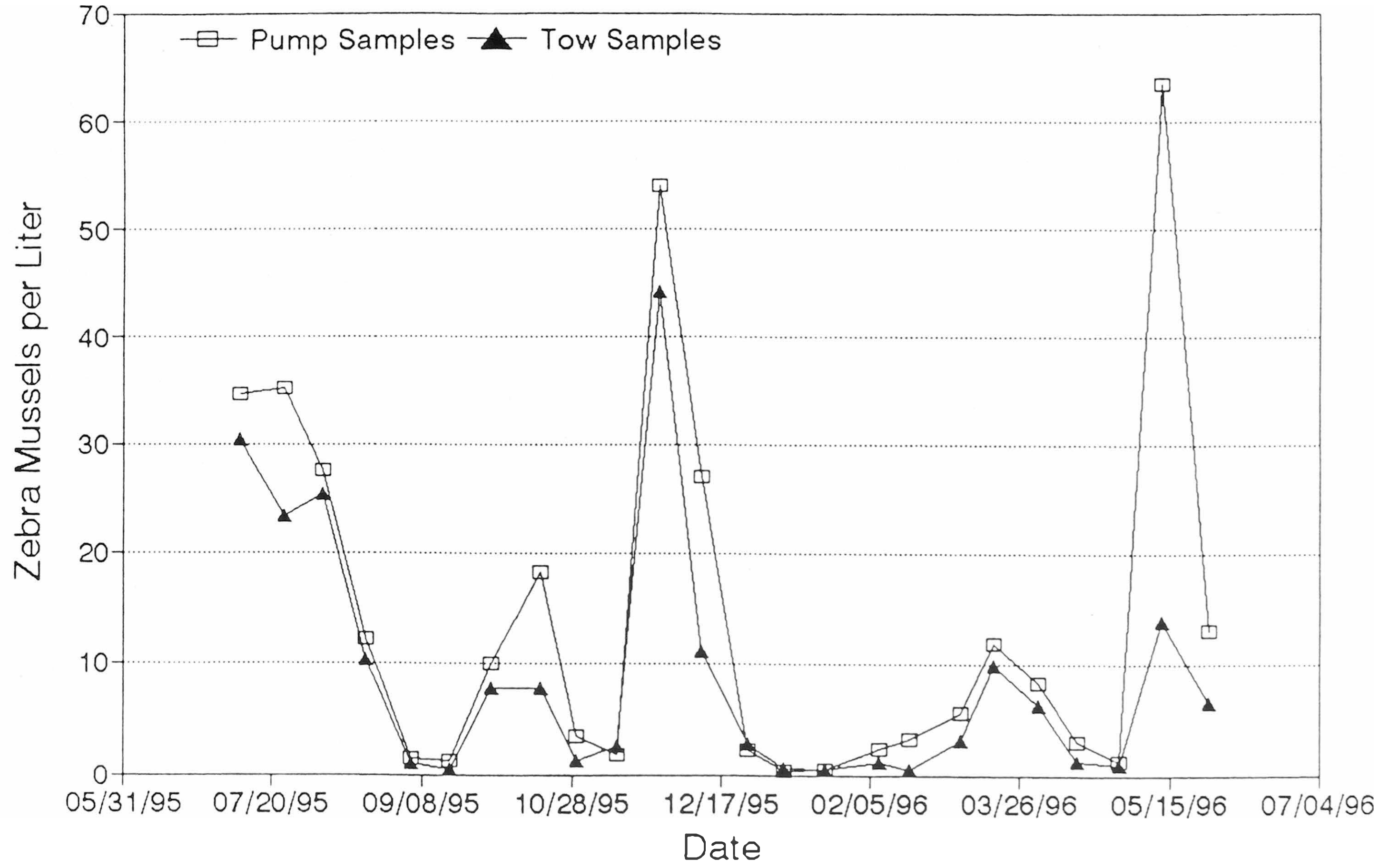

Figure 44. Comparison of zebra mussels collected in pump samples and densities of zebra mussels collected in pull samples among dates. Values for each date are averaged across four sample areas.

