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SEDIMENT-OVERLYING WATER RELATIONSHIPS AFFECTING WINTERTIME DISSOLVED OXYGEN CONDITIONS IN THE BIG EAU PLEINE RESERVOIR, WISCONSIN

by

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13. ABSTRACT (Maximum 200 words)

Effects of sediment disturbance and associated chemical oxygen demand on dissolved oxygen (DO) depletion were evaluated during the winters of 1989-1990 in the Big Eau Pleine Reservoir. As part of this effort, historical DO data, sediment physical and chemical composition, net sedimentation rates, and water quality characteristics were examined.

DO depletion and anoxia in the winter develop rapidly in the headwaters in association with drawdown conditions and low inflows from the Big Eau Pleine River. DO depletion also occurs near the dam of the reservoir. Entrainment of anoxic water from the headwaters and its downstream movement during the winter are promoted by continued withdrawal from the reservoir.

Three distinct zones of sedimentation (erosional, accumulation, and transport zones) were identified, based on the moisture content of the surficial sediment. Sediments in the erosional zone occupied 60 percent of the reservoir

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surface area and exhibited low moisture content, high sediment density, and low net sedimentation rates. Physical composition of erosional zone sediments varied greatly at different times of the year, indicating deposition, disturbance and/or resuspension, and removal of sediment. The erosional zone was within the region of average winter drawdown (1,128 ft MSL). This suggested that winter drawdown may be an important factor in sediment disturbance and longitudinal transport toward the dam. The accumulation zone was located in the basin near the dam and occupied only 2 percent of the reservoir surface area. Sediments in this zone exhibited a higher moisture content, lower sediment density, and higher net sedimentation rate, indicating sediment focusing. Sediment displacement from the erosional zone to the accumulation zone appeared to influence oxygen dynamics in the reservoir. In contrast, sediment in the transport zone, intermediate to the other two zones, was not found to be of critical importance for reservoir oxygen dynamics during this study.

Concentrations of soluble iron, manganese, organic carbon, and chemical oxygen demand (COD) in the interstitial water of the surficial sediments were found to be moderately high and have the potential to exert a substantial COD to the overlying water column during winter drawdown and sediment disturbance. In addition, decreases in the mass of oxygen stores and increases in the reservoir surface to volume ratio during the drawdown favor more rapid development of anoxic conditions, particularly in the headwaters, thus contributing to the further decline in DO levels.

The results of these studies were used to critically evaluate previous recommendations for managing the reservoir. This evaluation suggests that maintaining a higher pool elevation during the winter months may significantly improve DO conditions in the reservoir. Aeration systems do not appear effective in maintaining high DO levels in the water column when anoxic waters containing high levels of soluble metals and COD move into the region of reaeration. Thus, if a higher pool elevation can not be maintained, it is likely that additional aerators must be installed for incremental use to meet periodic heavy oxygen demands.

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Ammonium	Interstitial
BOD	Iron
COD	Manganese
Dissolved organic carbon	Oxygen sag
Fish kill	Phosphate
Hypolimnion	Sediment oxygen demand

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PREFACE

The work reported herein was conducted as a part of the Water Quality Research Program (WQRP), Work Unit 32694, "Sediment Oxygen Demand and Water Quality." The WQRP is sponsored by the Headquarters, US Army Corps of Engineers (HQUSACE), and is assigned to the US Army Engineer Waterways Experiment Station (WES) under the purview of the Environmental Laboratory (EL). Funding was provided under Department of the Army Appropriation No. 96X3121, General Investigation, to the WQRP. The WQRP is managed under the Environmental Resources Research and Assistance Programs (ERRAP), Mr. J. L. Decell, Manager. Mr. Robert C. Gunkel was Assistant Manager, ERRAP, for the WQRP. Technical Monitors during the study were Messrs. Pete Juhle and James Gottesman and Dr. John Bushman, HQUSACE.

The study was conducted in response to a request from the Wisconsin Department of Natural Resources (DNR) to the US Army Engineer District (USAED), St. Paul, for planning assistance under Section 22 of the Water Resources Development Act of 1974 (Public Law 93-251). The work was also authorized by Intra-Army Order No. 1-000437, 7 December 1989.

Principal investigator for this investigation, conducted at WES during the period December 1989 through May 1991, was Dr. John W. Barko, Aquatic Processes and Effects Group (APEG), EL. The studies described herein were conducted and the report was prepared by Messrs. William F. James and Harry L. Eakin and Drs. Douglas Gunnison and Barko, APEG. Ms. Cathy Wendt and Mr. Robert Wylie of the Wisconsin Valley Improvement Company (WVIC) provided extensive field assistance, and Mr. David M. Coon, WVIC, provided valuable discussions and a source of historical information and additional data during this study. This report was reviewed by Messrs. Coon and Robert W. Gall, WVIC; Messrs. Robert Martini and John Sullivan, Wisconsin, DNR; Drs. Robert F. Gaugush, Craig S. Smith, and William D. Taylor, APEG, EL, WES; and Mr. Daniel Wilcox, USAED, St. Paul.

This investigation was conduced at WES under the general supervision of Dr. John Harrison, Chief, EL, Mr. Donald L. Robey, Chief, Ecosystem Research and Simulation Division, and under the direct supervision of Dr. Thomas Hart, Chief, APEG.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander and Deputy Director was COL Leonard G. Hassell, EN.

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CONTENTS

CONVERSION FACTORS, NON-SI TO SI (METRIC)
UNITS OF MEASUREMENT

Non-SI units of measurement used in this report can be converted to SI (metric) units as follows:

Multiply	By	To Obtain
cubic feet	0.02831685	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048	metres
hectares	10,000.0	square metres
inches	2.54	centimetres
miles (US statute)	1,609.347	metres

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* To obtain Celsius (C) temperature reading from Fahrenheit (F) readings, use the following formula: $C = (5/9)(F-32)$. To obtain Kelvin (K) readings, use: $K = (5/9)(F-32) + 273.15$.

SEDIMENT-OVERLYING WATER RELATIONSHIPS AFFECTING
WINTERTIME DISSOLVED OXYGEN CONDITIONS IN THE
BIG EAU PLEINE RESERVOIR, WISCONSIN

PART I: INTRODUCTION

1. The Big Eau Pleine Reservoir on the Big Eau Pleine River in central
Wisconsin has experienced a long history of water quality problems. Most
prominently, these have included fish kills beneath the ice during the winter,
due to low dissolved oxygen (DO) conditions. Extensive studies of the reser-
voir were conducted between 1974 and 1979 to evaluate sources of water quality
problems and to suggest possible management options for improving general
environmental conditions (Shaw and Powers undated; Shaw, Sullivan, and Vennie
1980). Based on recent analyses of results of these earlier studies and addi-
tional data, Gunnison and Barko (1988, 1990) proposed a hypothetical scenario
of events (summarized in the following paragraphs) leading to reductions in DO
during the winter in the Big Eau Pleine Reservoir.

2. Deposition of nutrient- and organic-rich sediment in the headwaters
of the reservoir is accompanied by deposition of phytoplankton throughout the
reservoir. Microbiological oxidation of these materials in the sediment pro-
motes the development of intensively anaerobic conditions. Such conditions
favor the accumulation of materials having high biological and chemical oxygen
demands (BOD and COD). These materials include reduced inorganic substances
(e.g. iron and manganese) and easily degraded organic materials in the sedi-
ment. Disturbance and/or resuspension of sediment during winter drawdown in
the headwaters contribute materials to the water column. Low inflows, coupled
with continued drawdown, result in a net downstream movement of the dissolved
and suspended materials. Because these materials contain biologically avail-
able organic matter and oxygen-demanding reduced inorganic species, they exert
an oxygen demand which is manifested as a DO sag. Anaerobic conditions also
develop near the dam in the hypolimnion during the winter. As the region of
low DO in the hypolimnion expands, the approaching DO sag from upstream merges
with the former to involve much of the reservoir volume in anoxia.

3. The primary objective of most recent studies (1989 - 1991) presented
in this report as conducted by the Waterways Experiment Station on the Big Eau
Pleine reservoir was to evaluate to the extent possible the hypothetical

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scenario elaborated in paragraph 2. These studies were conducted during spring periods of high runoff and sediment transport and in the winter beneath the ice during periods of reservoir drawdown. These studies were designed to address seasonal changes in sediment physical and chemical composition and effects on water quality of exchanges (if any) with surficial sediment. In addition, historical data on winter oxygen levels were used to evaluate year to year differences in rates of system-wide DO loss.

4. Given new insights into events leading to wintertime DO depletion in the Big Eau Pleine Reservoir, this report allows reassessment of earlier management recommendations (Shaw and Powers undated; Gunnison and Barko 1988, 1990). The recommendations provided herein are based on a much more complete understanding of sediment interactions with water quality conditions in the reservoir and are intended to allow avoidance of fish kills in the future.

PART II: MATERIALS AND METHODS

Study Site

5. The Big Eau Pleine Reservoir, located in Marathon County in central Wisconsin, is an approximately 2,700-ha* reservoir created by the impoundment of the Big Eau Pleine River. The reservoir was constructed in 1937 by the Wisconsin Valley Improvement Company (WVIC) to assist in providing uniform flow in the Wisconsin River. Land use within the 945 km^2 drainage basin (including the reservoir area) is primarily agricultural with numerous dairy farms and mixed evergreen-hardwood forests. The reservoir is polymictic with maximum and mean depths of about 14 m and 4.8 m, respectively. The reservoir has a total volume of approximately 1.3×10^8 m^3 and a shoreline length of 107 km at maximum pool. Spring mixing begins in mid-April and may continue into early May. Stratification usually begins in early May and persists until late September or early October. Autumn mixing is usually extensive and complete by mid-October. Ice cover usually occurs between early December and early April.

Water Sampling

6. Water column samples were collected during midwinter periods of reservoir drawdown in February 1989 and again in January and February 1990 (Figure 1). Water sampling stations were located primarily in the upper reaches of the reservoir in February 1989 at river miles (RM) 8.0, 13.0, and 17.0 and in January 1990 at RM 8.0, 10.0, 11.0, 12.0, and 15.0. However, in February 1990, samples were collected at multiple stations located along the entire longitudinal axis of the reservoir between RM 0.3 and 18.3.

7. Vertical profiles of DO were measured at these stations with either a Surveyor II water quality monitor (Hydrolab Corp., Austin, TX) or a YSI Model 57 DO meter (Yellow Springs Instruments, Yellow Springs, OH) pre-calibrated using the Winkler (azide modified iodometric) method for DO

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* A table of factors for converting non-SI units of measurements to SI (metric) units is presented on page 4.

determinations (APHA 1985). Water samples were collected at 10- to 25-cm-depth intervals from 10 cm above the sediment to the water surface, using pneumatically driven close-interval syringe samplers as described in James, Barko, and Taylor (1990). Water samples were filtered in situ by attaching filter membranes (0.45 μm, Nalge No. 190-2045) to each syringe. Water samples were analyzed for COD, dissolved organic carbon (DOC), ammonium-nitrogen (ammonium-N), soluble reactive phosphorus (SRP), soluble iron (Fe), and soluble manganese (Mn). Additional water samples were collected with a Wildco 2.2-liter acrylic Van Dorn sampler (Wildlife Supply Co., Saginaw, MI) for analyses of chlorophyll $\underline{a}$. Samples were transferred to acid-washed plastic or glass bottles and preserved according to recommended methods (APHA 1985).

8. Ammonium-N and SRP were analyzed on a Technicon AutoAnalyzer II System (Technicon Instruments Corp., Tarrytown, NY) using salicylate-hypochlorite (Wall et al. 1975) and ascorbic acid (APHA 1985) methods, respectively. Soluble iron and manganese were determined by direct-aspiration flame photometry (APHA 1985) using a Perkin-Elmer Model 2380 Atomic Absorption Spectrophotometer (Perkin-Elmer Corp., Norwalk, CT). DOC was determined by the differential combustion-infrared method (APHA 1985) using a Beckman Model 915A Carbon Analyzer with Model 865 Nondispersive Infrared Detector (Beckman Instruments, Fullerton, CA). The analysis of COD utilized the closed reflux colorimetric method (Jirka and Carter 1975; APHA 1985) and the COD Test System (Hach Co., Loveland, CO). Chlorophyll $\underline{a}$ concentrations were determined spectrophotometrically after extraction with 90 percent acetone (APHA 1985). Chlorophyll $\underline{a}$, corrected for phaeopigments, was calculated according to Lorenzen (1967).

Sediment Sampling

9. Sediment samples were collected in May 1989 and January and May 1990 (Figures 2 and 3) for purposes of determining sedimentation rates and physical and chemical composition of the sediment and interstitial water. Stations were located at approximately 1-mile intervals, or less, along the longitudinal axis of the reservoir between RM 0.3 and 18.3. With three exceptions, stations along this axis were positioned laterally at the point of maximum depth (i.e. within the thalweg). Sampling stations outside of the thalweg at

RM 0.3, 4, 8, 11, 12, 13, and 16 were located along transects that ran perpendicular to the shoreline. Sampling stations were located during successive sampling periods to within 5 m by theodolite measurement of angles to the sampling location, and then electronic measurement of distances to each location. In May of both years, thalweg and nonthalweg stations were sampled. However, samples could not be collected between RM 1 and 7 in May 1989, due to difficulties in obtaining core samples (see below) in flocculent sediments. Winter drawdown restricted sampling to stations located only in the thalweg in January 1990.

10. Sediment cores were collected at these stations using a 2-in.-diam, 36-in.-long, single-barrel Wildco sampler fitted with polyethylene liners. Sediment cores were sealed, stored vertically at 4 °C in the dark, and transported intact within 48 hr to the Eau Galle Limnological Laboratory, Spring Valley, WI. In the laboratory, core samples were sectioned at 5-cm intervals. Core sections were weighed immediately for moisture content (Allen et al. 1974), then dried to a constant weight at 105 °C for sediment density determination. Sediment density was calculated as the dry mass divided by the volume of each core section. Organic matter concentrations in each core section were determined by loss on ignition at 550 °C (Allen et al. 1974). If preimpoundment soils were encountered in a sediment core sample, the fry mass of aquatic sediment above this material was used to calculate average sedimentation rates (i.e. James and Barko 1990). Preimpoundment soils were characterized visually as sandy, pebbly substrate and by low sediment density values when compared to aquatic sediment. Average net sedimentation rates were estimated as dry mass divided by the cross-sectional area of the core liner and reservoir age (approximately 50 years).

11. Surficial sediments were collected for additional analysis at the same sampling stations using a 15-cm by 15-cm Wildco Ekman grab sampler. Upon retrieval, samples were placed immediately in a covered container, purged with nitrogen, to maintain anoxic conditions. The upper 10 cm of sediment was transferred to plastic jars, also purged with nitrogen, and stored at 4 °C until transported (within 48 hr) to the US Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, for processing.

12. In the laboratory, surficial sediments were homogenized in a nitrogen atmosphere and then analyzed for moisture content, sediment density,

organic matter, and sediment COD. The analysis of sediment COD utilized a modification of the closed reflux colorimentric method (Jirka and Carter 1975; Plumb 1981; APHA 1985). Interstitial water was separated from sediments by high-speed centrifugation at 4 °C in a nitrogen atmosphere (Barko and Smart 1986). Interstitial water was analyzed for conductivity, SRP, ammonium-N, DOC, COD, soluble Fe, and soluble Mn utilizing methods described in the previous paragraphs.

Historical Data

13. This investigation also included examination of data obtained during previous studies of the Big Eau Pleine Reservoir. Much of what is known of the reservoir results from efforts of graduate students at the University of Wisconsin-Stevens Point (Sullivan 1978; Swalby 1979; Hammermeister 1982; Vennie 1982). In addition, the report of Gunnison and Barko (1988) was consulted with attention to information on DOC. DO isopleths for the winter months (January through March) of 1974-88 were provided by the WVIC. In evaluating these data, water was classified as low in DO (1.0 to 2.0 mg 1^{-1}) or essentially anoxic (less than 1.0 mg L^{-1} DO). Inflow data for the reservoir were obtained through the WVIC from the US Geological Survey gauge at Stratford, WI. Reservoir pool elevations were obtained from the WVIC.

PART III: RESULTS

Sedimentation and Sediment Composition

Temporal and spatial trends

14. Net sedimentation rates varied in a linear fashion increasing with
increasing water depth (Figure 4). The regression line of this linear rela-
tionship intercepted the depth axis at 2 m, indicating minimal net sedimenta-
tion at depths < 2 m. Differences in net sedimentation rates were minor
between thalweg and nonthalweg stations located at similar depths. Marked
longitudinal differences in net sedimentation rates existed in the thalweg
along the longitudinal axis of the reservoir (Figure 5). Net sedimentation
rates were lowest in the shallow headwater region (i.e. RM 13-17), increased
in a linear fashion between RM 11 and 7, and were greatest in the deepest
water near the dam between RM 0-6. These longitudinal variations in net
sedimentation rates also coincided with decreasing depth from the dam to the
headwaters.

15. Moisture content of the surficial sediment was greatest in deep
regions of the reservoir, and declined with decreasing water depth (Figure 6).
Based on Håkanson's (1977) relationships between energy environments and mois-
ture content, we identified three zones of sedimentation: an erosional zone
(moisture content < 50 percent), a transport zone (moisture content between
50 percent and 75 percent), and an accumulation zone (moisture content
> 75 percent). The erosional zone is defined here as that region where sedi-
mentation is minimal, due to scouring and sediment removal via disturbance and
resuspension. The transport zone is a transitional region where sediment is
both deposited and removed to deeper regions, while the accumulation zone is
the region of greatest sedimentation. The erosional zone was located at
depths less than 5 m; the transport zone was located at depths between 5 m and
10 m; and the accumulation zone was located at depths greater than about
10 m. Most nonthalweg stations exhibited low moisture contents reflective of
transport and/or erosional environments.

16. Mean moisture content also varied longitudinally in the thalweg of
the reservoir (Figure 7). Mean moisture content was generally less than
50 percent in the headwaters of the reservoir (between RM 12-17), indicating
that erosional forces were acting on this region. A region of sediment trans-
port between RM 7-11 was suggested by moisture contents ranging between 50 and

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75 percent, and a zone of sediment accumulation (moisture content > 75 percent) was observed between RM 0-6. Moisture content also varied markedly between sampling dates in the erosional zone of the reservoir, compared to lower variability in moisture content observed in the accumulation zone (Figure 8). The locations of these sedimentation zones, based on moisture content, also strongly coincided with longitudinal variations in net sedimentation rates (Figure 5).

17. The depth ranges over regions of potential sediment erosion, transport, and accumulation (i.e. from Figures 6 and 7) were used to estimate total reservoir surface areas enclosing these zones (Figure 9). The erosional zone (1.62 by 10^7 m^2) accounted for the greatest percentage of the total reservoir surface area (60 percent). In contrast, the accumulation zone encompassed a much smaller percentage of the total reservoir surface area (2 percent).

18. Sediment density was inversely related to moisture content (Figure 10) and therefore exhibited trends in relation to depth opposite to those for moisture content. Sediment density increased with both decreasing depth (Figure 11) and increasing distance from the dam (Figure 12). Variations in sediment density between sampling dates were also most pronounced in the headwaters of the reservoir (Figure 13). In the thalweg, sediment densities were high between RM 13-17 in May 1989 compared to those concentrations near the dam. Sediment densities declined markedly at these river miles in January 1990, approaching concentrations measured near the dam. In May 1990, peaks in sediment density occurred in the headwaters at RM 14 and 17.

19. Sediment organic matter content was greatest in deep regions and least in shallow and headwater regions of the reservoir (Figures 14 and 15). Although no sediment organic matter data were collected at RM 0-7 in May 1989, variations in this parameter between other sampling dates were minor over these river miles, when compared to variations occurring in upper regions of the reservoir (Figure 16). In general, organic matter concentrations between RM 14-17 were lowest in May 1989-90 and greatest in January 1990.

20. At stations located in the thalweg, sediment and interstitial water COD concentrations exhibited pronounced peaks at RM 10 and to a lesser extent for interstitial water COD at RM 11 during the May 1989 sampling period (Figures 17 and 18, respectively). Downstream values of sediment COD were also elevated during this period, with particularly high concentrations at RM 1, 5, and 6 and with only slightly lower concentrations at RM 2, 7, and 8 (Figure 17). Interstitial COD also exhibited relatively high values during

May 1989 at downstream locations between RM 3-7 (Figure 18). Concentrations of sediment and interstitial COD were lowest in the headwater region (i.e. > RM 10) during this period (Figures 17 and 18).

21. In January 1990, concentrations of both sediment COD and interstitial COD increased in the headwaters (Figures 17 and 18) as peaks in concentration diminished near RM 10 from values observed in May 1989. In May 1990, all sediment COD values were considerably less than those noted in both January and May 1990 (Figure 17). Interstitial COD levels were more erratic in their behavior over the May 1989 to May 1990 sampling period (Figure 18). Declines in interstitial COD were observed between May 1989 and January 1990 and additionally between January 1990 and May 1990 at RM 4, 5, 6, 8, 10, and 11. However, increases in interstitial COD were observed between May 1989 and January 1990 followed by decreases to or near the May 1989 levels by May 1990 at RM 0.3, 1, 2, 3, 7, 12, and 16. No explanations for this erratic behavior are evident from the data, but the magnitude of overall changes observed suggest that some sediment disturbance may have occurred, particularly between RM 1-2 and 10-13.

22. Interstitial concentrations of iron, manganese, and conductivity (Figures 19, 20, and 21, respectively) also exhibited distinct peaks in the thalweg at RM 10 and lower concentrations in the headwaters in May 1989. Concentrations of these variables increased in January 1990, and then declined in May 1990 in the headwaters. Concentrations were more homogeneous along the longitudinal axis of the reservoir during January and May 1990, than during May 1989. Distinct peaks in concentrations of these variables were not observed at midreservoir locations during May 1990 (Figures 19, 20, and 21), as in May 1989.

23. DOC in the interstitial water exhibited an extensive peak between RM 10 and 13, in May 1989 (Figure 22). In particular, the peak in interstitial DOC of 87.2 mg L^{-1} (Figure 22) at RM 10 was more than twice the magnitude of concentrations over the first 8 miles in May 1989. Interstitial DOC decreased substantially in January 1990 at RM 10-13, and concentrations were similar between stations along the longitudinal axis of the reservoir in May 1990. These seasonal variations in interstitial DOC, as well as in Fe, Mn, and conductivity (i.e. Figures 19, 20, and 21), suggest that significant releases of these dissolved materials may have occurred over the May to January timeframe in the vicinity of RM 10.

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24. Concentrations of ammonium-N and SRP in the interstitial water along the thalweg were erratic and difficult to interpret (Figures 23 and 24). High levels of ammonium-N were observed during all sampling dates at RM 2 (Figure 23). Large apparent increases in interstitial SRP samples occurred at RM 2-6, and 8 during May 1990, while large increases were evident during both January and May 1990 at RM 12 (Figure 24).

25. Comparisons between thalweg and nonthalweg stations for horizontal transects located at RM 0.3, 4, 8, 11, 12, 13, and 16 are shown in Table 1. Upstream of RM 8, concentrations of sediment COD and interstitial COD, Fe, and conductivity were generally greatest in the thalweg and least at shallow, nonthalweg stations. In contrast, concentrations of interstitial DOC and manganese were greatest at nonthalweg stations and lower in the thalweg. Concentrations of interstitial SRP, ammonium-N, and DOC showed less distinct trends with depth. Downstream near the dam, trends with depth were more variable. At RM 4 and 8, sediment COD and interstitial COD, Fe, conductivity, SRP, and ammonium-N were elevated in the thalweg, and lower at nonthalweg stations. Interstitial manganese and DOC, however, were greatest in concentration at shallow stations on these horizontal transects. At RM 0.3 sediment and interstitial COD were elevated at stations A and B (i.e. nearer to shore) as well as at the thalweg station.

Statistical trends

26. We pooled stations located in the thalweg of the accumulation and erosional zones for statistical comparisons. These zones were chosen to represent extremes in sedimentary environments. When all dates were pooled, sediments in the erosional zone exhibited significantly lower mean moisture content and organic matter and greater sediment density than in the accumulation zone (Table 2). However, there were no significant differences in chemical characteristics of the interstitial water, nor in COD, between the two zones. The lack of significant differences is attributed to the marked variability over sampling dates associated with means determined for each river mile (Figures 25-32). Standard errors were pronounced for sediment moisture content, sediment density, and sediment COD in the erosional zone when compared with the accumulation zone (Table 2). However, standard errors were more similar between the two zones for all chemical concentrations of the interstitial water (Table 2).

27. Statistically significant trends in the physical composition of the sediment and chemical constituents of the interstitial water as a function of

sampling date were not evident in the thalweg of the accumulation zone
(Table 3). While significant differences were observed between dates for many
variables (i.e. sediment COD and interstitial COD, Mn, and SRP) in this zone,
cause and effect relationships could not be distinguished. More apparent
trends were observed in the thalweg of the erosional zone (Table 4), as sedi-
ment moisture content, sediment organic matter, sediment COD, interstitial
COD, and interstitial Fe were significantly greater, while sediment density
was lower in January 1990 than in May 1989-90.

28. Some significant correlations existed between sediment and inter-
stitial water variables at stations located in the thalweg (Table 5). All
variables reflecting physical and chemical composition of the sediment (i.e.
moisture content, sediment density, sediment organic matter, and sediment COD)
were either positively or negatively correlated with depth. Sediment COD was
positively correlated with interstitial COD, interstitial Fe, and interstitial
Mn, suggesting relationships between soluble metals and COD. Interstitial Fe
was also positively correlated with interstitial SRP, suggesting possible
interactions between iron and phosphorus.

Historical Analysis of Dissolved Oxygen Conditions

29. During winter ice cover, the location and extent of low dissolved
oxygen concentrations in the reservoir varies markedly over time and among
years (Figure 33). During many years (i.e. 1974-76, 1980-82), low dissolved
oxygen concentrations (i.e. dissolved oxygen sag) first develop in the head-
waters, generally above RM 10, and move down reservoir over time. Low dis-
solved oxygen concentrations also develop at down-reservoir reaches, and in
the hypolimnion near the dam, during other years (i.e. 1977-81, 1984-86). In
particular, during 1976-78, 1980, and 1985, regions of low dissolved oxygen
developed near both the dam and the headwaters, converging in later months to
form a large stretch of low dissolved oxygen concentration.

30. Vertical patterns in dissolved oxygen in the headwaters also vary
considerably from year to year (Figure 34). In general, dissolved oxygen
depletion is most rapid in the hypolimnion (i.e. 1979-80, 1982-87) of the
headwaters. However, near-anoxic conditions often develop throughout the
water column by February (i.e. 1974-75, 1978, 1980-82, 1990). Dissolved
oxygen depletion appears to be most rapid in January to early February.
During years when dissolved oxygen measurements were made prior to January,

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concentrations in the headwaters were generally greater than 10 mg L^{-1} (i.e. 1974-75, 1981).

31. No clear quantitative relationships exist between reservoir drawdown (Figure 35) and the development of low dissolved oxygen conditions in the headwaters during winter (Figure 33). Although reservoir drawdown varies markedly between years, most rapid drawdown usually occurs during January (in particular, 1974-77, 1979, 1981, 1984-88; Figure 35). Pool elevations were $\leq$ 1135 ft MSL on 01 January 1974-75, 1977, and 1989-90 (Table 6), coincident with the development of near-anoxic conditions in the headwaters during the period January-February (Figure 33). However, near-anoxic conditions also developed in the headwaters during January of 1976, 1980-82, and 1985 (Figure 33) at higher pool elevations on 01 January (i.e. $\geq$ 1135 ft mean sea level (MSL), Table 6).

32. Periods of high inflow from the Big Eau Pleine River in January (i.e. $\geq$ 20 cfs; Tables 6 and 7), generally coincided with delayed or reduced dissolved oxygen depletion in the headwaters during January of 1978, 1983-84, and 1986-88 (Figure 33). During these years, relatively high inflows (i.e. > 20 cfs) often occurred in December as well (Table 6). During periods when inflows were < 20 cfs in January, near-anoxic conditions developed in the headwaters (i.e. 1974-77, 1981-82, 1989-90) under a variety of pool elevations, ranging from 1,126.92 ft MSL on 01 January 1977 to 1,141.63 ft MSL on 01 January 1981 (Tables 6 and 7). The years 1979, 1980, and 1985 were, however, exceptional and did not exhibit patterns typical of other years (Table 7).

33. Regions of dissolved oxygen depletion in late January to early February also vary longitudinally among years (Figure 36). Although dissolved oxygen depletion generally occurs upstream of RM 10, during years when drawdown is relatively rapid (i.e. > 5 ft per month; Table 6), regions of dissolved oxygen depletion often move downstream well below RM 10 (i.e. 1974-77) by late January to early February (Figure 36). After 1977, when drawdown in January became less extensive, dissolved oxygen depletion in late January was usually restricted to regions upstream of RM 10 (i.e. 1979-82, 1989-90). During all years of record (herein), hypolimnetic dissolved oxygen depletion occurred near the dam (Figure 36).

34. Changes in reservoir volume and the reservoir surface-to-volume ratio, at various reservoir pool elevations, were most pronounced in the headwaters of the reservoir (Figure 37). Reservoir volume, and therefore

potential oxygen stores in the water column, decrease markedly (as a percent of nominal pool elevation) in the headwaters as the pool is lowered, compared to lower percent volume decreases near the dam (Figure 37). The reservoir surface-to-volume ratio also increased tremendously in the headwaters when compared to the dam, as pool elevation is lowered.

35. During years when rapid dissolved oxygen depletion occurs in the headwaters, spatial variations in dissolved oxygen appear to be complex for the years 1982 and 1989-90. In 1982, dissolved oxygen depletion was observed in the vicinity of RM 10-14 and throughout the water column at depths > 3 m by early February (Figure 38). Regions of low dissolved oxygen also developed during that year in the hypolimnion near the dam. Volumetric rates of dissolved oxygen depletion were high in the headwaters (Figure 39), coinciding with the development of anoxic conditions. Anoxic conditions occurred throughout the water column near RM 12 by mid-February, and movement of this anoxic water to the dam was observed between late February and late March (Figure 38). As the zone of anoxia progressed down reservoir, dissolved oxygen concentrations increased in the headwaters. An aeration system, positioned near RM 6, increased dissolved oxygen concentrations within the metalimnion and hypolimnion, as suggested by deflections in the 2-6 mg L^{-1} contours on 04, 11, and 17 February (Figure 38). However, as the zone of anoxia moved into this region (i.e. 04 and 11 March), the aeration system did not appear to disrupt the dissolved oxygen sag.

36. A somewhat different pattern of dissolved oxygen depletion occurred during the winter of 1989 (Figure 40). During that year, dissolved oxygen depletion was again observed in the headwaters and in the hypolimnion near the dam, and near-anoxic conditions developed between RM 12-16 by 06 February (Figure 40). However, near-anoxic conditions persisted in the headwaters from February through March, particularly between RM 12-14, which contrasted with patterns observed in the same region in 1982.

37. Volumetric rates of dissolved oxygen depletion were greatest throughout the water column near RM 16 and at intermediate depths between RM 6-12 in early January 1989 (Figure 41). By mid-January, highest rates of dissolved oxygen depletion had progressed down reservoir to RM 10-14, and rates were also high above the sediment surface between RM 6-10. As anoxic conditions developed in the headwaters in late January, volumetric rates of dissolved oxygen depletion appeared to move further down reservoir.

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38. An aeration system, positioned near RM 6, again affected dissolved oxygen concentrations throughout January 1989 (Figure 40). In mid-February of that year, an additional aeration system was placed near RM 11. While a zone of anoxia existed upstream of this system by mid-February, aeration was effective in increasing dissolved oxygen levels in the vicinity of RM 10-11. However, in late February and early March, the zone of anoxia appeared to move down reservoir through the region of aeration, and dissolved oxygen concentrations declined markedly at RM 11. Further movement of the zone of anoxia down reservoir in March resulted in an apparent decrease in the effectiveness of the aeration system at RM 6 in maintaining dissolved oxygen concentrations, as dissolved oxygen concentrations declined to about 4 mg L^{-1} or less throughout much of the hypolimnion.

39. A more severe pattern of dissolved oxygen depletion occurred during the winter of 1990 (Figure 42). Anoxic conditions developed rapidly by early January, both in the headwaters and in the hypolimnion near the dam, coinciding with very low inflows ($\leq$ 2 cfs) from the Big Eau Pleine River in December and January.* A fishkill in the headwaters was associated with this rapid dissolved oxygen depletion. Aerators placed at RM 11 and RM 6 became ineffective in increasing dissolved oxygen levels and disrupting zones of anoxia by late January. It appeared that this inefficiency coincided with the expansion of near-anoxic conditions upstream of each aeration system. As the zone of anoxia increased in the headwaters from 16 January to 05 February, dissolved oxygen concentrations decreased to 2 mg L^{-1} or less in the region of aeration at RM 11. A similar decrease in dissolved oxygen occurred in the region of aeration at RM 6 by 19 Feb, which was associated with increases in the zone of anoxia between RM 6-9, February 05-26.

40. In contrast, dissolved oxygen depletion was very moderate during the winter of 1991 (Figure 43), when pool elevations remained above 1,140 ft MSL during January and February. This pattern was similar to dissolved oxygen conditions observed during those winters when pool elevations were greater than 1,135 ft MSL in January and average flows from the Big Eau Pleine River were Greater than 20 cfs (Table 7 and Figure 36). During the winter of 1991, oxygen depletion was observed in both the headwaters and in the hypolimnion near the dam. Anoxia developed near the dam by 07 Mar; however, bottom water remained well oxygenated (i.e., > 2 mg L^{-1}) in the headwaters. In addition,

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* Personal Communication, March 1991, R. Gall and D. Coon.

the headwaters did not experience severe decreases in oxygen throughout the water column, as was observed during 1982, 1989, and 1990. In the downstream portion of the reservoir, the upper 4 m of the water column was relatively high in dissolved oxygen throughout February. In contrast, during 1982, 1989, and 1990, when pool elevations were lower in January and February, high oxygen concentrations were confined only to the surface waters.

Water Chemistry

41. Substantial peaks (i.e. > 50 μg L^{-1}) in chlorophyll a concentration occurred in the surface waters from RM 10-16 in February 1990 (Figure 44). Chlorophyll a concentrations were much lower at stations located near the dam. Concentrations of dissolved organic carbon, soluble nutrients and metals, and COD increased substantially between RM 12-18 from 10 January to 15 February 1990 (Figure 44). In particular, concentrations of ammonium-N, SRP, soluble Fe, soluble Mn, and COD exhibited marked gradients of increasing concentration in the bottom waters above the sediment in this region on 15 February, coinciding with the development of anoxic conditions (i.e. Figure 42). Extremely high concentrations of these variables occurred at RM 18 on 15 February, where the fishkill was most concentrated. Concentrations of SRP, soluble Fe, soluble Mn, and COD were also elevated in the hypolimnion above the sediment near the dam on 15 February, coinciding with anoxic conditions.

PART IV: DISCUSSION

Sediment Composition, Resuspension, and Transport

42. Based on physical composition of the sediment, it is apparent that sediment disturbance, introducing oxygen-demanding material into the water column during the winter, is pronounced in the Big Eau Pleine Reservoir. This is particularly true in the headwaters, where disturbance and resuspension is likely to be followed by displacement and transport downstream to deeper regions near the dam. Net sedimentation rates are relatively low in the headwaters, even though loading to the Big Eau Pleine Reservoir is high (Shaw and Powers undated, Gunnison and Barko 1988). Moisture content is also very low (< 50 percent), while sediment density is high in the headwaters, indicating the probable action of erosional forces that disturb and remove fine sediment from this region (e.g., Håkanson 1977). This sedimentary pattern is unusual for reservoirs (Thornton et al. 1981) where high sedimentation rates (James et al. 1987) and sediment delta formation (Pharo and Carmack 1979) have been observed in the upper reaches near tributary inflows.

43. Investigations in both lakes and reservoirs have shown that erosional forces (e.g. wave scouring) and basin morphometry result in the focusing of sediment to deep basins (Likens and Davis 1975; Håkanson 1977; Evans and Rigler 1980, 1983; Hilton 1985; Hilton, Lishman, and Allen 1986; James and Barko 1990). In the Big Eau Pleine Reservoir, sediment disturbance is evident in the deep thalweg of the headwater region, as well as at shallow depths throughout the reservoir. Our results suggest that sediment loads deposited in the headwaters are being disturbed in the winter, and potentially transported along the longitudinal axis of the reservoir to the deeper basin near the dam. The seasonal variability of sediment moisture content, sediment density, and organic matter in the headwater sediments, compared to the levels of these parameters in sediments located near the dam, also suggest that sediments are being deposited and removed from the headwater region. The large area (60 percent of the reservoir surface) occupied by the erosional zone is within the range of the region of average maximum drawdown for the years 1974-90 (mean = 1,128 ft MSL), suggesting that winter drawdown and spring refilling may be the principle factors in disturbance of sediment and longitudinal transport toward the dam.

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Sediment COD and Interstitial Water Quality

44. Interstitial water of the surficial sediment in the headwaters exhibited moderately high concentrations of iron and manganese. Both sediment and interstitial water COD were highly correlated with concentrations of iron and manganese in the interstitial water, indicating that these metals may have provided an important source of COD to the water column during reservoir drawdown and sediment disturbance. Gunnison and Barko (1990) proposed that mobilization of these metals and other sources of COD from the sediment into the water column via sediment disturbance and resuspension, diffusion, and/or ice scouring could result in the immediate removal of over one-half of the dissolved oxygen, at saturation levels (13.1 mg L^{-1} at 4 °C) in the overlying water column.

45. Throughout the reservoir, sediment and interstitial COD, Fe, and Mn were generally much less variable along the longitudinal axis during the winter of 1990 than in either the spring of 1989 or 1990. In particular, peaks in concentrations of these variables at midreservoir locations observed in May 1989 had diminished by January 1990. These marked seasonal variations between sampling dates suggest mobilization of sedimentary COD during winter drawdown and transport downstream. Sediment disturbances during winter drawdown appear to be important mechanisms in the mobilization and transport of COD. Increased flow velocities in the headwaters, as a result of decreased channel width during drawdown, may promote sediment disturbance. Diffusion of reduced chemical species out of the sediment is probably enhanced by these same processes. Ice scour and shelving during drawdown may also disturb sediments, resulting in mobilization of COD.

Dissolved Oxygen Dynamics

46. It is clear that the headwaters of Big Eau Pleine Reservoir represent an important region of dissolved oxygen depletion during the winter. While anoxia usually develops in the headwaters in January, the timing of anoxia appears to be dependent, to some extent, on the magnitude of inflows from the Big Eau Pleine River. Rapid dissolved oxygen depletion in the headwaters generally coincides with periods of reduced inflow, and therefore resulting in a higher water retention time. In contrast, higher water inflows and lower retention times appear to delay the onset of anoxia, often until

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February, suggesting a close association between retention time and the development of anoxia in the headwaters.

47. During January of 1982 and 1989, volumetric rates of dissolved oxygen depletion were relatively high (i.e. 0.4-0.5 mg L^{-1} d^{-1}) in the headwaters of the Big Eau Pleine Reservoir, compared with downstream locations, suggesting high biological and/or chemical oxygen demands in this region. Winter volumetric rates of dissolved oxygen depletion in the headwaters of this reservoir are within the range of rates reported for ice-covered lakes in the upper midwest (Ellis and Stefan 1989) and similar to hypolimnetic depletion rates reported for the headwaters of DeGray Lake (Kennedy and Nix 1986) and embayments in Richard B. Russell Lake (James et al. 1985, 1986).

48. Dissolved oxygen depletion in the headwaters is exacerbated by removal of oxygen mass during winter drawdown, since this region already experiences low water volumes and thus low oxygen mass at this time (i.e. Figure 37). As reservoir water volume and oxygen mass decline during the winter, smaller oxygen stores in the reservoir are also affected by exposure to increasingly larger surface to volume ratios in the headwaters, favoring more rapid development of anoxic conditions.

49. Nix (1981) showed that low inflows coupled with continuous withdrawal caused entrainment and movement of anoxic water containing reduced nutrients and metals from the headwater region of DeGray Lake, Arkansas. A similar pattern appears to be occurring in Big Eau Pleine Reservoir during the winter, due to continuous withdrawal. Thus, downstream movement of the dissolved oxygen sag during winter appears to be associated with the hydrology of the system. Movement of high dissolved oxygen demands down reservoir may be caused by advective movement of the oxygen sag. This oxygen sag is due to entrainment of oxygen-demanding materials originating in the headwaters into density currents created by reservoir discharge. Mixing of these materials into oxygenated water located ahead of the oxygen sag may further exacerbate oxygen demands down reservoir, as suggested by the extensive anoxia that developed throughout much of the reservoir during late winter periods in 1982, 1989, and 1990. Additional hypolimnetic oxygen depletion near the dam increases the severity of problems resulting from movement of the oxygen sag into this region (Gunnison and Barko 1988).

50. During many years (i.e. 1974-76, 1982), movement of the oxygen sag in the Big Eau Pleine Reservoir is accompanied by replacement with oxygenated water in the headwaters, suggesting that the initial oxygen demand imposed on

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the headwaters can become diminished by late winter (February-March). However, during other years (i.e. 1989-90), anoxia persists in the headwaters as the oxygen sag moved through the reservoir, resulting in development of an extensive region of anoxia. Although we have no specific information explaining these differences in the persistence of anoxia in the headwaters, several factors may be involved. One possibility is that a larger mass of reduced chemical species accumulates during some years than other years, thus resulting in greater demand on oxygen imports to the region. Alternatively, during dry years lower initial pool elevations may allow sediment disturbances to begin earlier in the winter and persist over a longer period than in years when initial pool elevations are higher.

51. The aeration systems were not always effective in offsetting dissolved oxygen depletion nor in maintaining dissolved oxygen concentrations at moderate levels during the winter. By February of 1989 and 1990, large volumes of anoxic water developed upstream of the aeration systems. Movement of this anoxic water into regions of aeration provided a substantial oxygen deficit that was not lowered by the aeration systems. During February 1990, high concentrations of soluble Fe, Mn, and COD occurred in the reservoir (particularly above RM 11), providing a significant source for dissolved oxygen loss as these reduced metals moved into the regions of aeration. These observations strongly indicate that the aeration systems must be effective in meeting the oxygen requirements imposed by reduced metals (i.e. COD) and anoxic water moving into the region, as well as the local dissolved oxygen depletion rate. Similar considerations were important in determining oxygen injection rates at Richard B. Russell Reservoir located in Georgia and South Carolina (James et al. 1985, 1986).

Contributions of Algal Production and BOD to Oxygen Demand

52. Based on the findings of this study and previous investigations (Gunnison and Barko 1988, 1990, and literature cited therein), it is likely that phytoplankton produced during the summer growing season are decomposed prior to ice-cover. The oxygen demands resulting from the decomposition of this material can be quite high, having a BOD_5 estimate of 2.3 to 4.6 mg L^{-1} (Gunnison and Barko 1990). However, this material is unlikely to contribute directly to oxygen problems during the winter, based on two observations. First, the organic matter content of the sediments is not particularly high

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and does not vary much seasonally (this study), indicating a relatively stable level of refractory organic matter. Second, the Big Eau Pleine Reservoir has a relatively short water residence time (Gunnison and Barko 1988), and much of the algal material produced in the summer probably leaves the system before winter drawdown. In addition, because algal material is often highly labile (Gunnison and Alexanders 1975), most of the decomposition probably occurs shortly after dieback of algal blooms in the summer. Nonetheless, rapid microbial degradation of deposited algal material during the warmer months may contribute to anoxia and accumulation of reduced inorganic and organic substances in the sediment surface layers. These materials may then exert a COD when released from sediments to the water column during the winter months.

53. Limited measurements of chlorophyll and phosphorus concentrations beneath the ice indicate great potential for phytoplankton production during winter, as long as sufficient light is available for photosynthesis. Photosynthesis by phytoplankton beneath the ice may increase oxygen concentrations (with light); however, respiration, autolysis, and decay under heavy snow cover (no or very limited light) will decrease phytoplankton production and oxygen concentrations.

54. BOD was not examined in the present investigation; however, several previous studies examined the role of BOD in dissolved oxygen depletion in the Big Eau Pleine Reservoir (Swalby 1979; Gunnison and Barko 1988, 1990; Shaw and Powers undated). Swalby found that BOD alone was not sufficient to explain the extremely low dissolved oxygen levels in the reservoir during the winter, thereby implicating the importance of COD in wintertime dissolved oxygen depletion. Gunnison and Barko (1988) measured annual BOD fluxes into and out of the reservoir. They found that for all but 2 of the 14 years examined, estimated loss of BOD in outflows greatly exceeded imports from the Big Eau Pleine River, suggesting that some form of BOD (probably algal production) was generated within the system.

PART V: CONCLUSIONS AND RECOMMENDATIONS

55. The results of these investigations support the hypothetical
scenario of events leading to depletion in dissolved oxygen during the winter
in the Big Eau Pleine Reservoir (Gunnison and Barko 1988). Dissolved oxygen
depletion and anoxia in the headwaters of the Big Eau Pleine Reservoir are
associated with winter drawdown, coupled with low inflows. Dissolved oxygen
depletion and anoxia also occur in the hypolimnion near the dam. Entrainment
of anoxic water and its downstream movement during winter are promoted by
continual withdrawal from the reservoir. Anoxic waters originating from the
headwaters often converge with hypolimnetic pockets of anoxia near the dam,
forming an extensive region of low dissolved oxygen by late winter.

56. Exertion of BOD in the sediment and water column only partially
explain the volumetric oxygen depletion rate in the winter. Measured high
rates of dissolved oxygen depletion during the winters of 1982 and 1989 sug-
gest involvement of COD in addition to BOD. Sediment disturbance, enhanced
diffusion, and effects of ice or current scouring during winter drawdown may
in combination move soluble reduced metals and organic material into the water
column. Portions of these substances are rapidly oxidized, consuming much or
all of the dissolved oxygen in the immediate area, while the remaining
material is more slowly oxidized, contributing to the oxygen demand
downstream.

57. The composition of the surficial sediment and net sedimentation
rates indicate substantial disturbance of sediment in the headwaters and sedi-
ment focusing to the deep basin, near the dam of the reservoir. Physical
sediment composition varies greatly at different times of the year in the
headwaters, suggesting deposition, sediment disturbance, and removal of
sediment.

58. Interstitial water concentrations of soluble Fe, Mn, DOC, and COD
are moderately high in the surficial sediments of the headwaters and have the
potential to exert a substantial COD to the overlying water column, if sedi-
ments are resuspended or scoured by ice movement. High levels of phosphorus
and suspended solids in the water column during winter drawdown suggest
possible sediment disturbance and resuspension. However, the exact mechanisms
affecting sediment resuspension during winter drawdown are currently unknown.
Interstitial water concentrations of soluble Fe, Mn, DOC, and COD, while some-
what lower in the downstream reaches of the project, also have the potential

to exert a COD on the overlying water column. Since sediments in the downstream areas do not appear to be resuspended during drawdown, the release of oxygen-demanding materials from these sediments is probably limited to diffusion alone. Nonetheless, significant downstream oxygen depletion can occur, particularly near the dam.

59. Decreases in the volume of oxygen stores and increases in the reservoir surface-to-volume ratio during winter drawdown favor more rapid development of anoxic conditions, particularly in the headwaters. Drawdown also results in decreased channel width and increased flow velocities in the headwaters, promoting potential sediment scour, disturbance and/or resuspension, and enhanced diffusion. During 1991, when pool elevations remained above 1,140 ft MSL during January and February, dissolved oxygen concentrations were substantially higher in the headwaters, and anoxic conditions had not developed as late as early March. These observations strongly suggest that maintaining a higher pool elevation may significantly improve dissolved oxygen conditions in the reservoir.

60. The aeration systems, as presently configured, do not appear to control dissolved oxygen levels in the water column when anoxic waters containing high levels of soluble metals and COD move downstream. Thus, the present aeration systems appear to lack the capacity to handle additional oxygen deficits and COD imposed by anoxic water moving into the region of aeration.

61. Gunnison and Barko (1988) offered four different management alternatives to eliminate or minimize the problems associated with the development and downstream propagation of the dissolved oxygen sag. Two of these alternatives, sediment removal by dredging and construction of an upstream sedimentation pool, now appear impractical based on an increased knowledge of the system. Instead, it may be important that the period of winter ice-cover begin with a full pool. Adjustments in the reservoir drawdown schedule with allowance for a greater volume of water at the point of maximum drawdown (perhaps in concert with continued aeration), particularly if inflows from the Big Eau Pleine Reservoir are low during December and January, should prevent fish kills in the reservoir during winter. We currently do not know the minimum pool elevation required to delay and/or prevent the development of anoxia. However, results from the winter of 1991 (Figure 43) suggest that a minimum pool elevation of 1,140 ft MSL in January may reduce the likelyhood of sediment disturbance and high dissolved oxygen depletion. If the maximum possible

water volume is maintained during the winter, aeration may only be required occasionally.