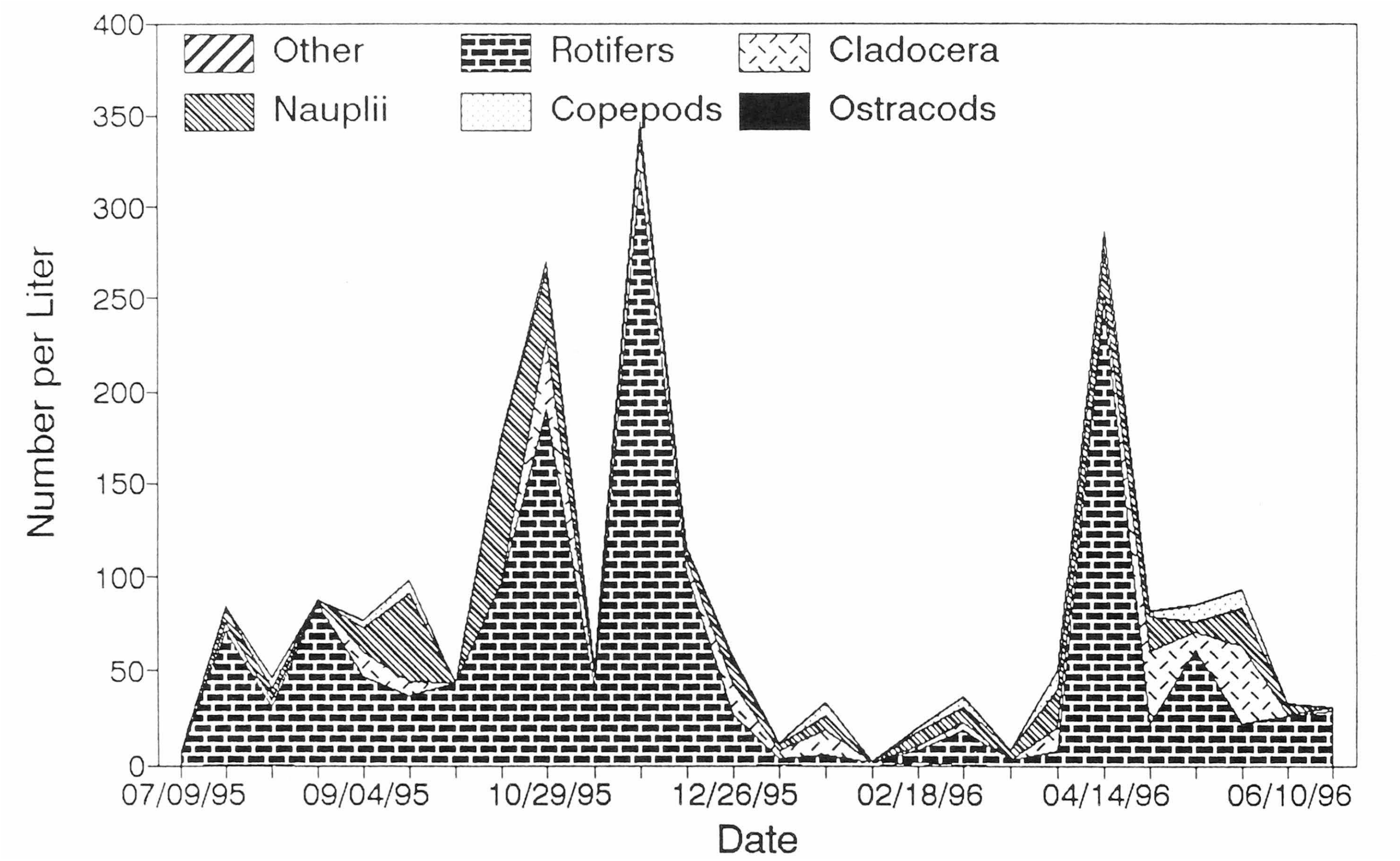

Figure 45. Changes in densities of zooplankton (exclusive of zebra mussels) collected in pump samples at the Big Piney area of Lake Dardanelle, AR, since July 9, 1995.