62. Given the very low concentrations of dissolved oxygen, even near the aerators during the 1989/90 winter, it is clear that the magnitude of oxygen consumption in the reservoir exceeds the capacity of the aeration systems. It is likely that fish kills at isolated upstream locations, which are not protected by aeration (as in the winter of 1989/90) may occur as the reservoir is drawn down during the winter. The frequency and severity of these localized fish kills will probably vary with reservoir volume, in concert with the severity of winter conditions and the events that have occurred during the preceding year. Without modification to the drawdown schedule and/or volume of water discharged during winter drawdown, it may be necessary to install additional aerators throughout the reservoir for incremental use as needed to enhance oxygen diffusion processes. The difficulty with this approach is that a large capital outlay will be required for purchase of additional aerators, and additional yearly maintenance expenses will also be incurred to maintain units that may be needed only every 5 or 10 years. Moreover, additional engineering studies may be necessary to determine optimal aerator configurations and operational schedules.

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Table 1

Variation Among River Miles in Means and Standard Errors (±1 S.E.)

Variable	Station at River Mile 0.3				
	A*	B	C Thalweg	D*	E*
Depth, m	7.4	7.8	12.0	3.5	3.6
Sediment COD, mg g^{-1}	86.2	51.1 (14.7)	62.4 (17.8)	11.0	23.2
Interstitial COD, mg L^{-1}	119.7	73.3 (35.1)	108.2 (20.2)	30.4	90.0
Interstitial Fe, mg L^{-1}	5.1	4.3 (1.1)	21.2 (3.4)	9.2	4.0
Interstitial Mn, mg L^{-1}	1.7	6.1 (3.6)	3.1 (0.5)	4.1	17.4
Interstitial SRP, mg L^{-1}	0.102	0.232(0.095)	0.225(0.103)	0.137	0.370
Interstitial NH$_4$, mg L^{-1}	5.0	4.1 (0.6)	9.6 (2.0)	2.7	5.1
Interstitial DOC, mg L^{-1}	11.3	38.8 (10.1)	30.8 (1.7)	76.2	35.2
Interstitial Cond. μmhos cm^{-2}	304	204 (16)	418 (83)	161	303

Variable	Station at River Mile 4.0	
	A Thalweg	B
Depth, m	10.0	3.3
Sediment COD, mg g^{-1}	78.0 (15.3)	37.8 (16.5)
Interstitial COD, mg L^{-1}	131.2 (14.8)	76.6 (53.5)
Interstitial Fe, mg L^{-1}	27.0 (4.7)	11.2 (3.0)
Interstitial Mn, mg L^{-1}	5.3 (1.4)	19.0 (14.1)
Interstitial SRP, mg L^{-1}	0.502(0.443)	0.316(0.236)
Interstitial NH$_4$, mg L^{-1}	10.7 (0.7)	9.1 (1.1)
Interstitial DOC, mg L^{-1}	28.9 (1.9)	58.8 (19.8)
Interstitial Cond. μmhos cm^{-2}	388 (28)	357 (13)

(Continued)

Note: COD - chemical oxygen demand, Fe - iron, Mn - manganese, SRP - soluble reactive phosphorous, NH$_4$ - ammonium-N, DOC - dissolved organic carbon, Cond. - conductivity. Values in parentheses denote standard error.
* Indicates that only one sample was collected.

Table 1 (Continued)

Variable	Station at River Mile 8.0		
	A	B Thalweg	C
Depth, m	4.7	8.5	4.4
Sediment COD, mg g^{-1}	33.0 (11.2)	86.9(22.8)	62.8(27.8)
Interstitial COD, mg L^{-1}	77.8 (40.2)	146.7(25.5)	66.1(45.0)
Interstitial Fe, mg L^{-1}	8.3 (5.3)	37.7 (1.9)	11.4 (7.6)
Interstitial Mn, mg L^{-1}	13.8 (8.4)	4.1 (0.6)	14.1(10.2)
Interstitial SRP, mg L^{-1}	0.779(0.201)	2.02 (.60)	1.96(0.09)
Interstitial NH$_4$, mg L^{-1}	3.9 (1.0)	8.4 (0.9)	5.3 (0.3)
Interstitial DOC, mg L^{-1}	100.2 (58.9)	39.2 (0.6)	57.7(25.5)
Interstitial Cond. μmhos cm^{-2}	262 (22)	363 (67)	333 (57)

Variable	Station at River Mile 11.0	
	A Thalweg	B
Depth, m	7.9	3.9
Sediment COD, mg g^{-1}	54.0 (11.1)	35.3 (15.4)
Interstitial COD, mg L^{-1}	159.9 (39.9)	94.0 (35)
Interstitial Fe, mg L^{-1}	24.3 (5.1)	10.2 (5.6)
Interstitial Mn, mg L^{-1}	4.0 (0.6)	14.9 (12.0)
Interstitial SRP, mg L^{-1}	0.377(0.206)	0.480(0.300)
Interstitial NH$_4$, mg L^{-1}	9.1 (2.9)	5.9 (2.6)
Interstitial DOC, mg L^{-1}	43.5 (8.1)	136.3 (84.7)
Interstitial Cond. μmhos cm^{-2}	367 (76)	317 (56)

(Continued)

Table 1 (Continued)

Variable	Station at River Mile 12.0						
	A*	B		C		D Thalweg	
Depth, m	2.7	4.1		5.2		7.0	
Sediment COD, mg g^{-1}	12.3	15.7	(5.6)	53.0	(1.3)	59.4	(5.9)
Interstitial COD, mg L^{-1}	97.0	65.5		123.1	(46.5)	123.0	(28.7)
Interstitial Fe, mg L^{-1}	6.4	15.1		18.7	(9.5)	30.5	(10.5)
Interstitial Mn, mg L^{-1}	7.2	3.7		16.0	(11.6)	4.8	(0.4)
Interstitial SRP, mg L^{-1}	0.080	0.459	(0.139)	1.480	(0.897)	1.335	(0.643)
Interstitial NH$_4$, mg L^{-1}	5.0	3.7	(0.8)	11.8	(1.2)	14.0	(2.9)
Interstitial DOC, mg L^{-1}	37.8	106.3	(60.7)	53.6	(16.1)	39.6	(2.7)
Interstitial Cond. μmhos cm^{-2}	200	298	(45.5)	542	(76)	421	(49)

Variable	Station at River Mile 13.0		
	A Thalweg	B	C*
Depth, m	6.3	3.0	2.2
Sediment COD, mg g^{-1}	60.2 (32.6)	19.3 (15.5)	18.8
Interstitial COD, mg L^{-1}	130.2 (41.4)	103.4 (70.7)	127.0
Interstitial Fe, mg L^{-1}	15.9 (7.3)	5.3 (3.3)	3.6
Interstitial Mn, mg L^{-1}	3.7 (0.7)	5.5 (4.0)	21.0
Interstitial SRP, mg L^{-1}	0.350 (0.046)	0.318 (0.163)	2.100
Interstitial NH$_4$, mg L^{-1}	5.5 (2.5)	5.5 (4.0)	12.3
Interstitial DOC, mg L^{-1}	46.9 (14.1)	58.3 (12.3)	56.2
Interstitial Cond. μmhos cm^{-2}	369 (74)	329 (31)	376

(Continued)

Table 1 (Concluded)

	Station at River Mile 16.0		
	A Thalweg	B	C*
Depth, m	4.8	3.2	2.1
Sediment COD, mg g^{-1}	44.9 (23.2)	17.0 (6.6)	14.6 (11.5)
Interstitial COD, mg L^{-1}	114.9 (34.2)	79.8 (50.3)	55.3 (42.7)
Interstitial Fe, mg L^{-1}	21.3 (4.9)	5.7 (0.9)	4.9 (2.1)
Interstitial Mn, mg L^{-1}	4.2 (0.4)	17.4 (12.5)	7.3 (2.7)
Interstitial SRP, mg L^{-1}	0.781(0.147)	0.111(0.071)	0.058(0.018)
Interstitial NH$_4$, mg L^{-1}	7.3 (0.4)	8.4 (3.4)	3.8 (1.7)
Interstitial DOC, mg L^{-1}	38.2 (6.0)	49.5 (21.8)	30.9 (2.0)
Interstitial Cond. μmhos cm^{-2}	441 (66)	438 (87)	304 (46)

Table 2

Overall Means and Standard Errors (±1 S.E.) for Surficial Sediment and Interstitial Water Variables in the Thalweg of the Accumulation and Erosional Zones

Variable	Accumulation Zone*	Erosional Zone*
Sediment moisture content, %	76.1 (1.0)[a]	41.4 (4.5)[b]
Sediment density, g mL^{-1}	0.25 (0.01)[b]	0.91(0.15)[a]
Sediment organic matter, %	11.1 (1.0)[a]	4.2 (0.7)[b]
Sediment COD, mg g^{-1}	82.2 (6.5)[a]	56.0 (11.9)[a]
Interstitial COD, mg L^{-1}	123.9 (7.1)[a]	127.3 (14.5)[a]
Interstitial Fe, mg L^{-1}	27.4 (1.9)[a]	19.7 (2.2)[a]
Interstitial Mn, mg L^{-1}	4.4 (0.3)[a]	4.5 (0.3)[a]
Interstitial SRP, mg L^{-1}	0.59 (0.12)[a]	0.32(0.11)[a]
Interstitial NH$_4$, mg L^{-1}	12.3 (1.5)[a]	7.7 (0.9)[a]
Interstitial DOC, mg L^{-1}	38.2 (1.8)[a]	38.1 (3.9)[a]

* Different letters associated with individual variables indicate significant differences ($p < 0.05$) based on Duncan's Multiple Range Analysis.

Table 3

Variations in Means and Standard Errors by Date for Surficial Sediment and Interstitial Water Variables in the Thalweg of the Accumulation Zone

Variable	May 1989*	Jan 1990*	May 1990*
Sediment moisture content, %	72.7 (1.1)[a]	78.5 (1.6)[a]	76.9 (1.8)[a]
Sediment density, g mL^{-1}	0.29 (0.01)[a]	0.22 (0.2)[a]	0.23 (0.2)[a]
Sediment organic matter, %	2.7 (1.2)[b]	12.1 (1.4)[a]	12.3 (0.9)[a]
Sediment COD, mg g^{-1}	99.3 (13.7)[a]	91.6 (5.3)[a]	55.7 (7.4)[b]
Interstitial COD, mg L^{-1}	123.9 (16.7)[ab]	149.4 (3.3)[a]	98.4 (4.0)[b]
Interstitial Fe, mg L^{-1}	25.1 (4.2)[a]	23.8 (3.1)[a]	33.3 (1.5)[a]
Interstitial Mn, mg L^{-1}	5.5 (0.7)[a]	3.3 (0.2)[b]	4.4 (0.5)[ab]
Interstitial SRP, mg L^{-1}	0.26 (0.09)[b]	0.35 (0.10)[b]	1.18 (0.22)[a]
Interstitial NH_4, mg L^{-1}	12.6 (3.0)[a]	10.7 (2.3)[a]	13.7 (2.4)[a]
Interstitial DOC, mg L^{-1}	26.1 (2.0)[a]	34.9 (4.2)[a]	35.8 (1.5)[a]

* Different letters associated with individual variables indicate significant differences ($p < 0.05$) based on Duncan's Multiple Range Analysis.

Table 4

Variations in Means and Standard Errors by Date for Surficial Sediment and Interstitial Water Variables in the Thalweg of the Erosional Zone

Variable	May 1989*		Jan 1990*		May 1990*	
Sediment moisture content, %	31.8	(7.6)[b]	55.3	(2.5)[a]	37.0	(8.5)[b]
Sediment density, g mL^{-1}	1.04	(0.13)[a]	0.51	(0.05)[b]	1.17	(0.40)[a]
Sediment organic matter, %	2.0	(0.3)[b]	6.5	(0.6)[a]	3.7	(1.8)[b]
Sediment COD, mg g^{-1}	35.2	(4.4)[b]	94.4	(7.3)[a]	12.9	(1.8)[c]
Interstitial COD, mg L^{-1}	78.8	(5.0)[b]	169.9	(4.6)[a]	93.5	(2.5)[b]
Interstitial Fe, mg L^{-1}	11.7	(1.5)[b]	24.9	(1.9)[a]	18.9	(2.3)[b]
Interstitial Mn, mg L^{-1}	4.1	(0.8)[a]	4.8	(0.3)[a]	4.4	(0.6)[a]
Interstitial SRP, mg L^{-1}	0.35	(0.27)[a]	0.30	(0.18)[a]	0.32	(0.18)[a]
Interstitial NH$_4$, mg L^{-1}	8.5	(1.0)[a]	6.6	(1.7)[a]	9.0	(1.0)[a]
Interstitial DOC, mg L^{-1}	37.2	(11.9)[a]	37.3	(5.1)[a]	41.9	(1.0)[a]

* Different letters associated with individual variables indicate significant differences ($p < 0.05$) based on Duncan's Multiple Range Analysis.

Table 5

Pearson Correlation Coefficients (r)

	MOIS	DENS	SED_OM	SED_COD	INT_COD	INT_Fe	INT_Mn	INT_SRP	INT_NH$_4$	INT_DOC
DEPTH	0.79*	-0.67*	0.58*	0.36*	-0.13	0.16	-0.09	-0.0002	0.31*	-0.29
MOIS		-0.91*	0.76*	0.50*	0.08	0.30*	0.02	0.09	0.24	-0.18
DENS			-0.65*	-0.46*	-0.14	-0.37*	-0.07	-0.13	-0.26	0.15
SED_OM				0.24	-0.09	0.26	-0.10	0.05	0.32*	0.02
SED_COD					0.62*	0.30*	0.31*	-0.17	0.16	0.08
INT_COD						0.38*	0.35*	-0.04	-0.01	0.46*
INT_Fe							0.63*	0.39*	0.37*	0.40*
INT_Mn								0.02	0.49*	0.28*
INT_SRP									0.15	0.19
INT_NH$_4$										-0.06

Note: Coefficients include moisture content (MOIS), sediment density (DENS), sediment organic matter (SED_OM), sediment COD (SED_COD), and interstitial COD (INT_COD), Iron (INT_Fe), manganese (INT_Mn), SRP (INT_SRP), ammonium-N (INT_NH$_4$), and DOC (INT_DOC). All stations in the thalweg region for all dates are included in the analysis.

* Indicates significant correlations at the 5 percent level or less.

Table 6

Minimum Pool Elevation from Big Eau Pleine River

Year	Minimum Pool ft MSL	Date	Pool EL. ft MSL 01 Dec	01 Jan	01 Feb	Average Discharge, cfs Dec	Jan	Feb
1974	1,120.38	03 Mar	1,134.10	1,130.93	1,121.35	13.9	9.3	9.1
1975	1,117.26	08 Feb	1,134.46	1,130.17	1,121.18	6.6	7.9	7.4
1976	1,115.85	10 Mar	1,138.94	1,140.69	1,133.80	152.0	15.6	42.9
1977	1,115.64	31 Jan	1,129.52	1,126.92	1,115.80	3.2	0.4	0.5
1978	1,123.73	23 Mar	1,140.72	1,142.28	1,138.88	101.0	19.6	9.7
1979	1,124.78	19 Mar	1,144.20	1,142.14	1,137.90	21.9	17.5	21.0
1980	1,125.72	19 Mar	1,144.82	1,143.01	1,140.32	41.7	64.2	8.9
1981	1,134.40	17 Feb	1,144.60	1,141.63	1,136.76	15.0	8.0	216.0
1982	1,126.30	19 Mar	1,142.66	1,140.21	1,136.52	20.8	12.8	13.4
1983	1,138.19	01 Mar	1,145.19	1,144.89	1,141.52	185.0	40.1	42.1
1984	1,137.28	13 Feb	1,145.21	1,144.70	1,139.92	48.2	34.2	372.0
1985	1,138.42	23 Feb	1,145.30	1,145.25	1,142.07	101.0	33.5	35.7
1986	1,131.27	18 Mar	1,145.27	1,144.48	1,141.50	34.8	30.2	36.9
1987	1,132.10	07 Mar	1,143.72	1,140.55	1,136.83	28.3	20.9	19.5
1988	1,133.61	09 Mar	1,139.35	1,140.60	1,138.26	96.4	14.6	13.8
1989	1,129.69	24 Mar	1,136.50	1,135.76	1,134.10	15.1	--	--
1990	1,131.33	09 Mar	1,133.94	1,132.32	1,131.80	--	--	--

Table 7

Qualitative Comparisons Between Average Flows,
Big Eau Pleine River, above RM 10

Average Flow in January cfs	Pool Elevation on 01 January*	
	>1,135 ft MSL	<1,135 ft MSL
>20	78, 80**, 83, 84	
	85**, 86, 87, 88	
<20	76**, 79, 81**, 82**	74**, 75**, 77**, 89**, 90**

* According to year.
** Years when near-anoxic conditions occurred in the headwaters in
    January.
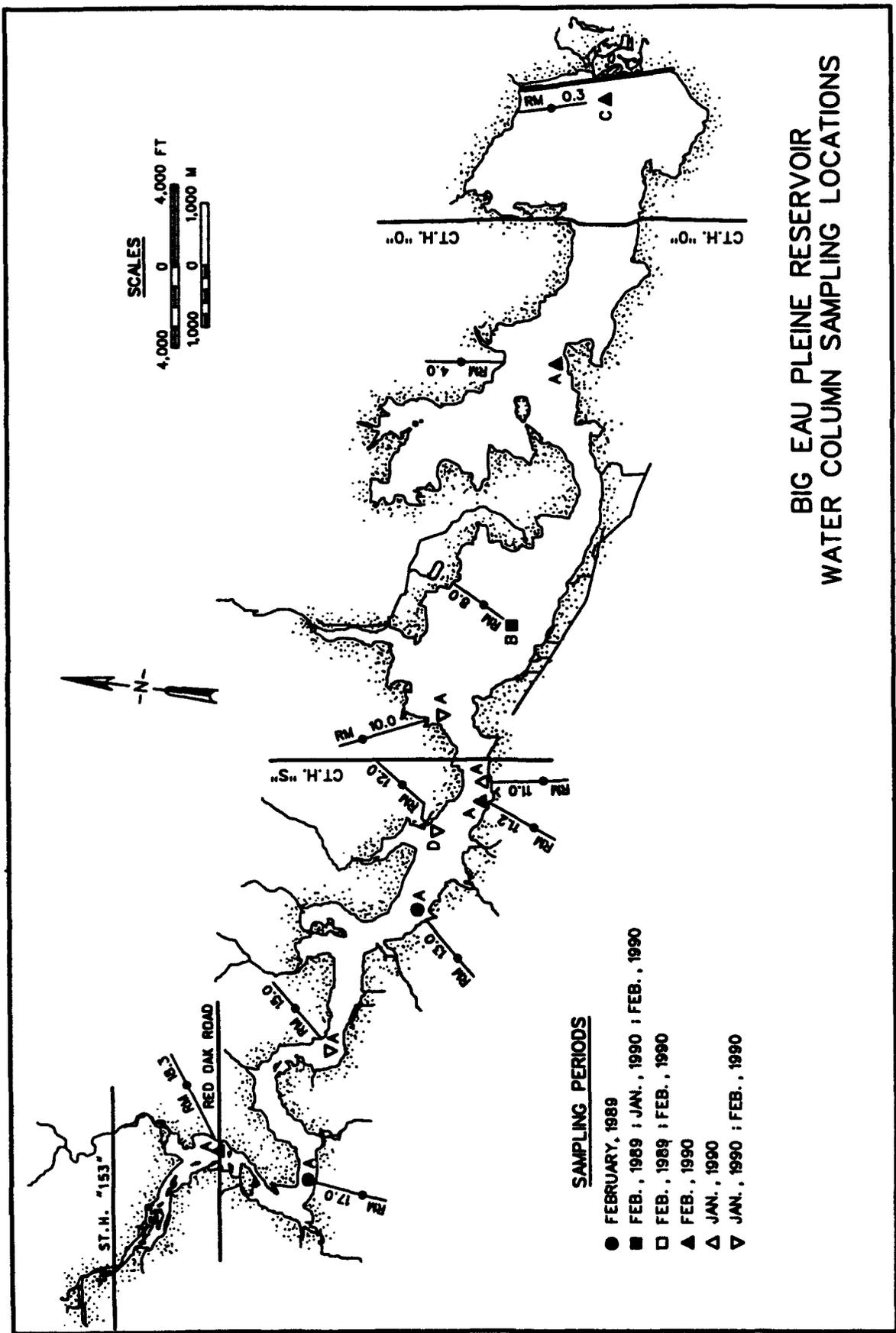
Figure 1. Water column sampling locations and dates

Figure 2. Sediment core sampling locations and dates

BIG EAU PLEINE RESERVOIR
SURFICIAL SEDIMENT SAMPLING LOCATIONS

SAMPLING PERIODS

● MAY, 1989
○ MAY, 1989 ; JAN., 1990
▽ MAY, 1989 ; JAN., 1990 ; MAY, 1990
■ MAY, 1989 ; MAY, 1990
□ MAY, 1990
▲ JAN., 1990
△ JAN., 1990 ; MAY, 1990
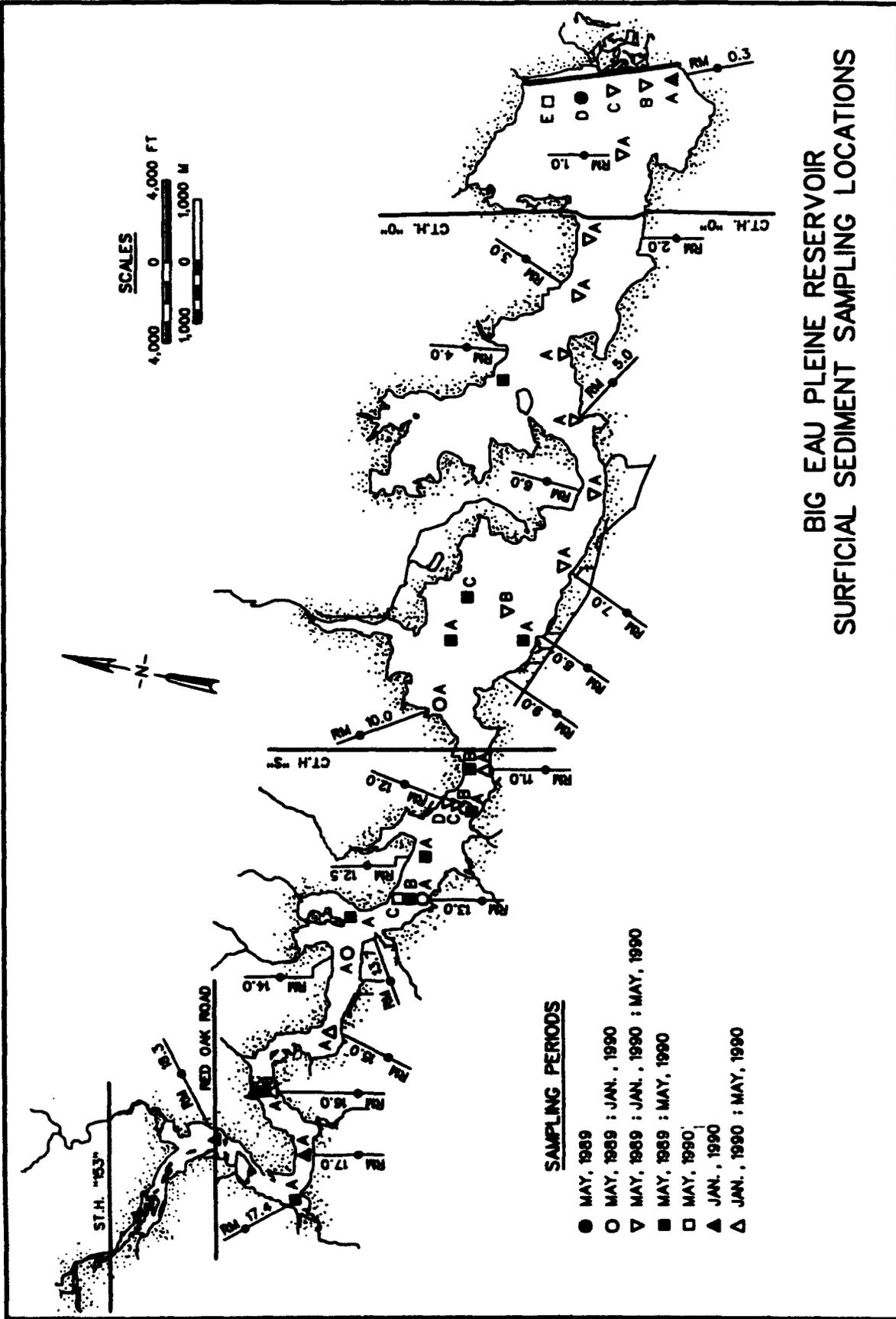
Figure 3. Surficial sediment sampling locations and dates
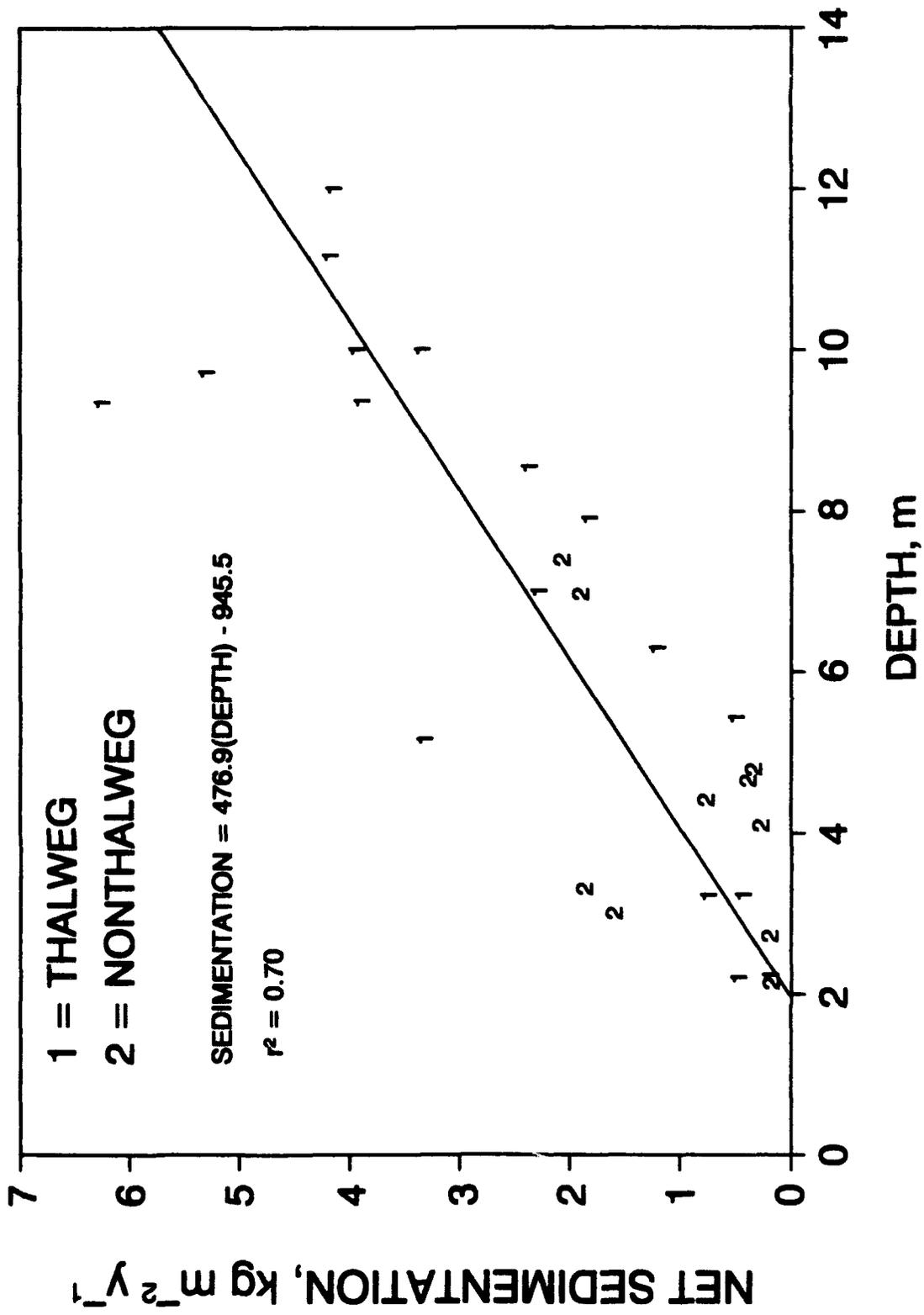
Figure 4. Variations in net sedimentation rates with depth for stations located both within and outside the thalweg
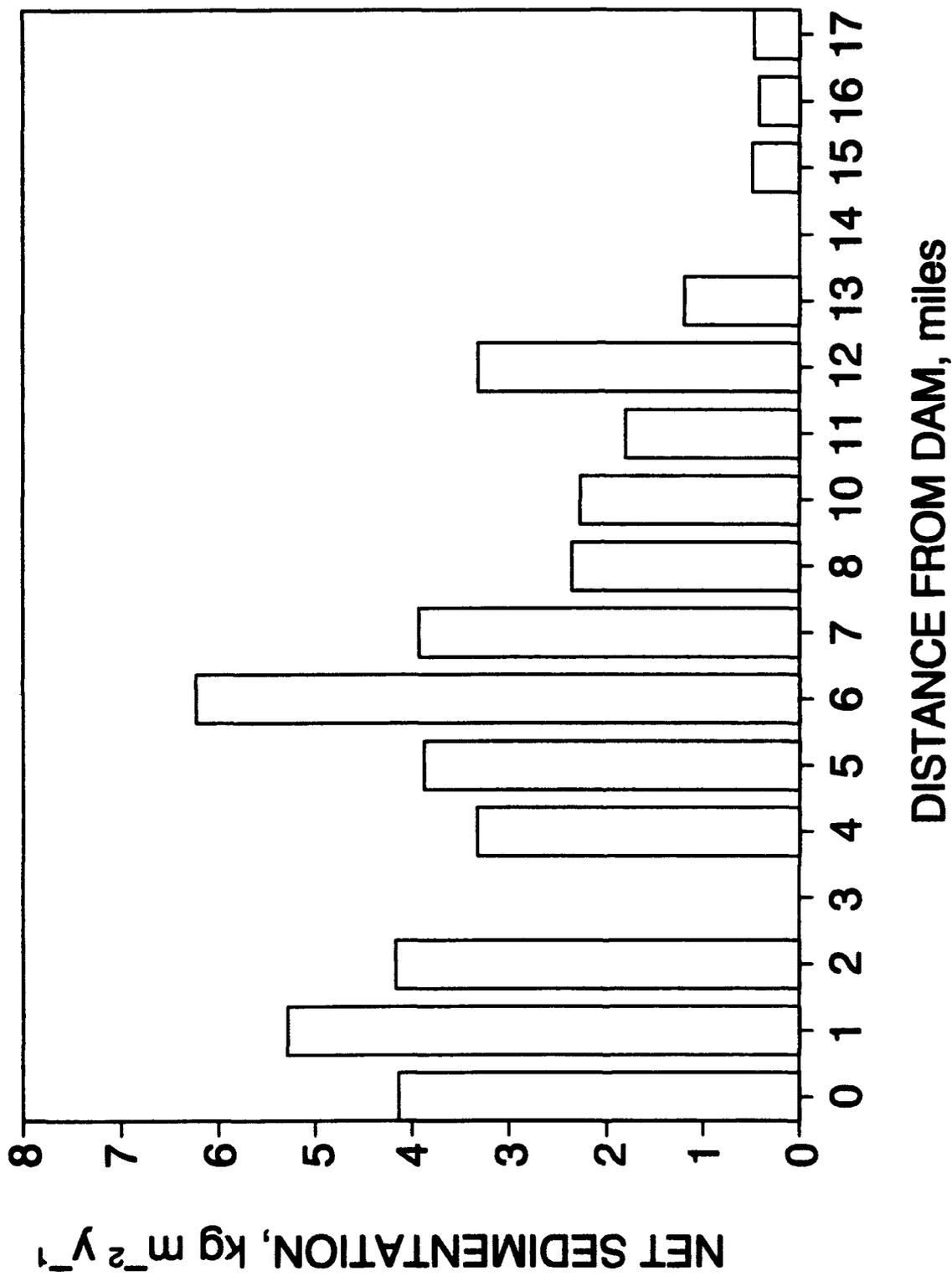
Figure 5. Variations in net sedimentation rates with distance from the dam for stations located within the thalweg
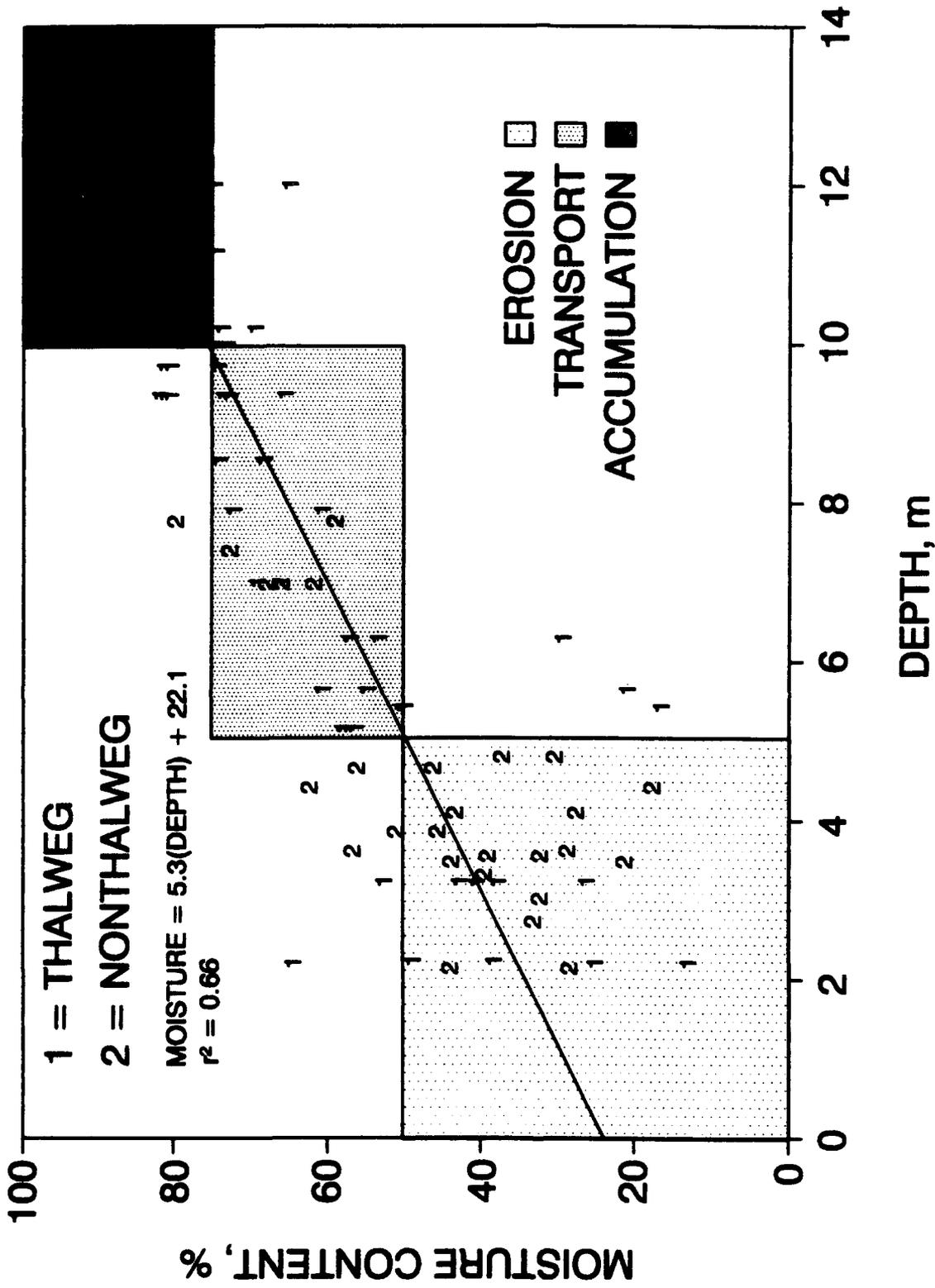
Figure 6. Variations over all dates in moisture content of the surficial sediment with depth for stations located both within and outside the thalweg. Zones of sediment erosion, transport, and accumulation are estimated based on moisture content (see text). 1 = Thalweg, 2 = Nonthalweg
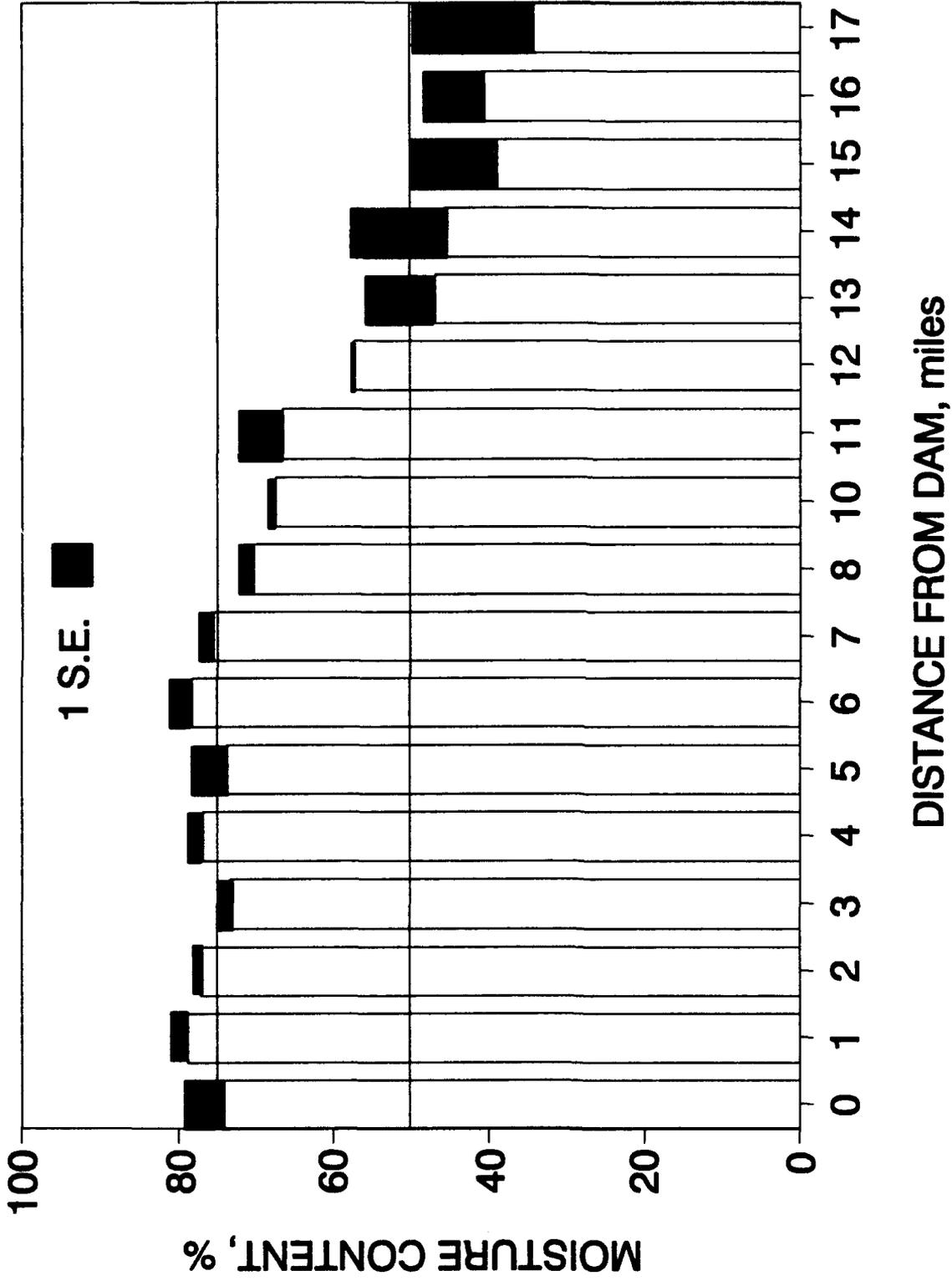
Figure 7. Variations in mean (± 1 S.E.) moisture content of the surficial sediment with distance from the dam for stations located in the thalweg. Zones of sediment erosion, transport, and accumulation are estimated based on moisture content (see text)
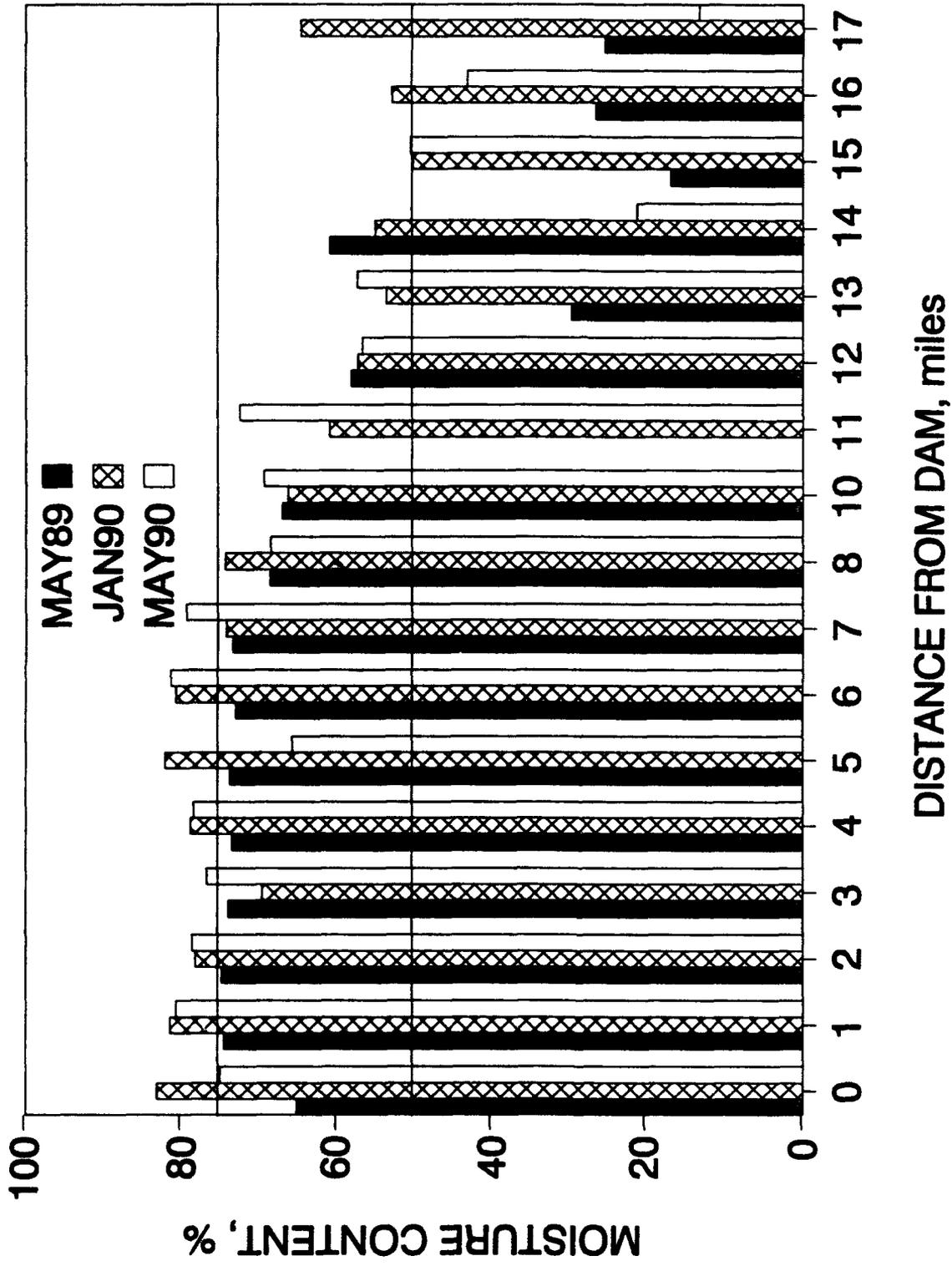
Figure 8. Variations in moisture content of the surficial sediment with distance from the dam during individual sampling dates for stations located in the thalweg
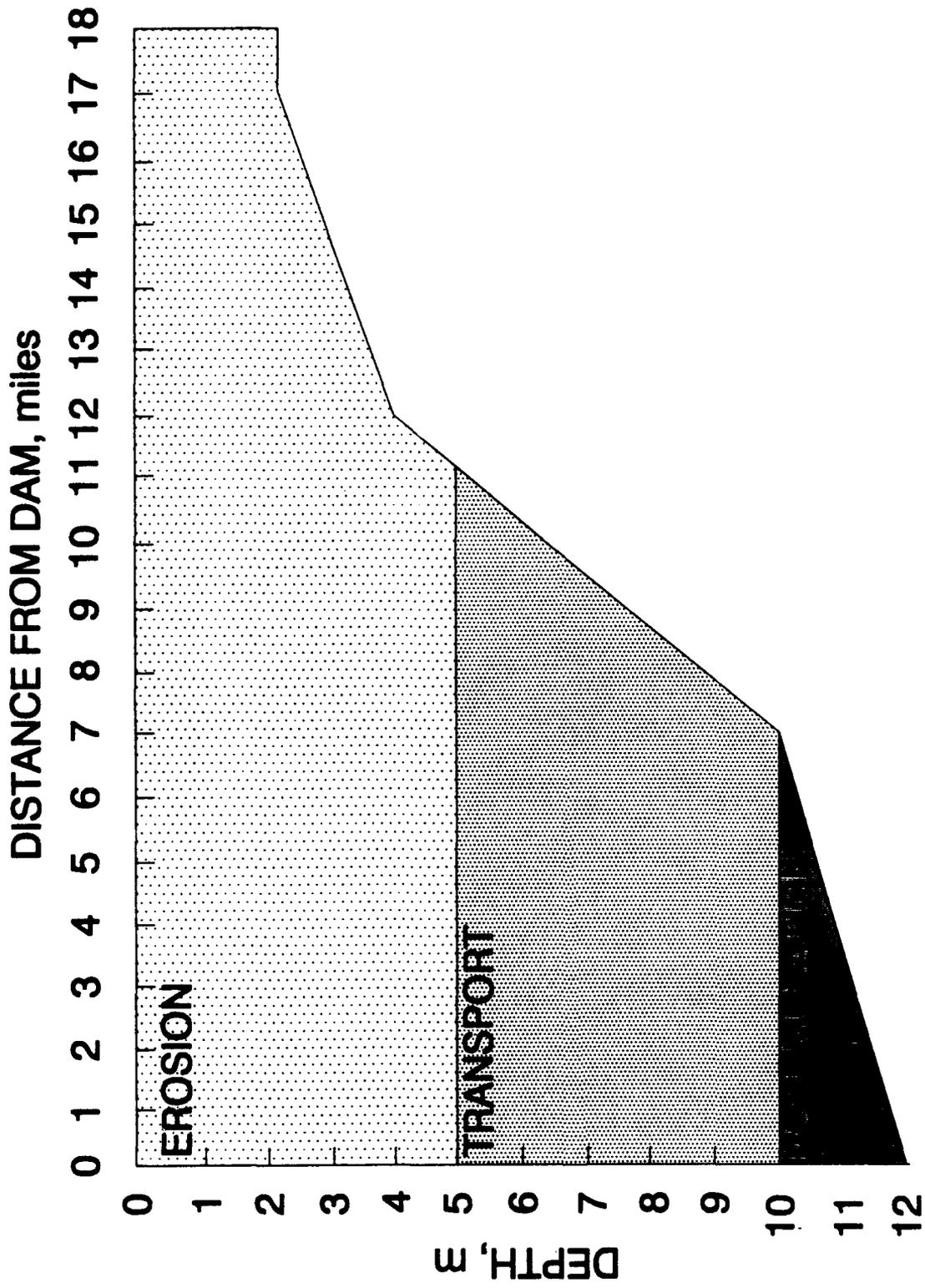
Figure 9. Estimated zones of sediment erosion, transport, and accumulation as a function of both depth and distance from the dam