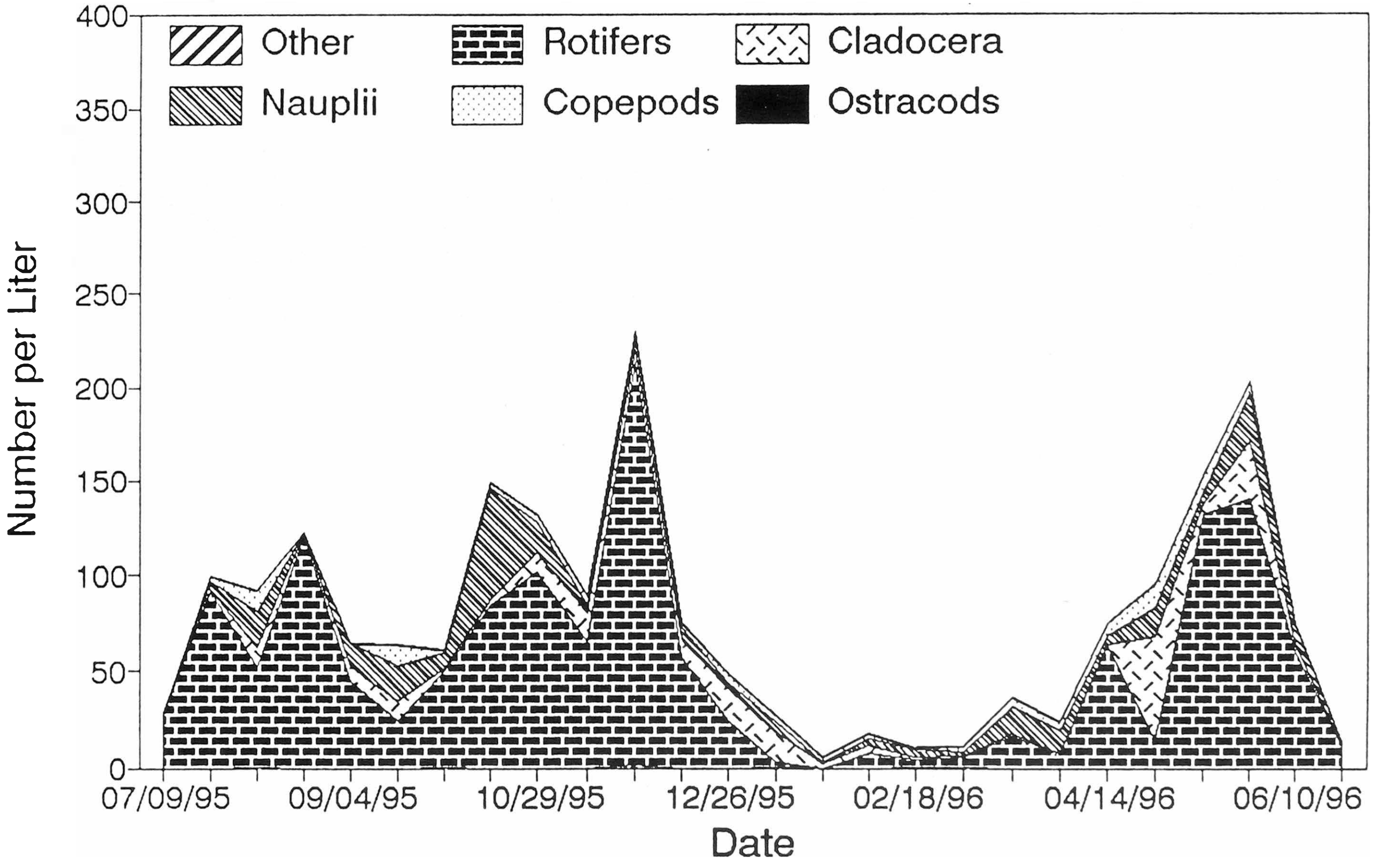

Figure 46. Changes in densities of zooplankton (exclusive of zebra mussels) collected in vertical tow samples at the Big Piney area of Lake Dardanelle, AR, since July 9, 1995.