Figure 10. Density of the surficial sediment in relation to moisture content for stations located within and outside the thalweg
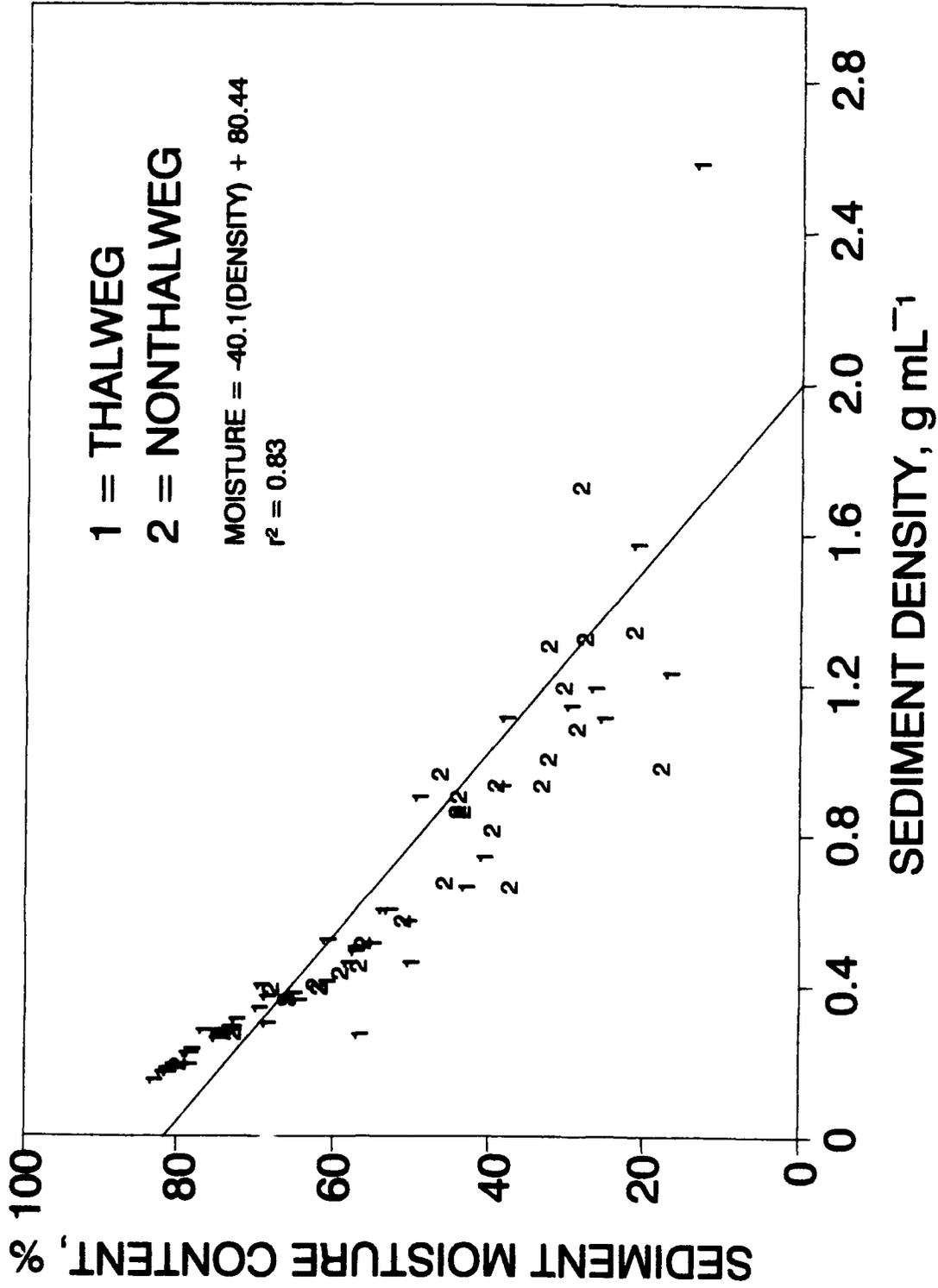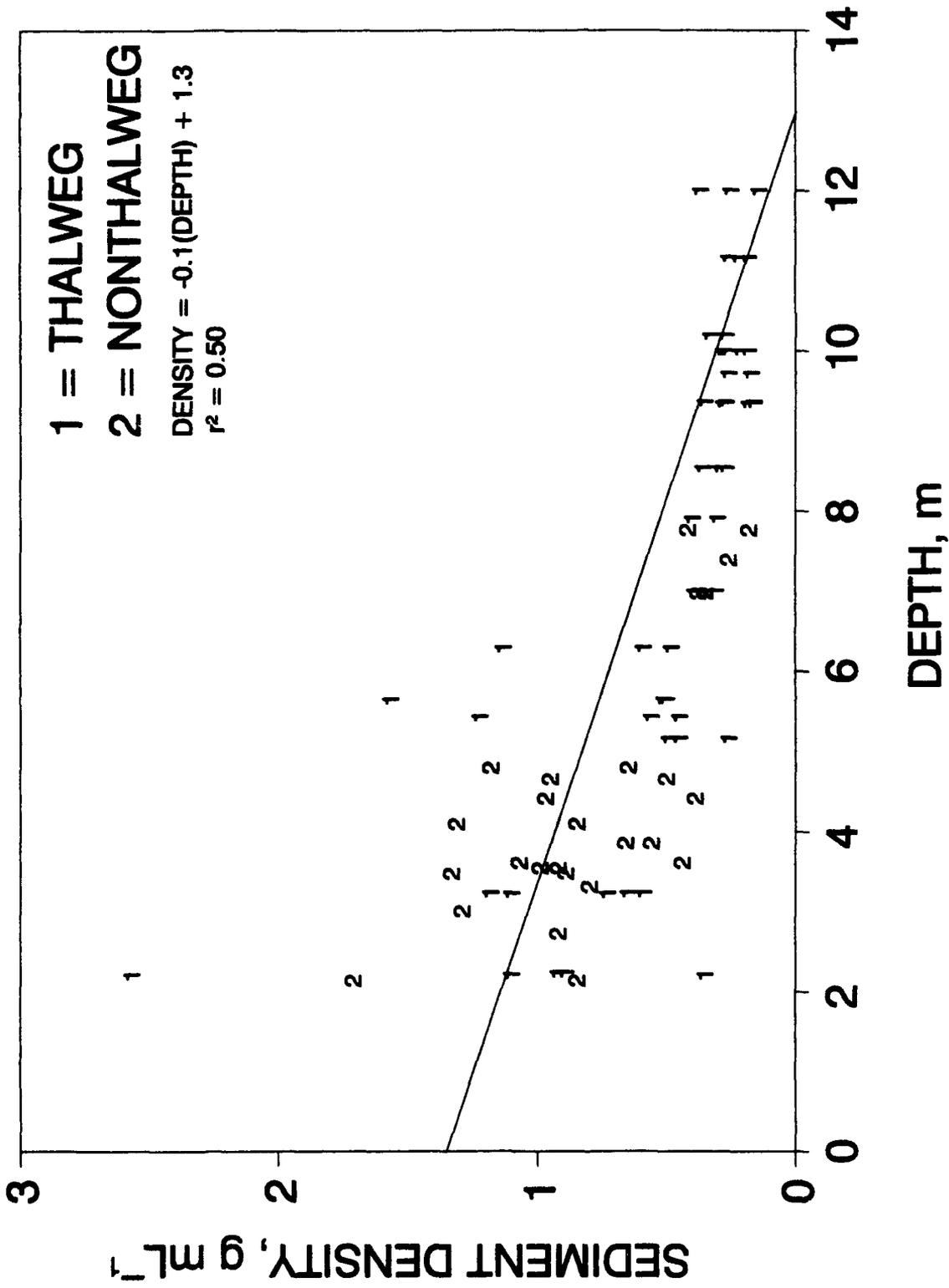
Figure 11. Variations over all dates in density of the surficial sediment with depth for stations located within and outside the thalweg
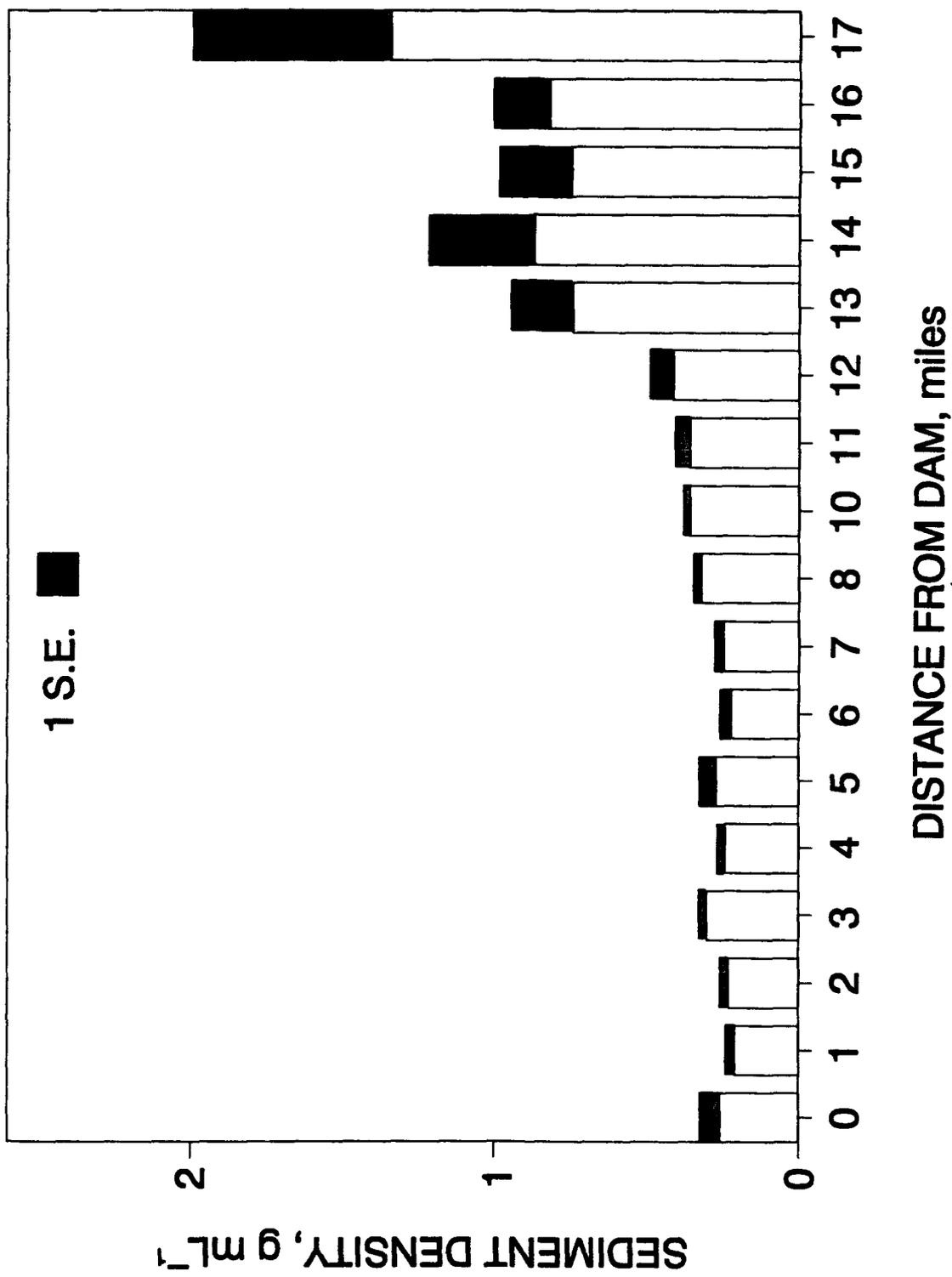
Figure 12. Variations in mean ($\pm$ 1 S.E.) density of the surficial sediment with distance from the dam for stations located in the thalweg
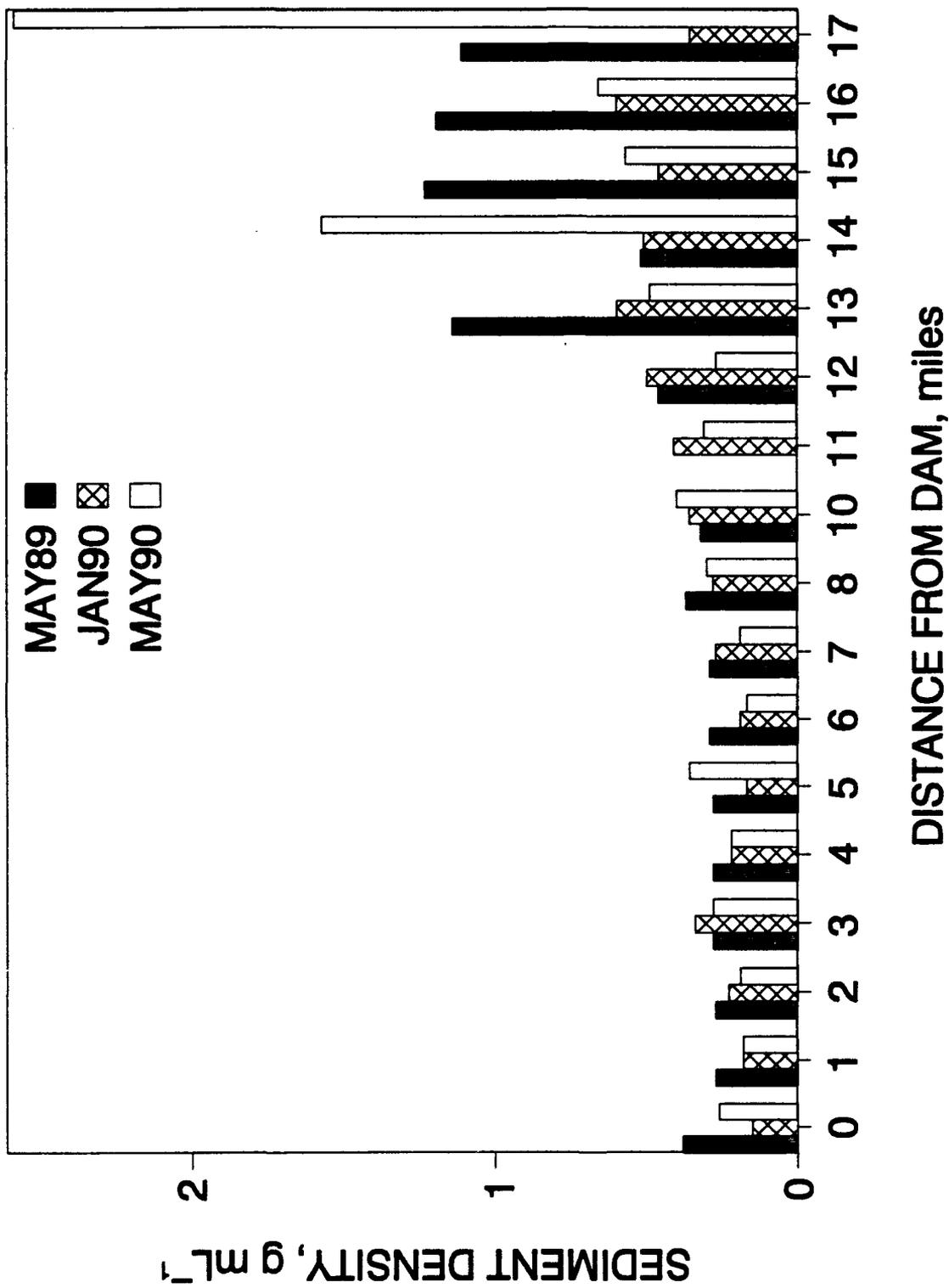
Figure 13. Variations in density of the surficial sediment with distance from the dam during individual sampling dates for stations located in the thalweg

Figure 14. Variations over all dates in organic matter of the surficial sediment with depth for stations located within and outside the thalweg
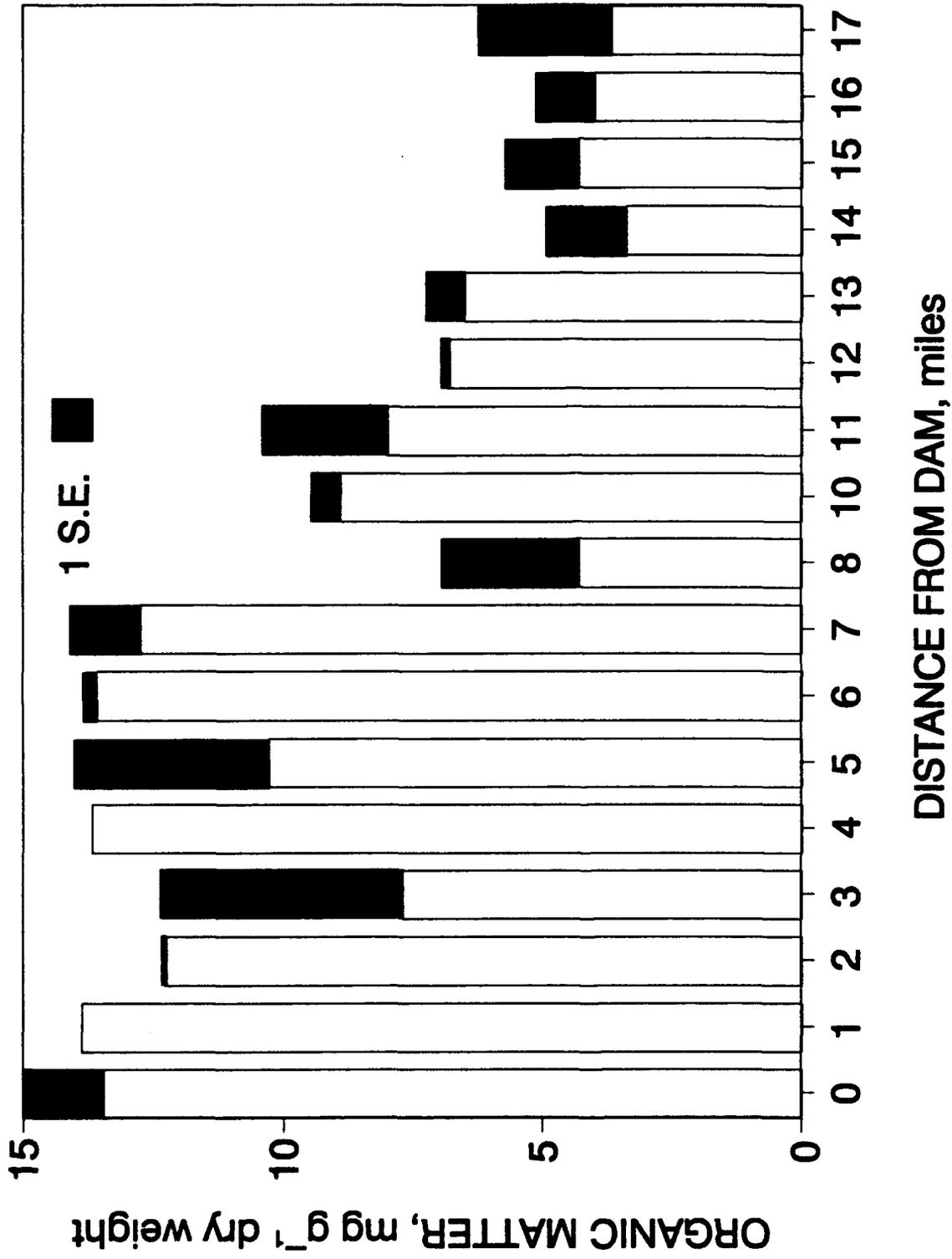
Figure 15. Variations in mean (± 1 S.E.) organic matter of the surficial sediment with distance from the dam for stations located in the thalweg
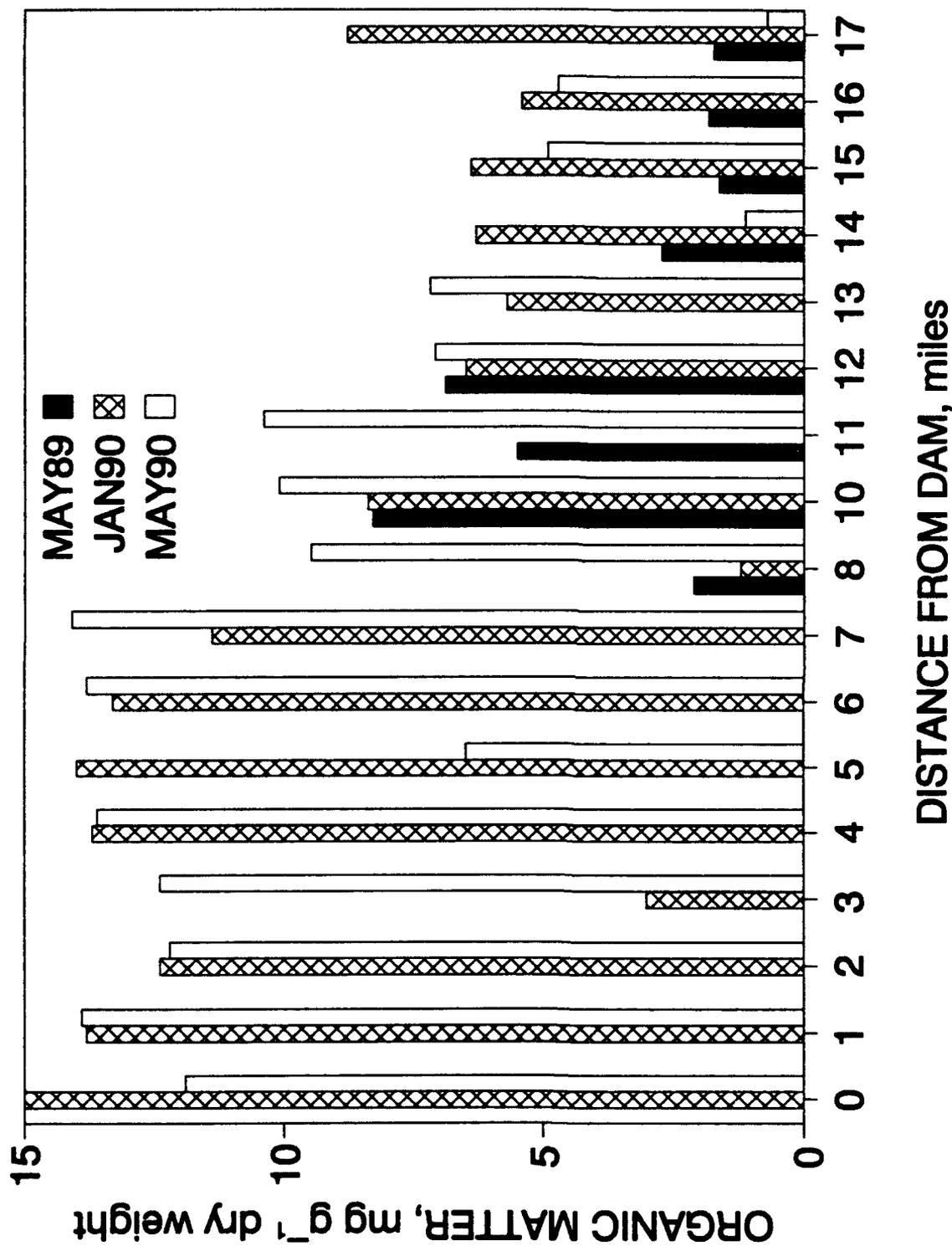
Figure 16. Variations in organic matter of the surficial sediment with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
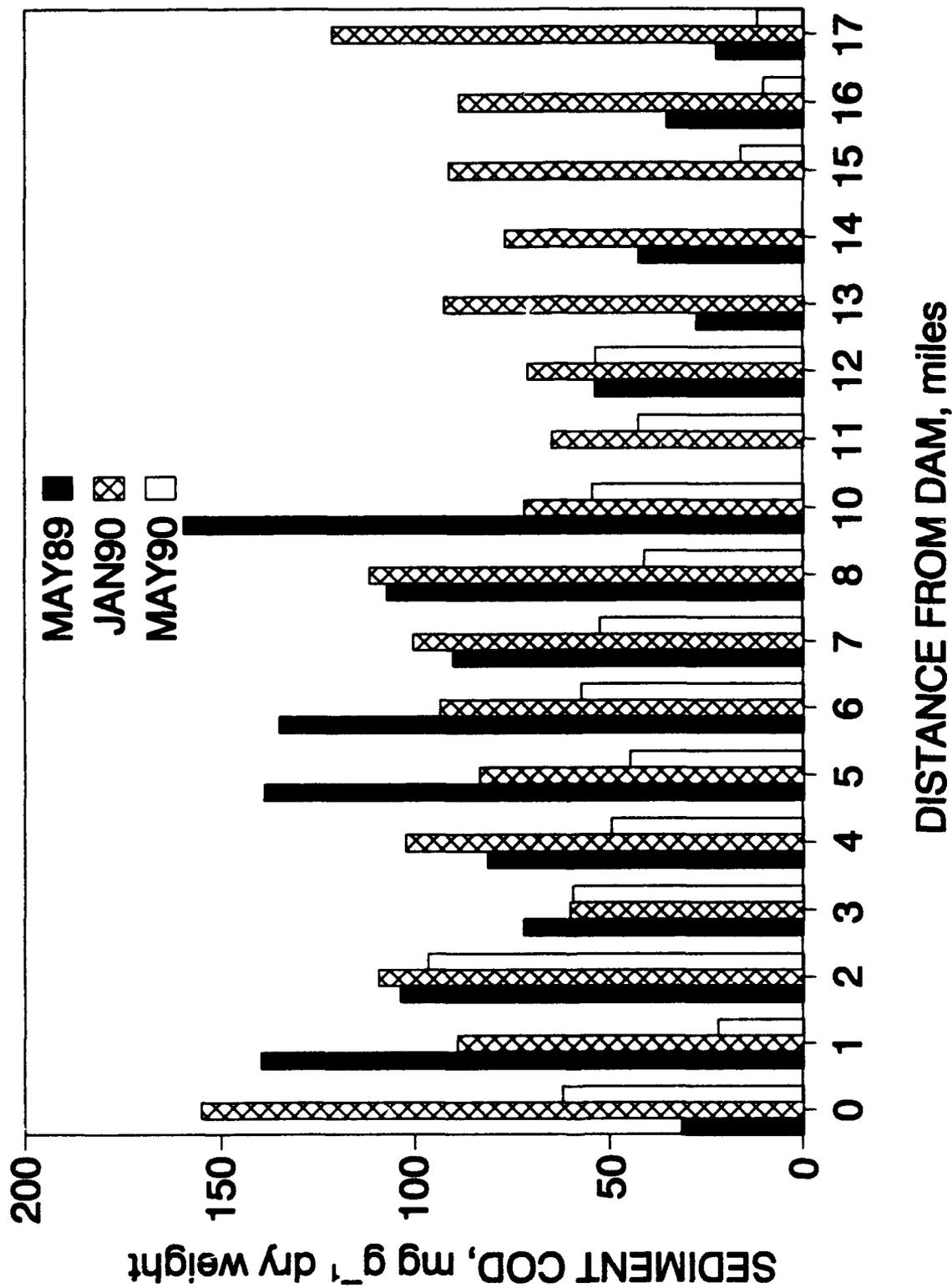
Figure 17. Variations in chemical oxygen demand of the surficial sediment with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
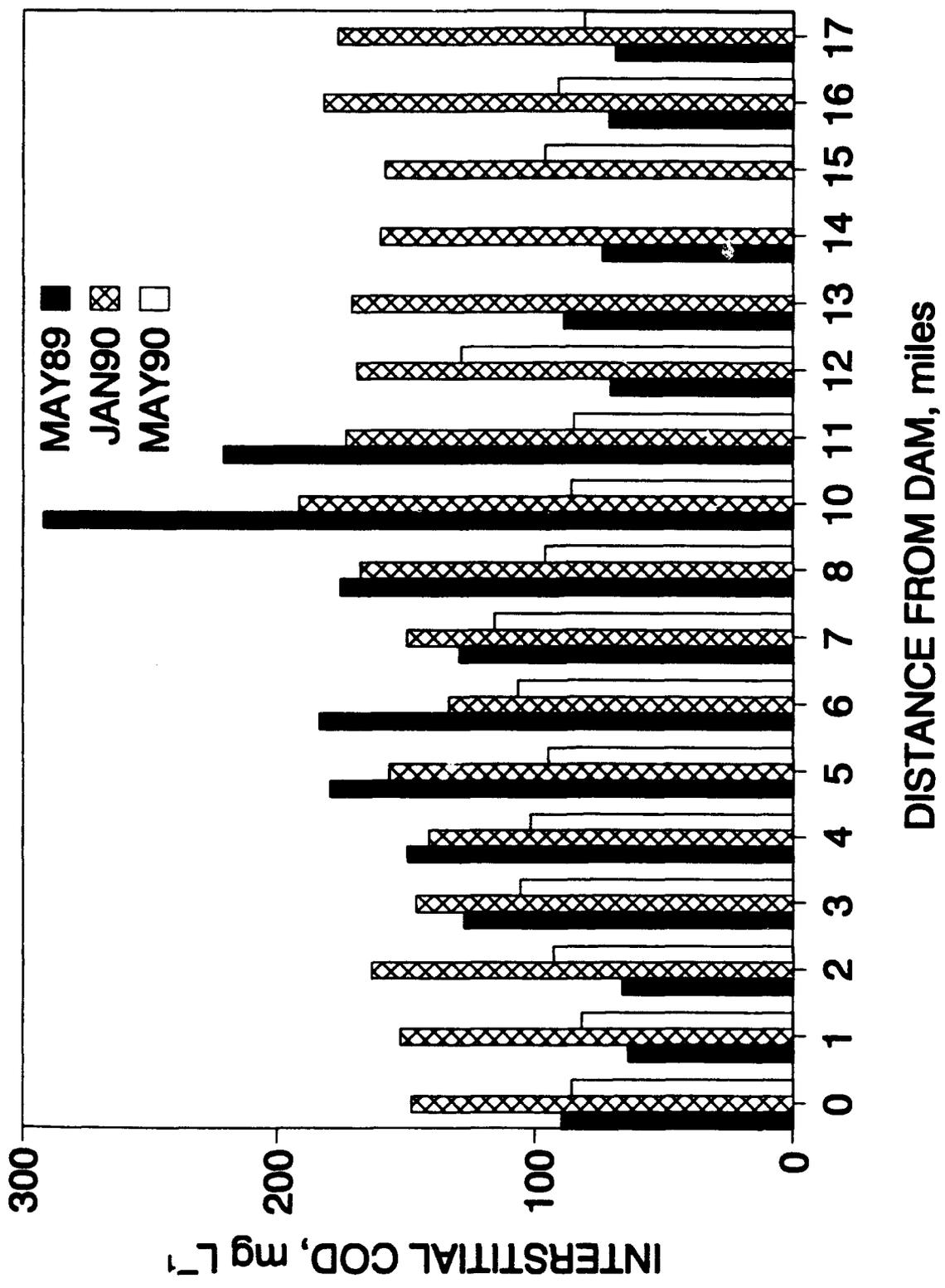
Figure 18. Variations in chemical oxygen demand of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
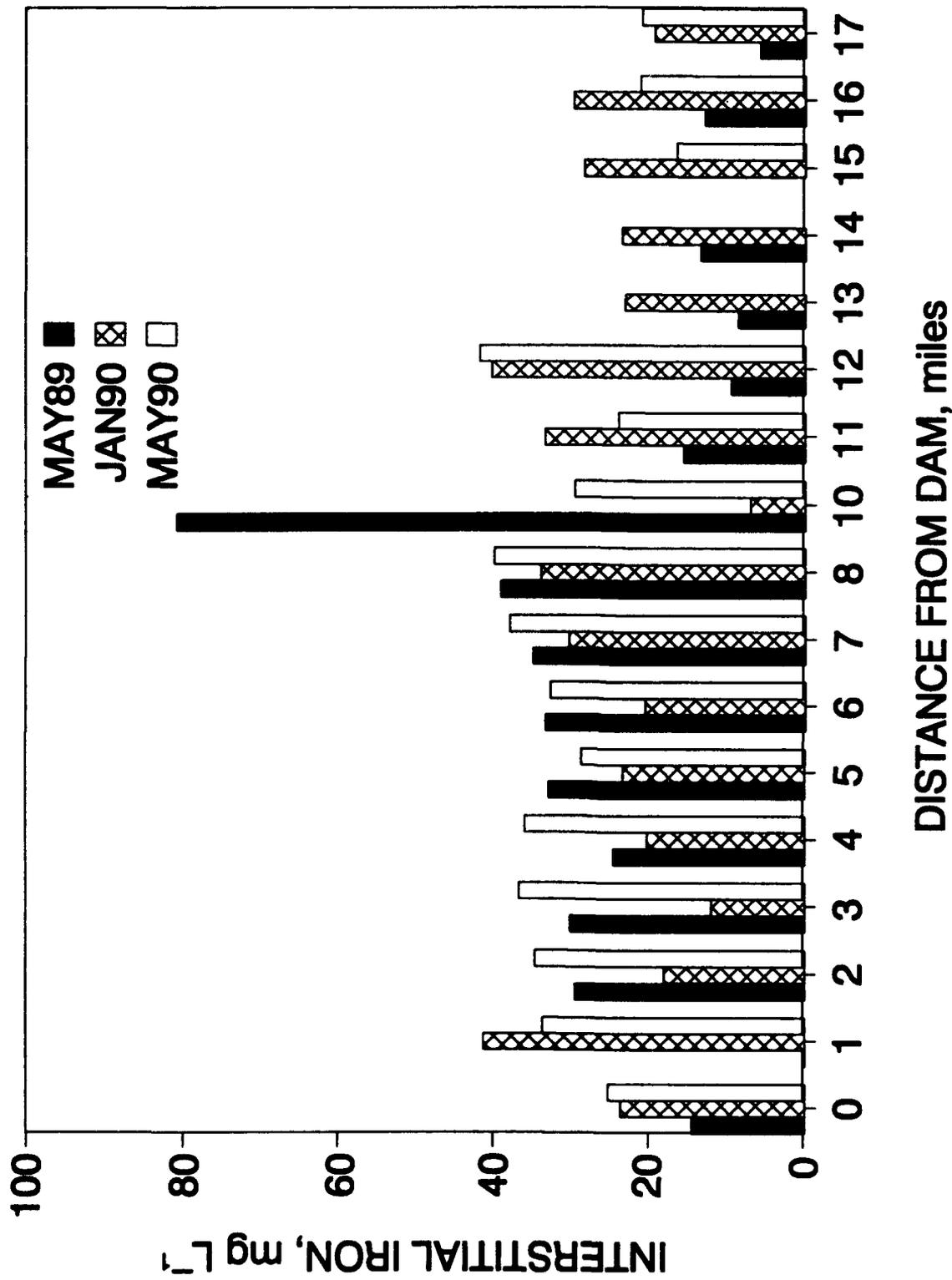
Figure 19. Variations in soluble iron of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
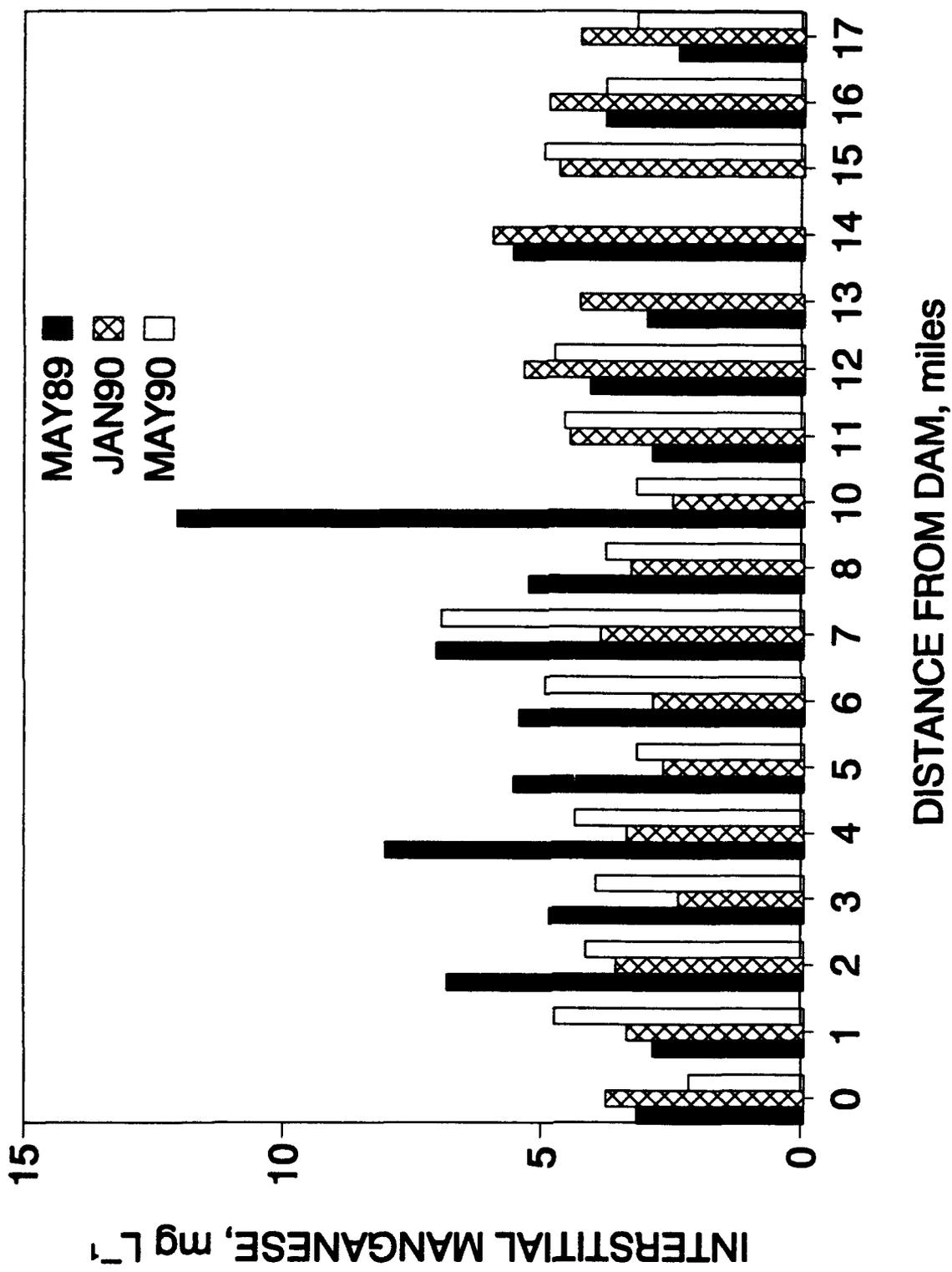
Figure 20.   Variations in soluble manganese of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
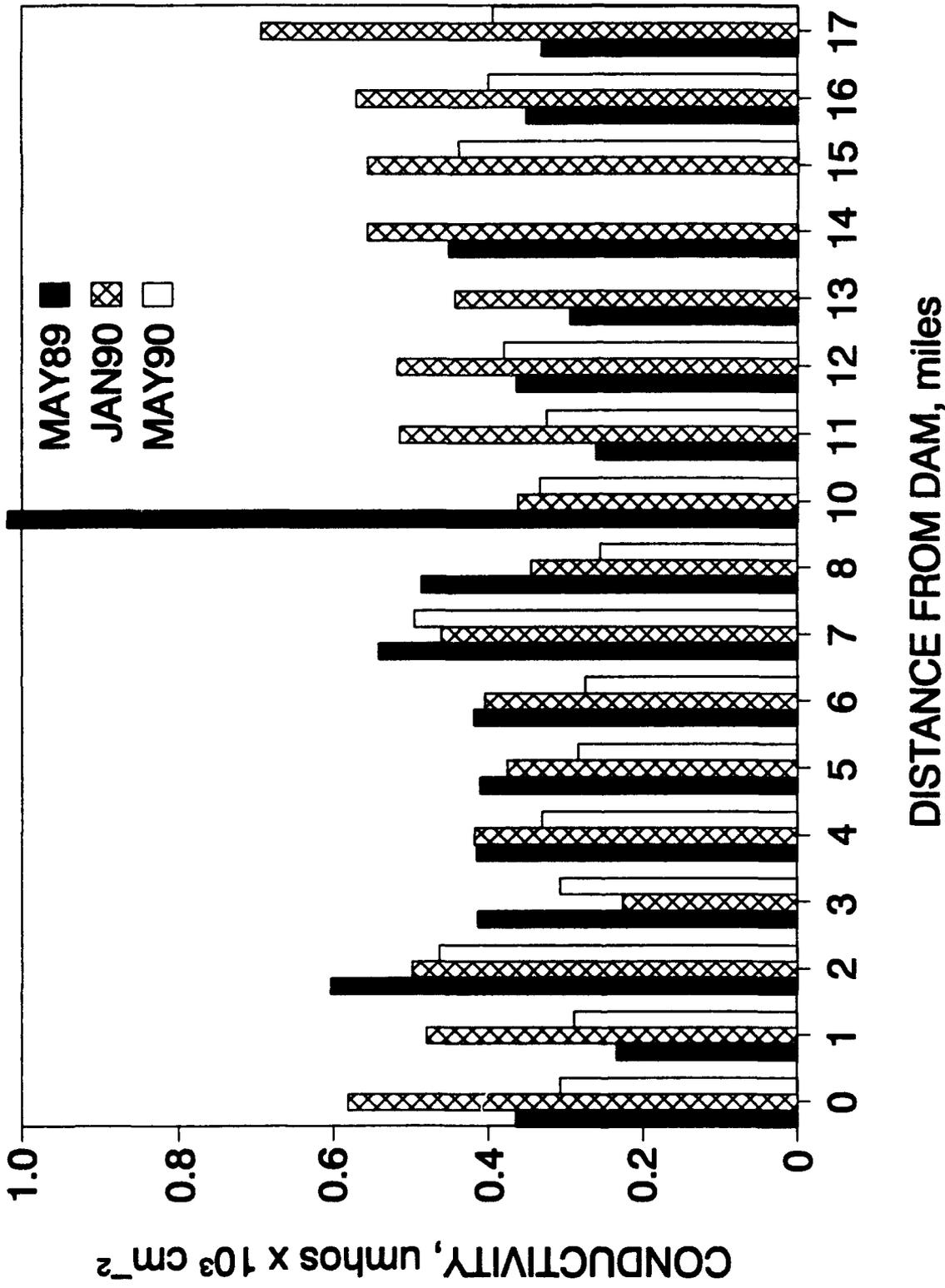
Figure 21. Variations in conductivity of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
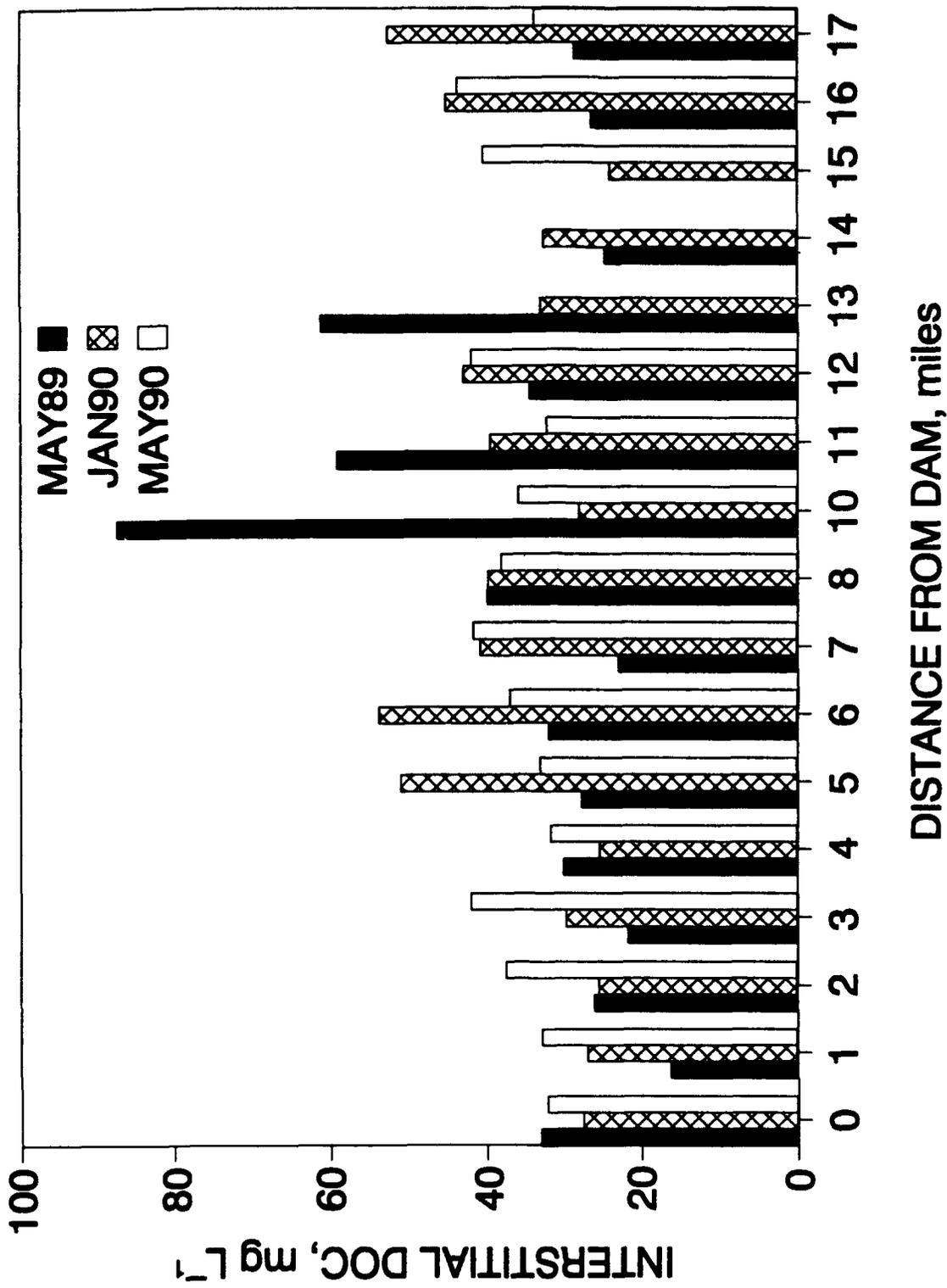
Figure 22. Variations in dissolved organic carbon of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
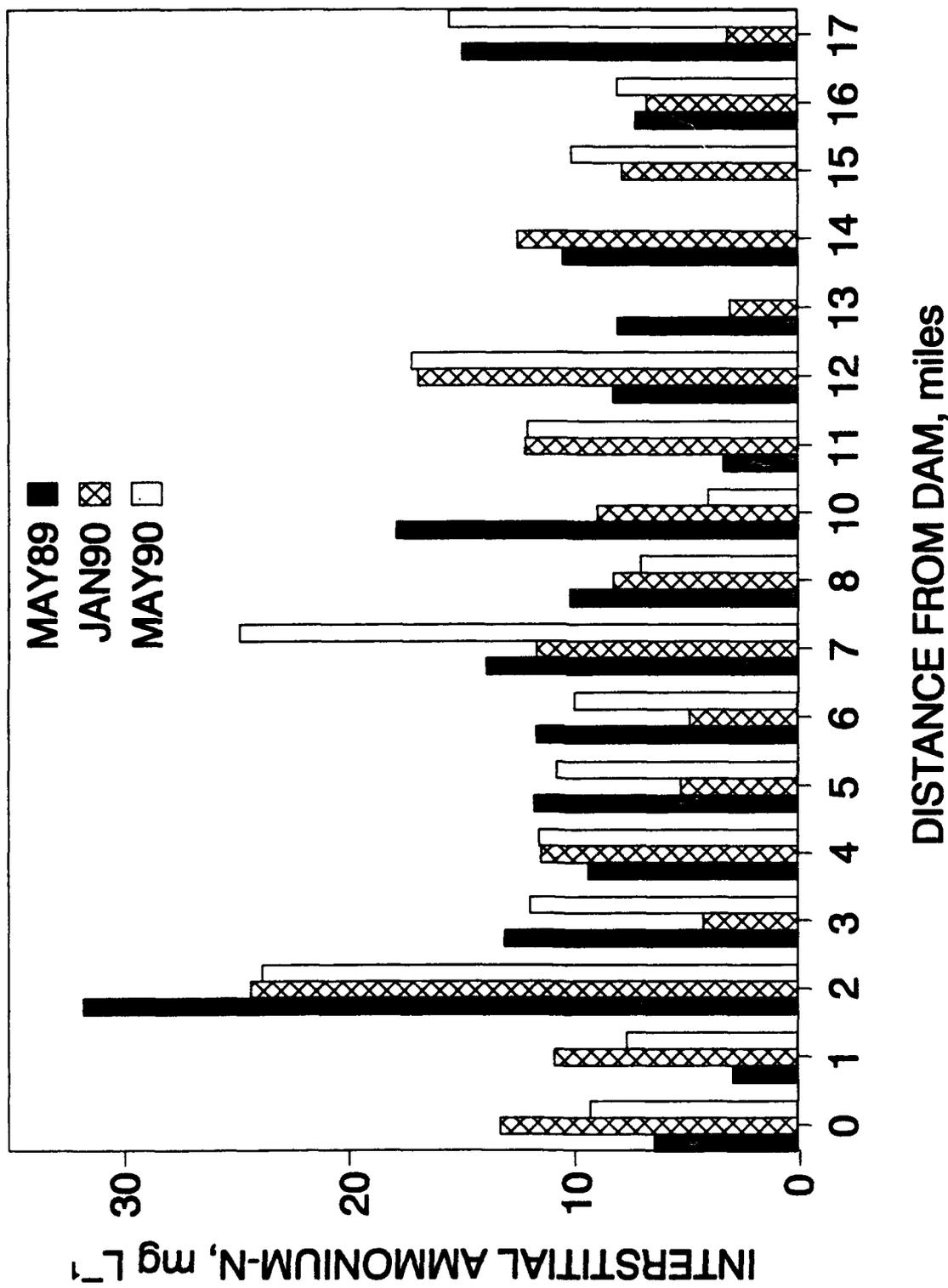
Figure 23. Variations in soluble ammonium-N of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
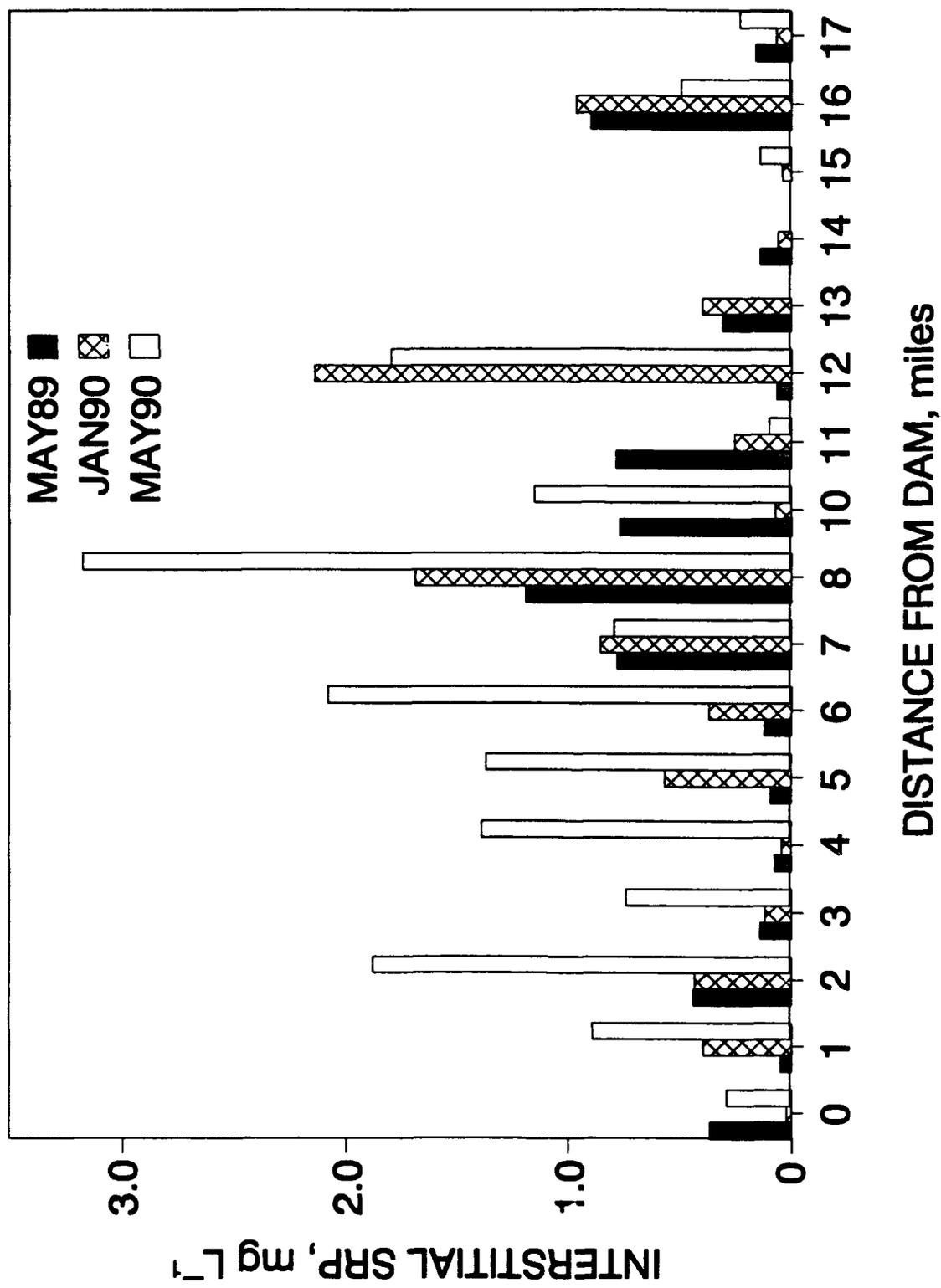