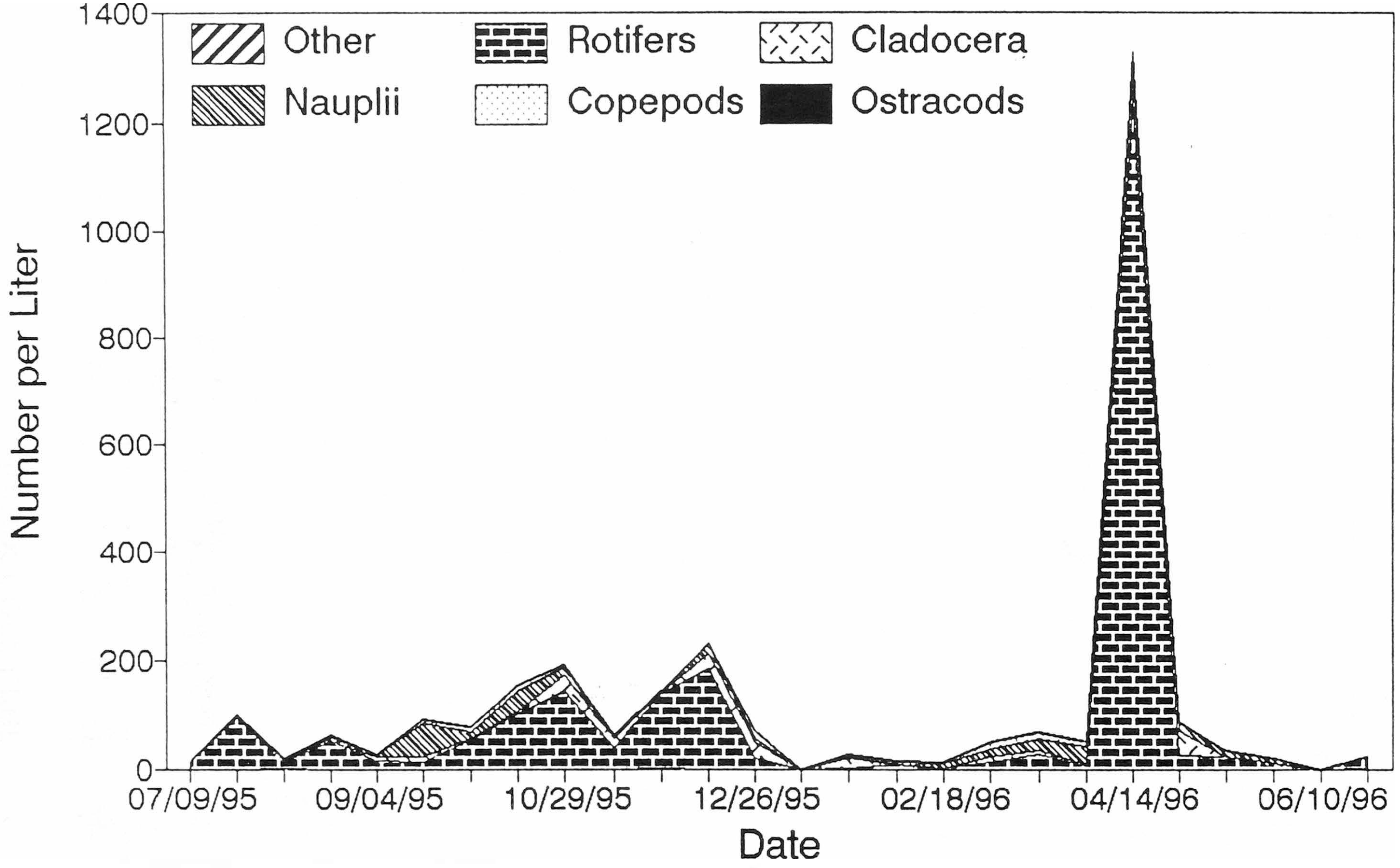

Figure 47. Changes in densities of zooplankton (exclusive of zebra mussels) collected in pump samples at the outlet area of Lake Dardanelle, AR, since July 9, 1995.