Figure 24. Variations in soluble reactive phosphorus of the interstitial water with distance from the dam during May 1989 and January and May 1990 for stations located in the thalweg
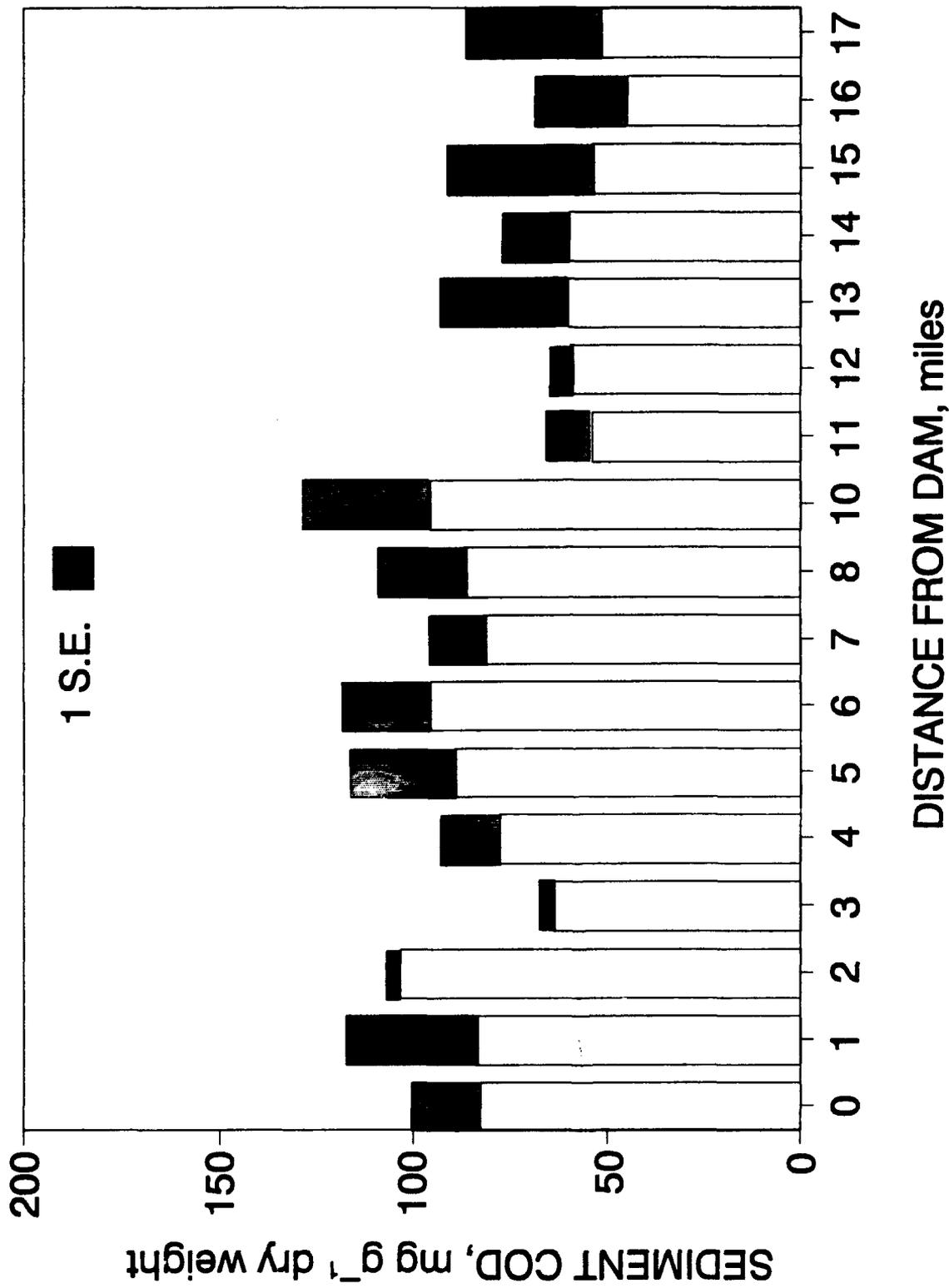
Figure 25.   Variations in mean (± 1 S.E.) chemical oxygen demand of the surficial sediment with distance from the dam for stations located in the thalweg
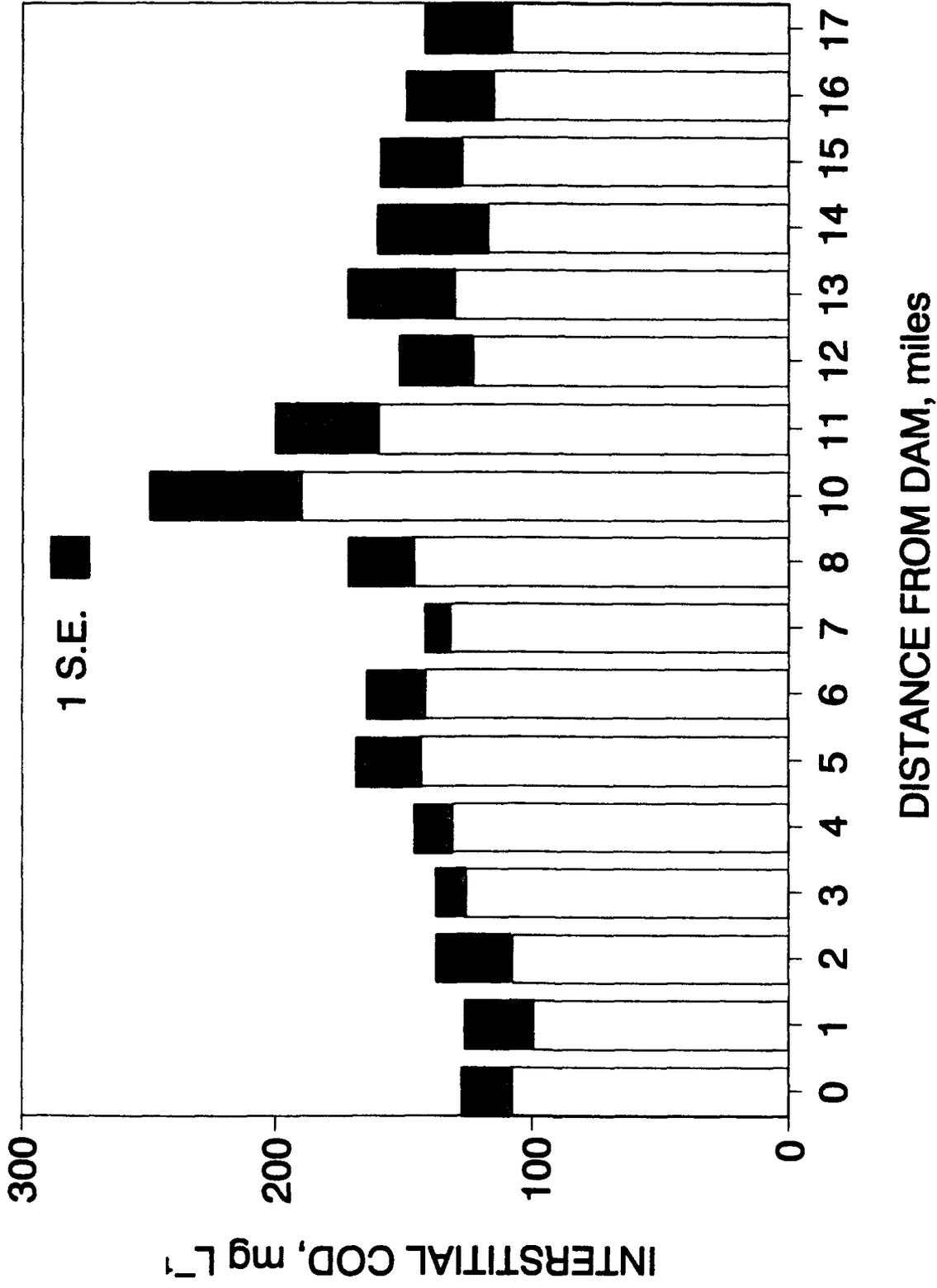
Figure 26. Variations in mean (± 1 S.E.) chemical oxygen demand of the interstitial water with distance from the dam for stations located in the thalweg
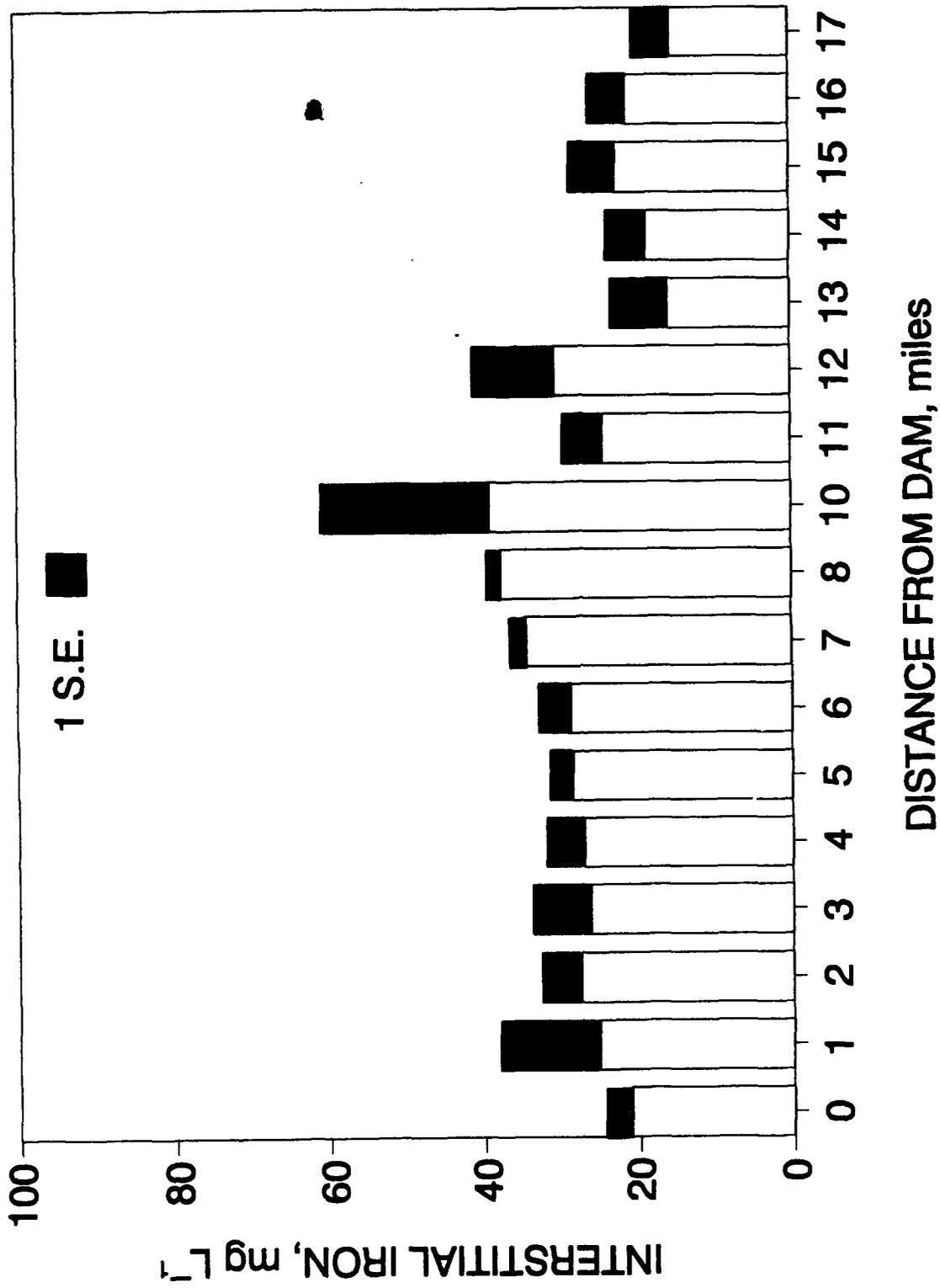
Figure 27. Variations in mean (± 1 S.E.) soluble iron of the interstitial water with distance from the dam for stations located in the thalweg
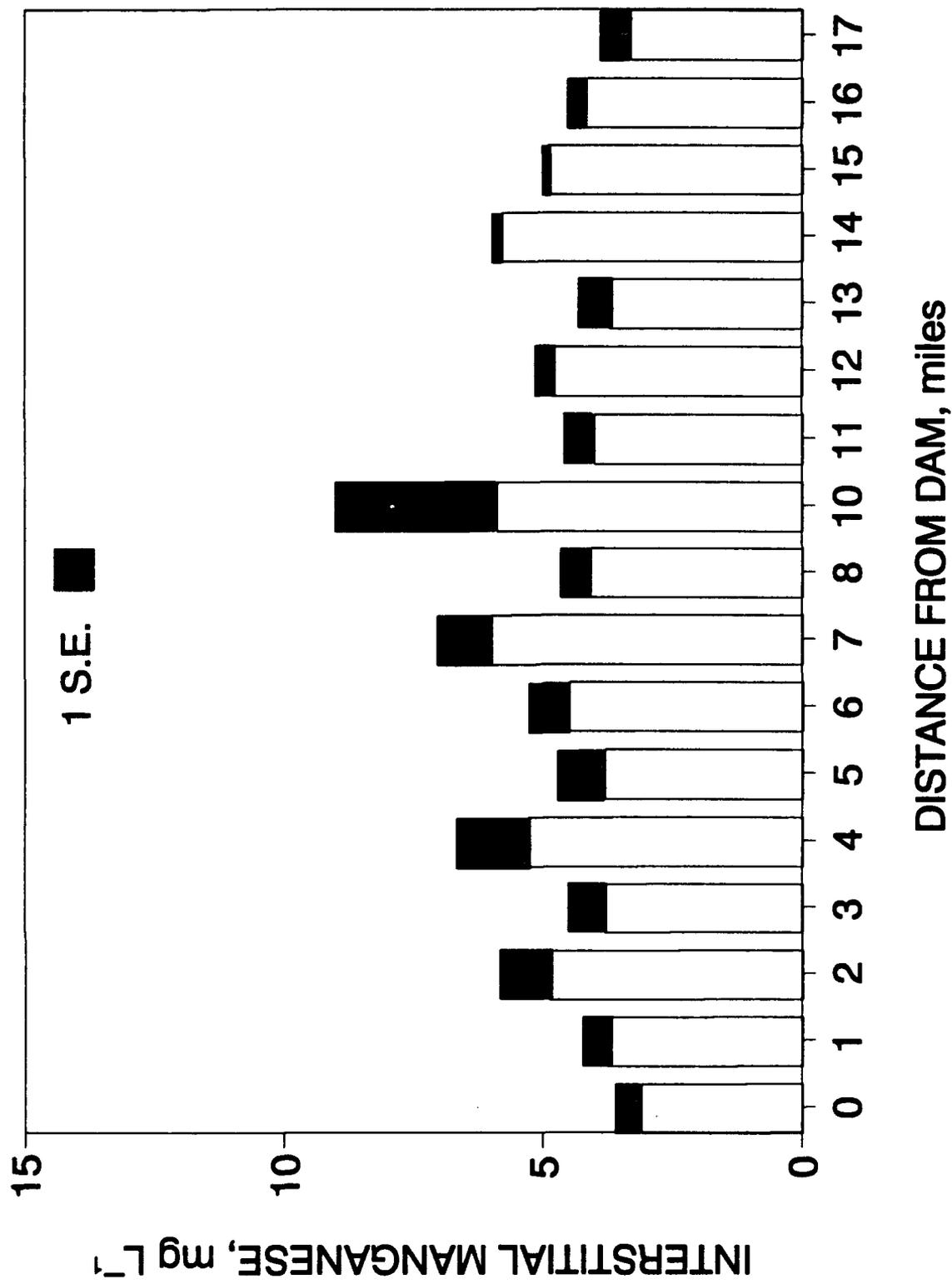
Figure 28. Variations in mean (± 1 S.E.) soluble manganese of the interstitial water with distance from the dam for stations located in the thalweg
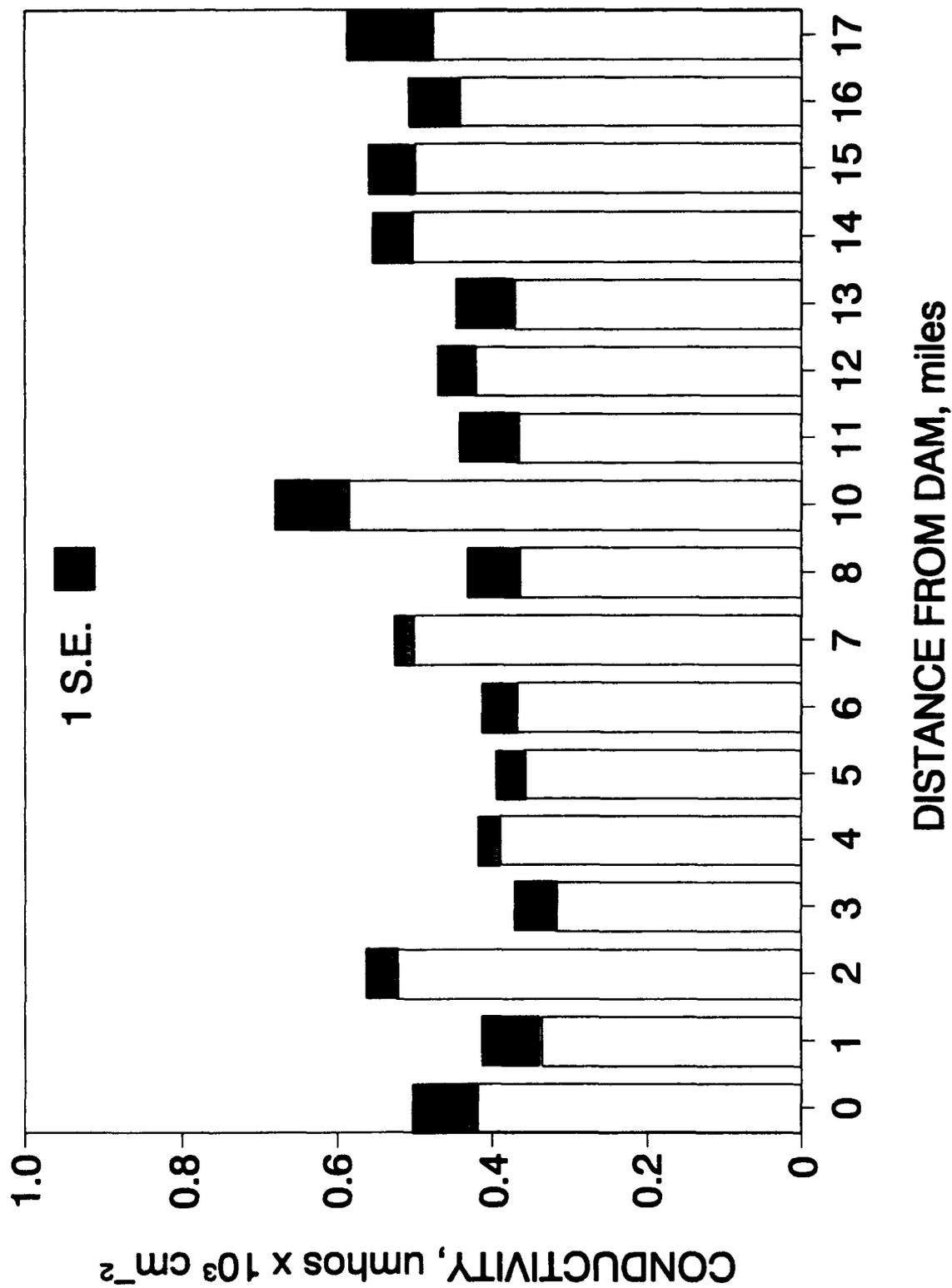
Figure 29. Variations in mean (± 1 S.E.) conductivity of the interstitial water with distance from the dam for stations located in the thalweg
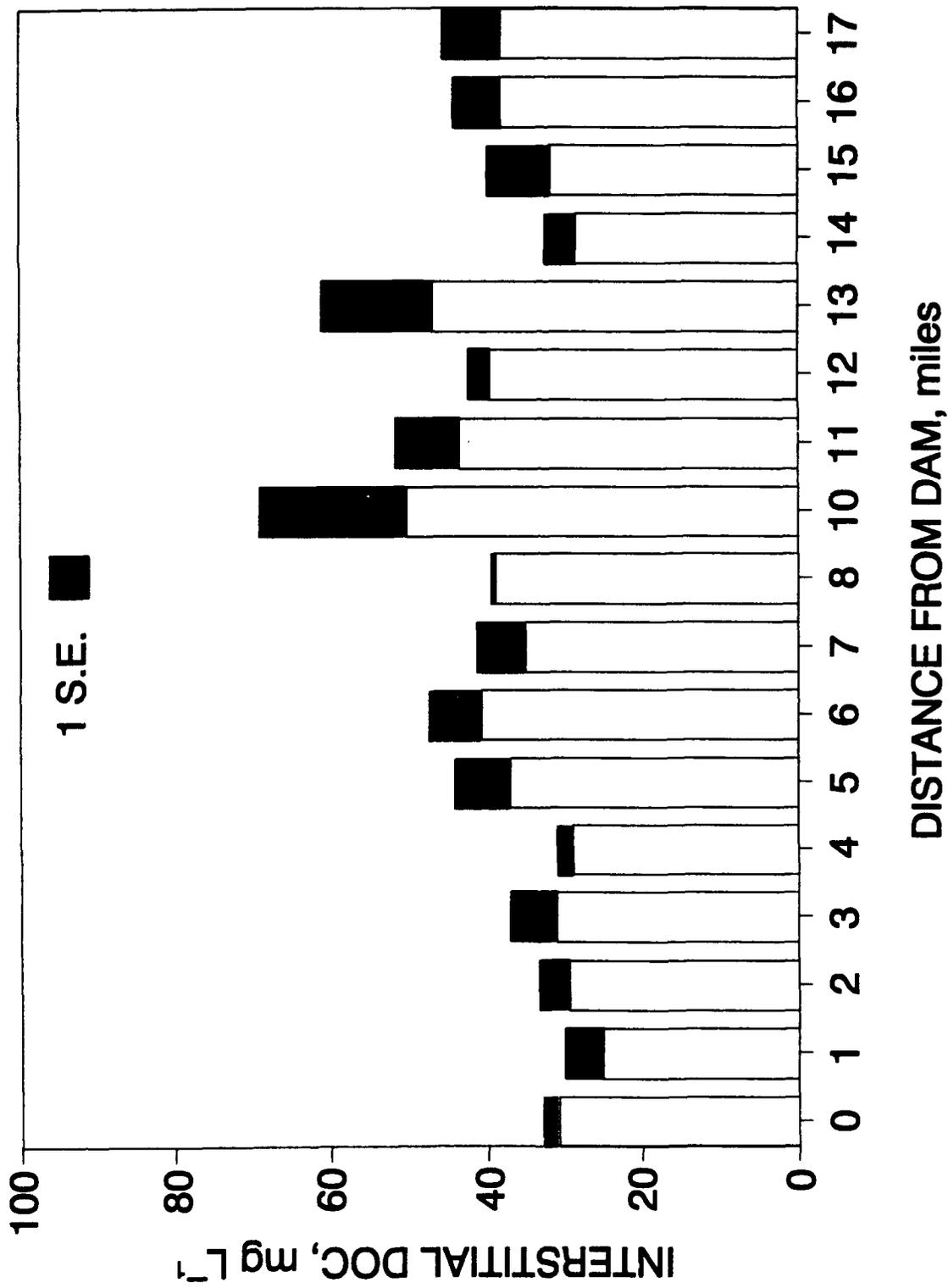
Figure 30. Variations in mean (± 1 S.E.) dissolved organic carbon of the interstitial water with distance from the dam for stations located in the thalweg
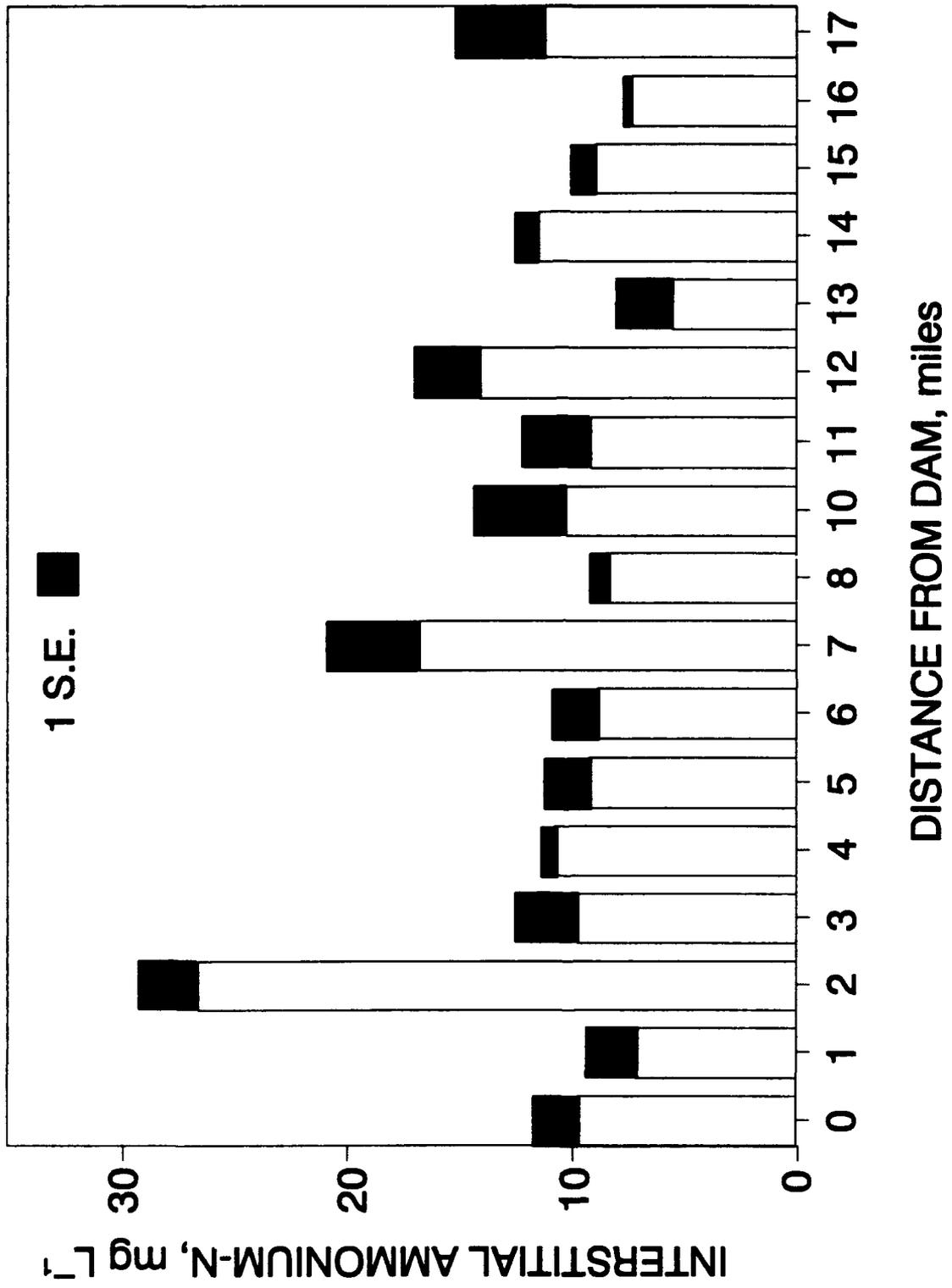
Figure 31. Variations in mean ($\pm$ 1 S.E.) soluble ammonium-N of the interstitial water with distance from the dam for stations located in the thalweg
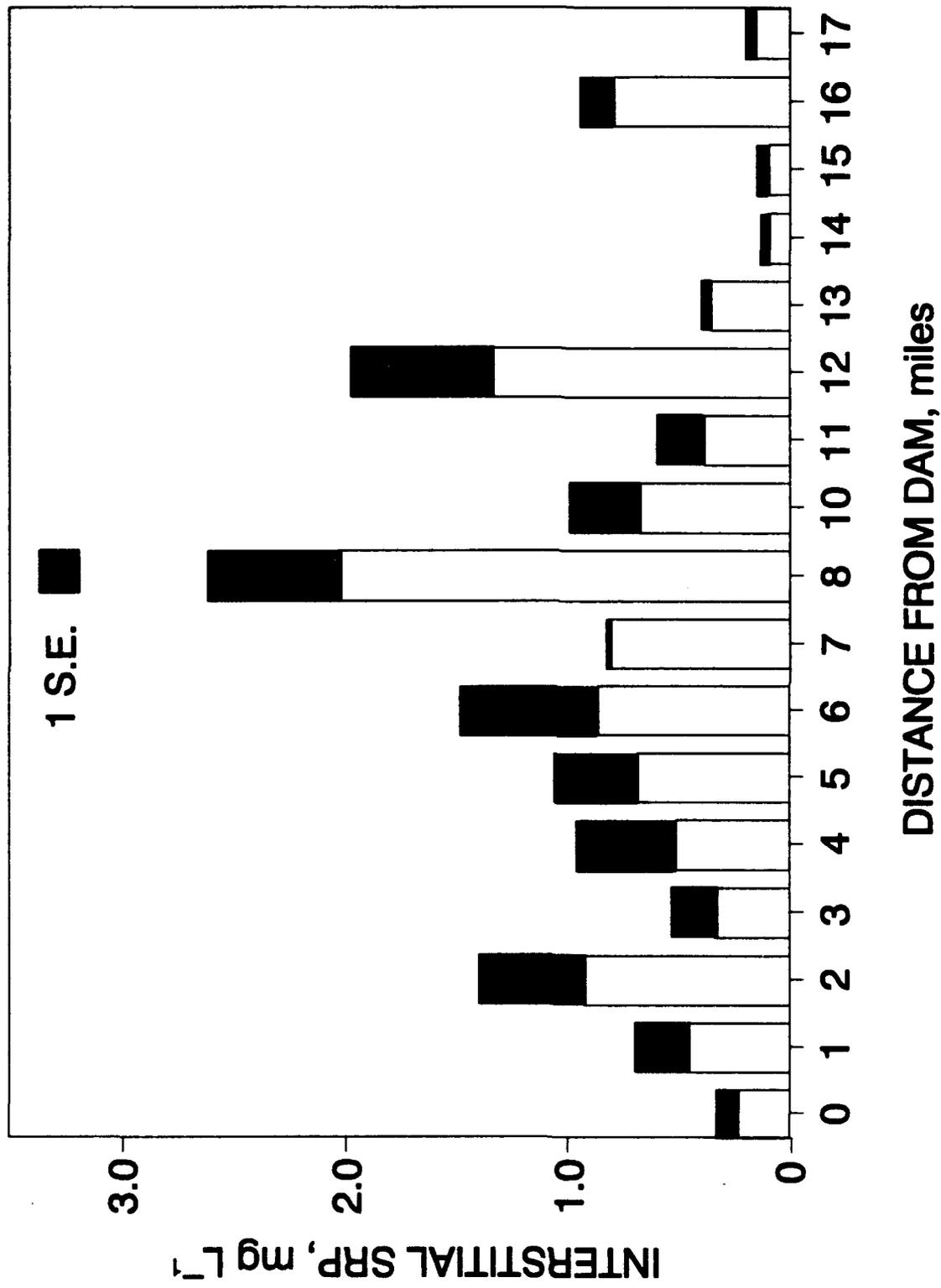
Figure 32. Variations in mean ($\pm$ 1 S.E.) soluble reactive phosphorus of the interstitial water with distance from the dam for stations located in the thalweg