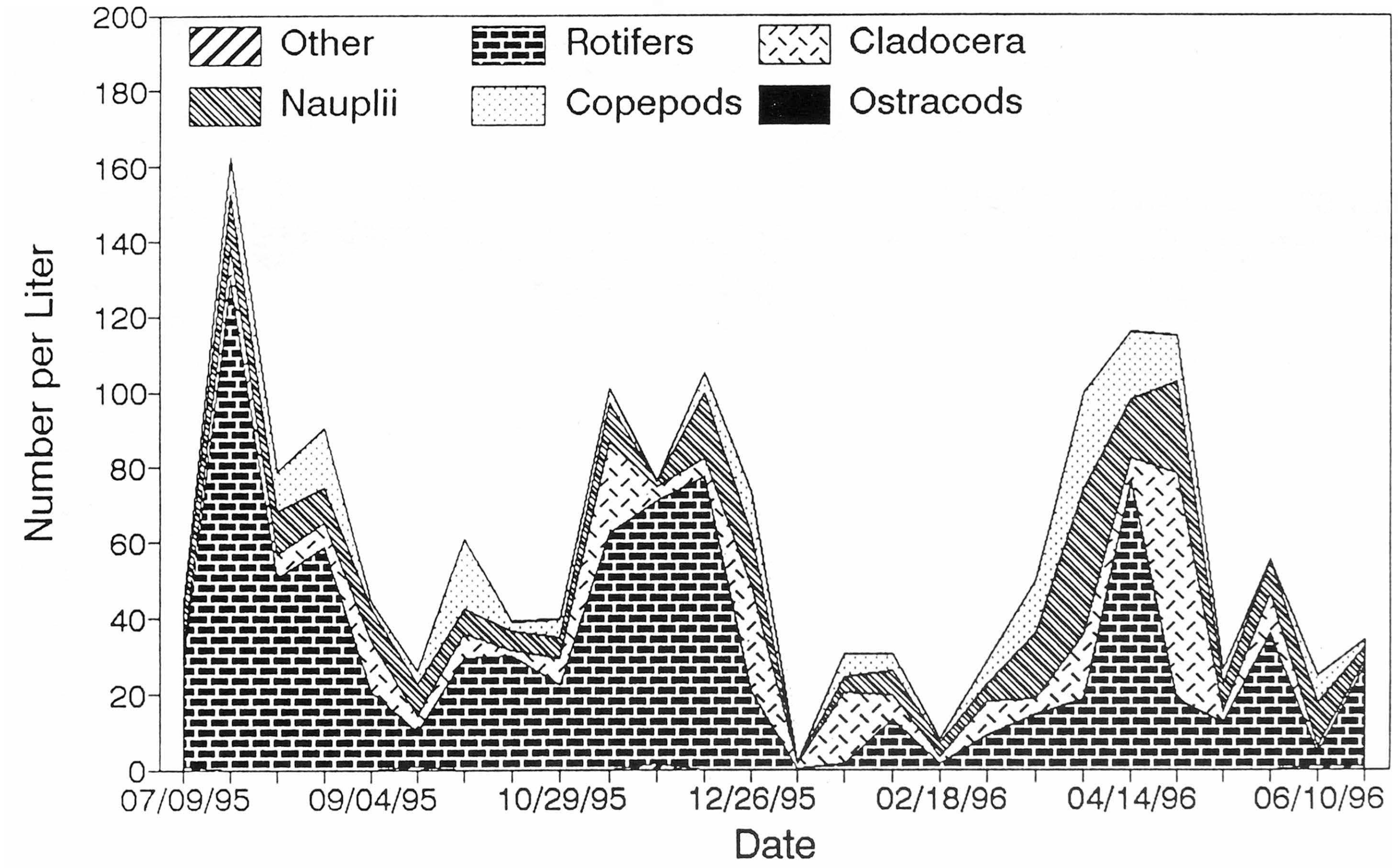

Figure 48. Changes in densities of zooplankton (exclusive of zebra mussels) collected in vertical tow samples at the outlet area of Lake Dardanelle, AR, since July 9, 1995.

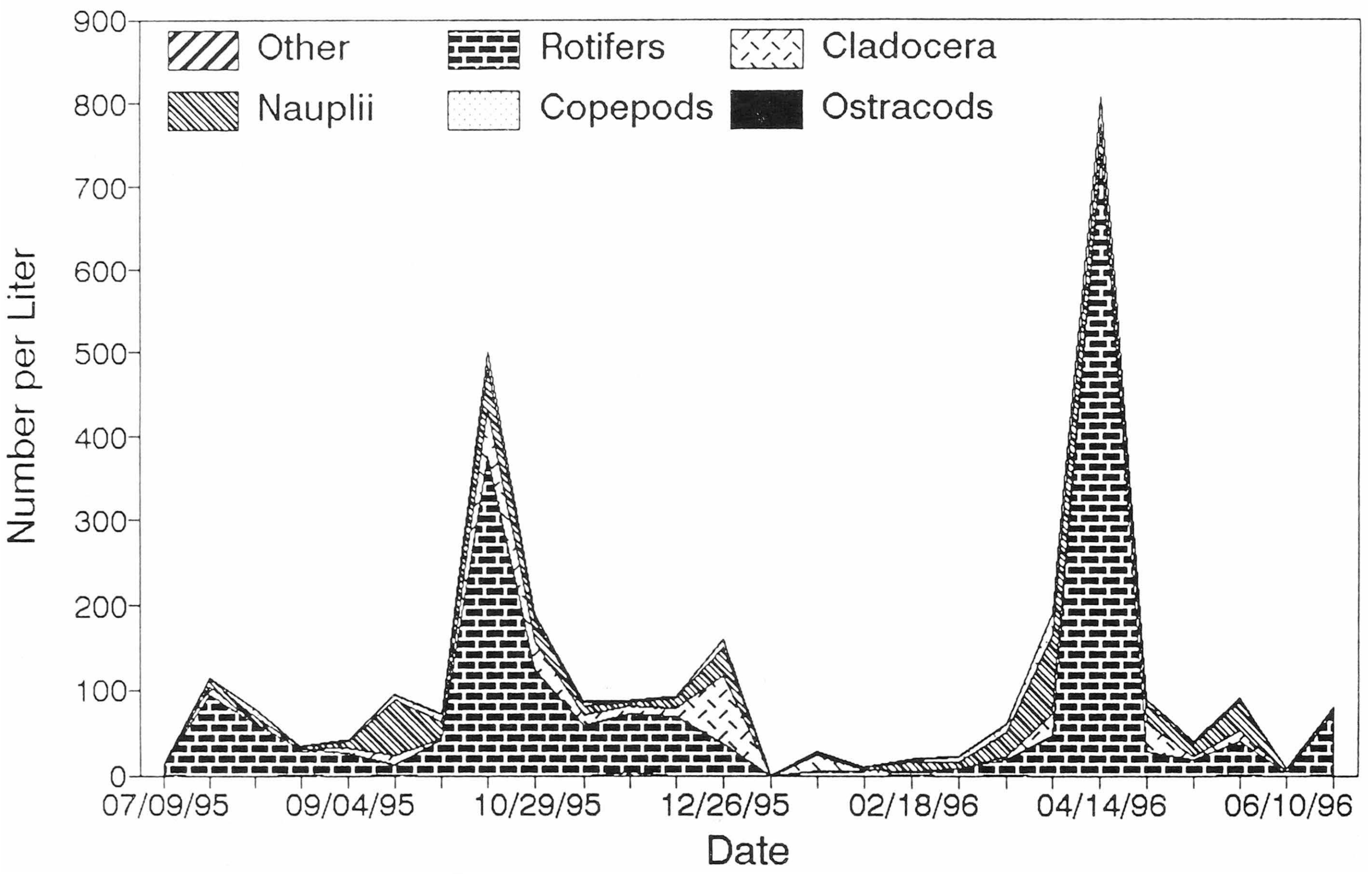

Figure 49. Changes in densities of zooplankton (exclusive of zebra mussels) collected in pump samples at the river channel area of Lake Dardanelle, AR, since July 9, 1995.

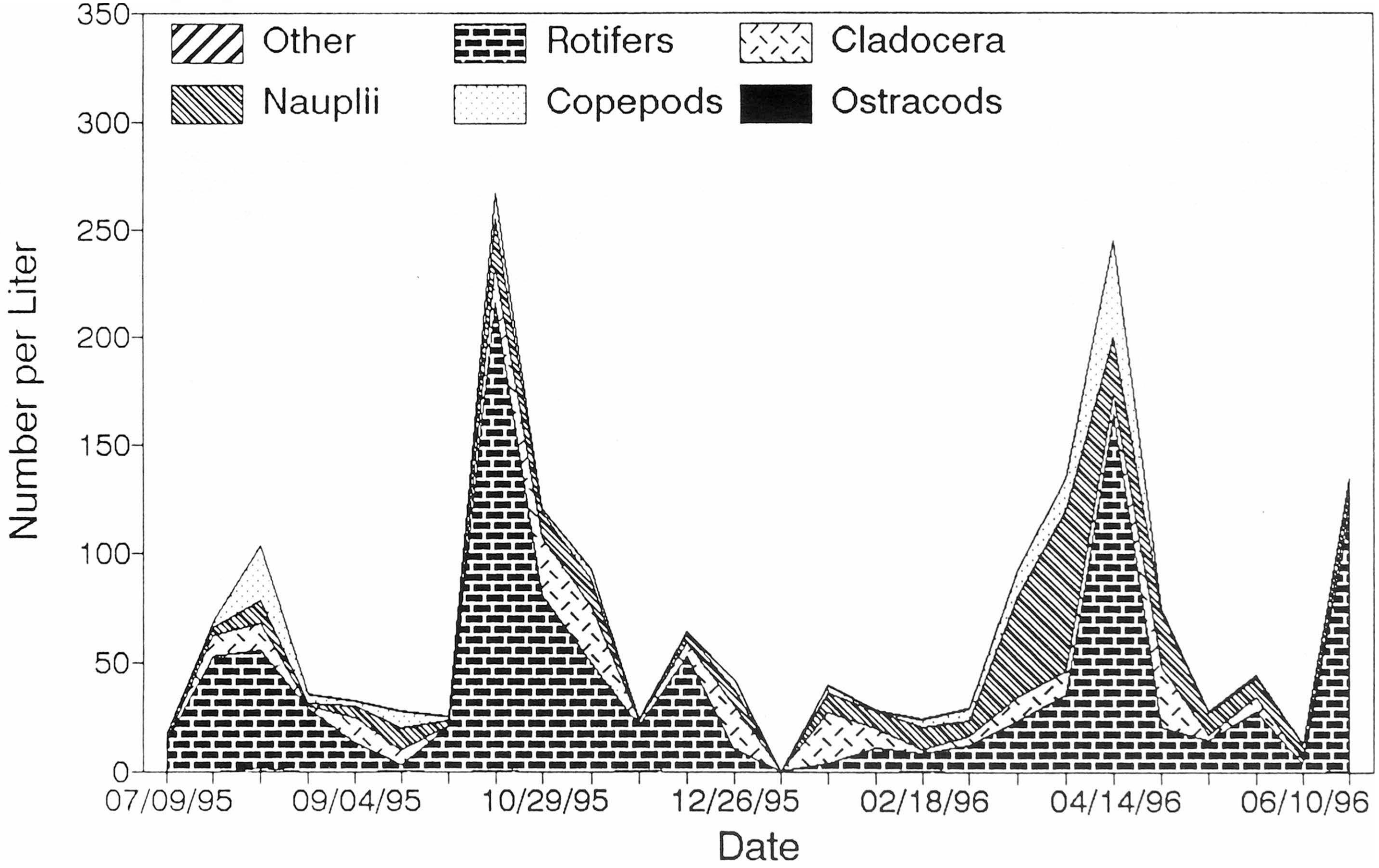

Figure 50. Changes in densities of zooplankton (exclusive of zebra mussels) collected in vertical tow samples at the river channel area of Lake Dardanelle, AR, since July 9, 1995.

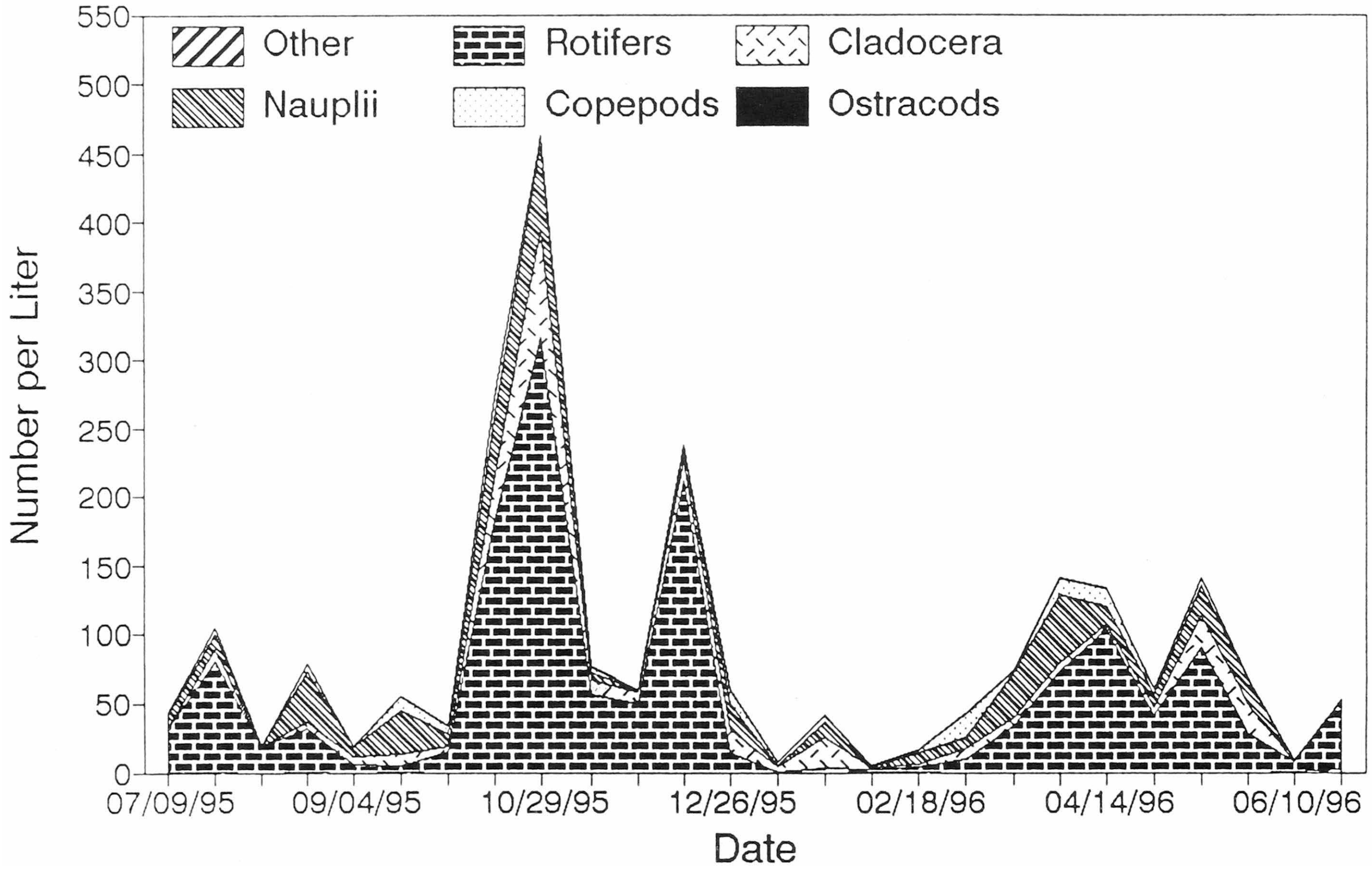

Figure 51. Changes in densities of zooplankton (exclusive of zebra mussels) collected in pump samples at the Illinois Bayou area of Lake Dardanelle, AR, since July 9, 1995.

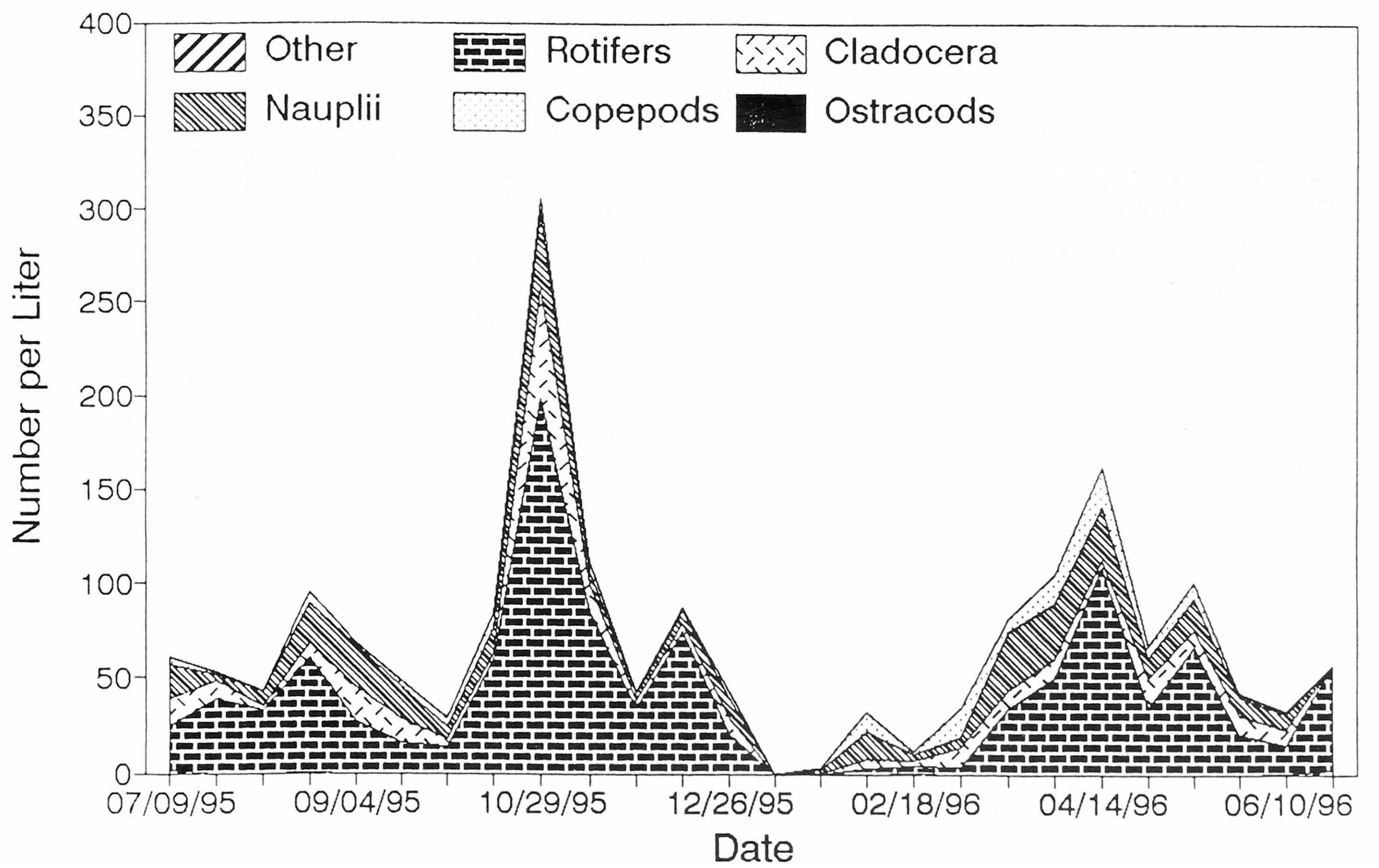

Figure 52. Changes in densities of zooplankton (exclusive of zebra mussels) collected in vertical tow samples at the Illinois Bayou area of Lake Dardanelle, AR, since July 9, 1995.