WINTER TO SPRING 1974

WINTER TO SPRING 1975

WINTER TO SPRING 1976

WINTER TO SPRING 1977

DISTANCE FROM DAM, MILES
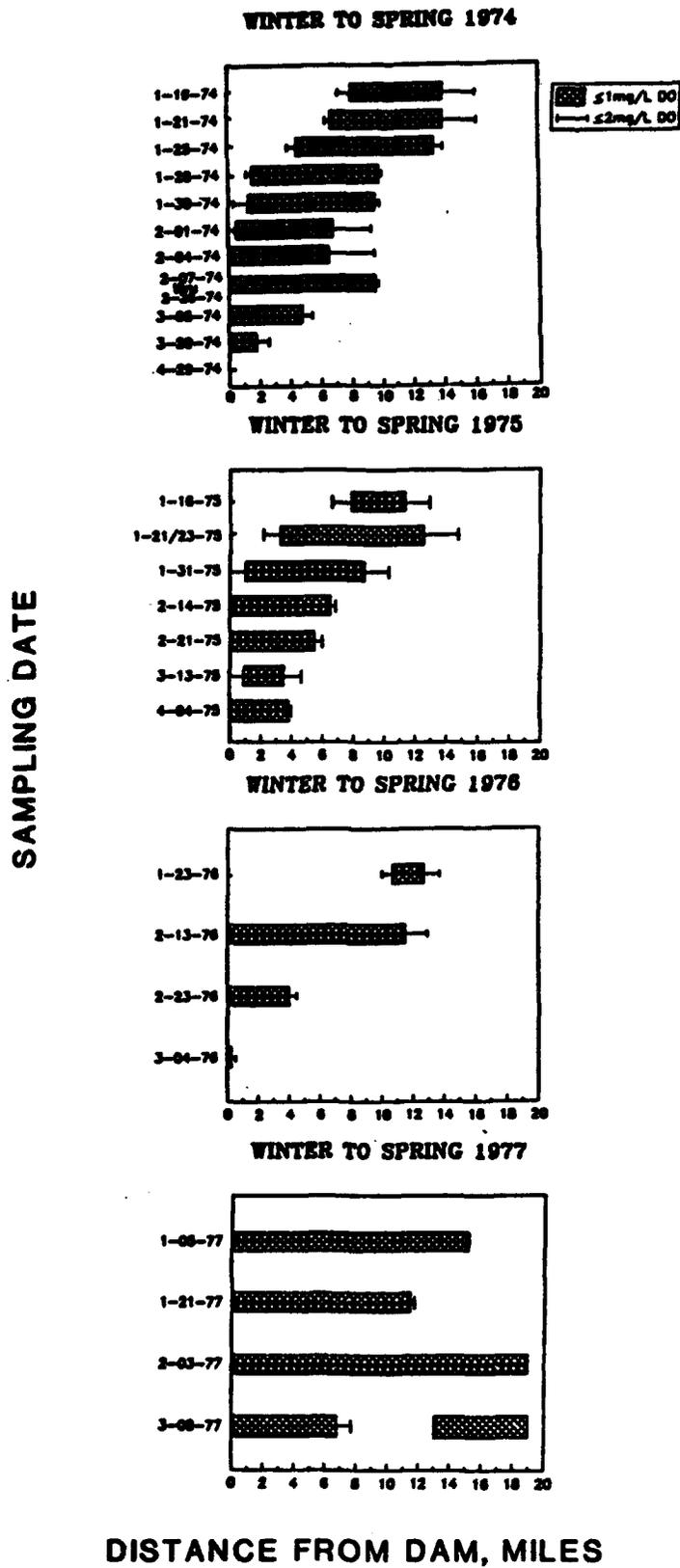
Figure 33. Longitudinal position of dissolved oxygen levels (≤ 1 and ≤ 2 mg L^{-1} DO) along the bottom of the reservoir during winter (from Gunnison and Barko 1988) (Sheet 1 of 4)

WINTER TO SPRING 1978
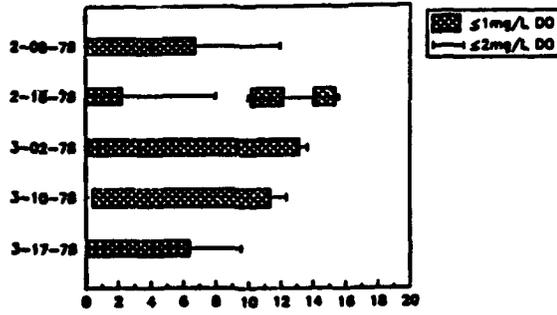
WINTER TO SPRING 1979
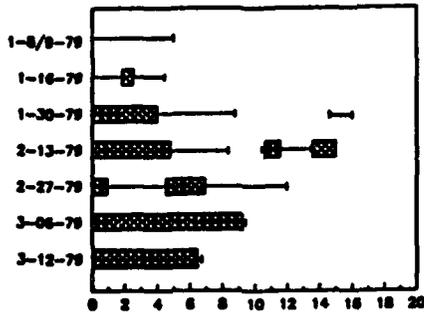
WINTER TO SPRING 1980
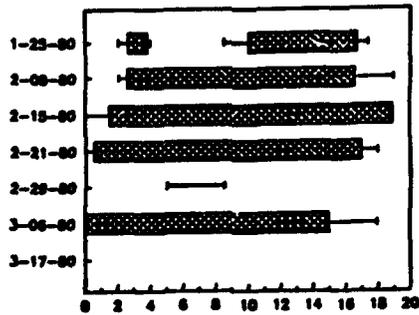
WINTER TO SPRING 1981

SAMPLING DATE

DISTANCE FROM DAM, MILES

Figure 33.   (Sheet 2 of 4)

WINTER TO SPRING 1982

WINTER TO SPRING 1983

WINTER TO SPRING 1984

WINTER TO SPRING 1985

SAMPLING DATE

DISTANCE FROM DAM, MILES

Figure 33.   (Sheet 3 of 4)

WINTER TO SPRING 1986

WINTER TO SPRING 1987

WINTER TO SPRING 1988

SAMPLING DATE
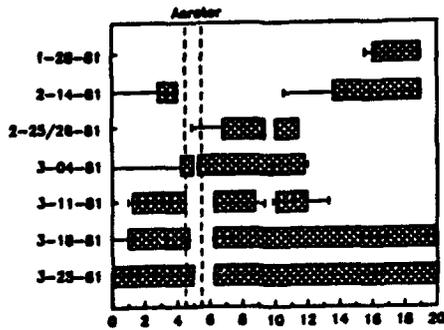
DISTANCE FROM DAM, MILES
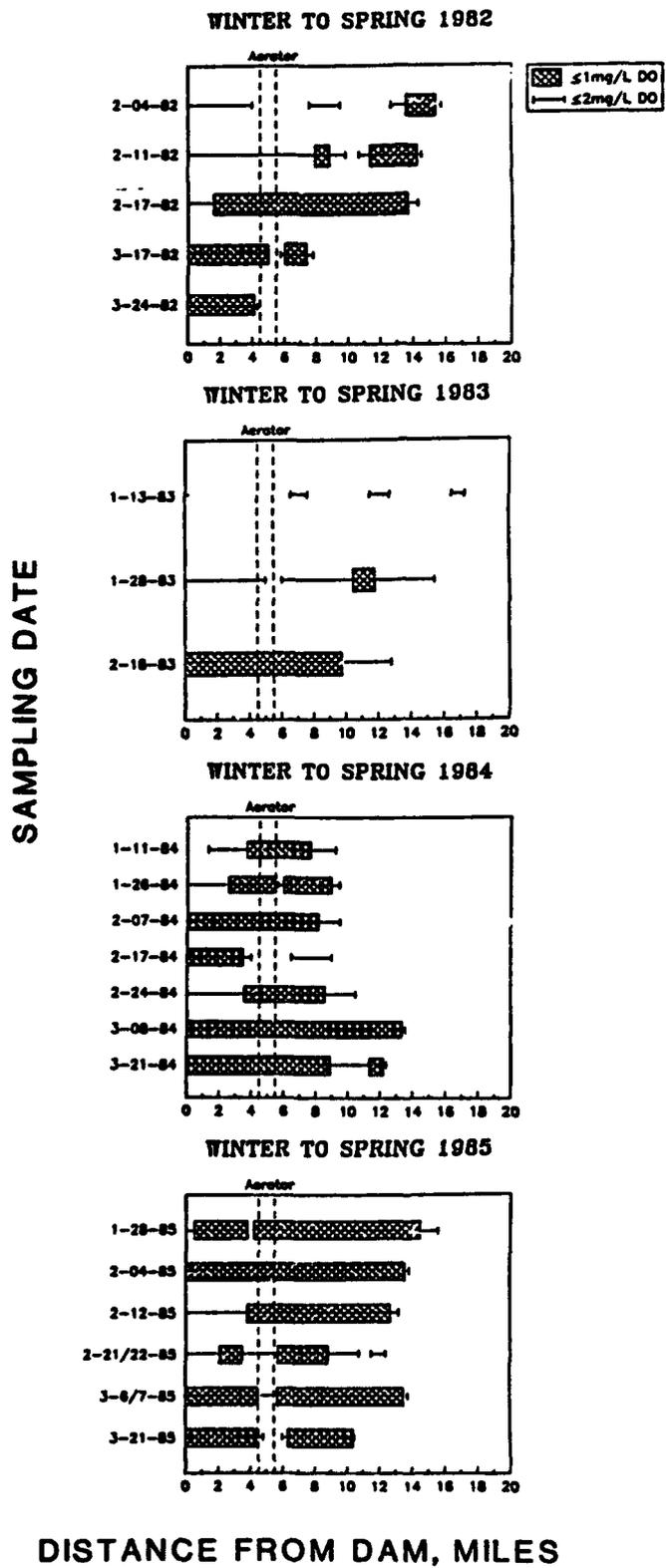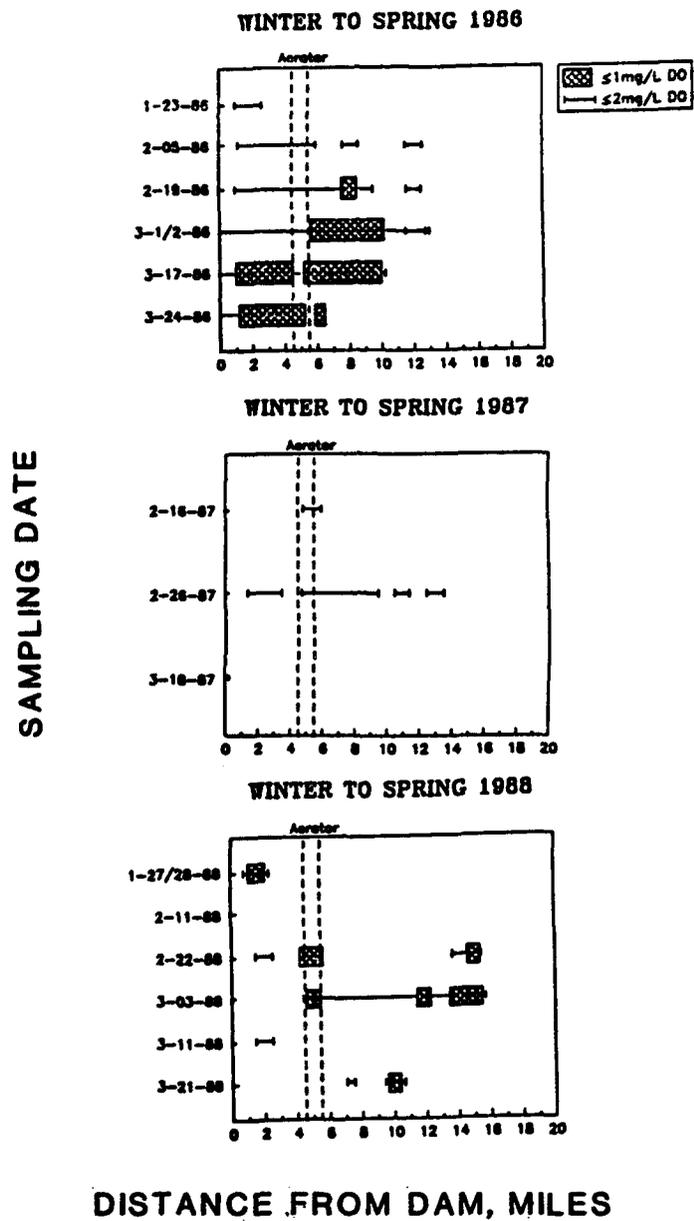
Figure 33.   (Sheet 4 of 4)
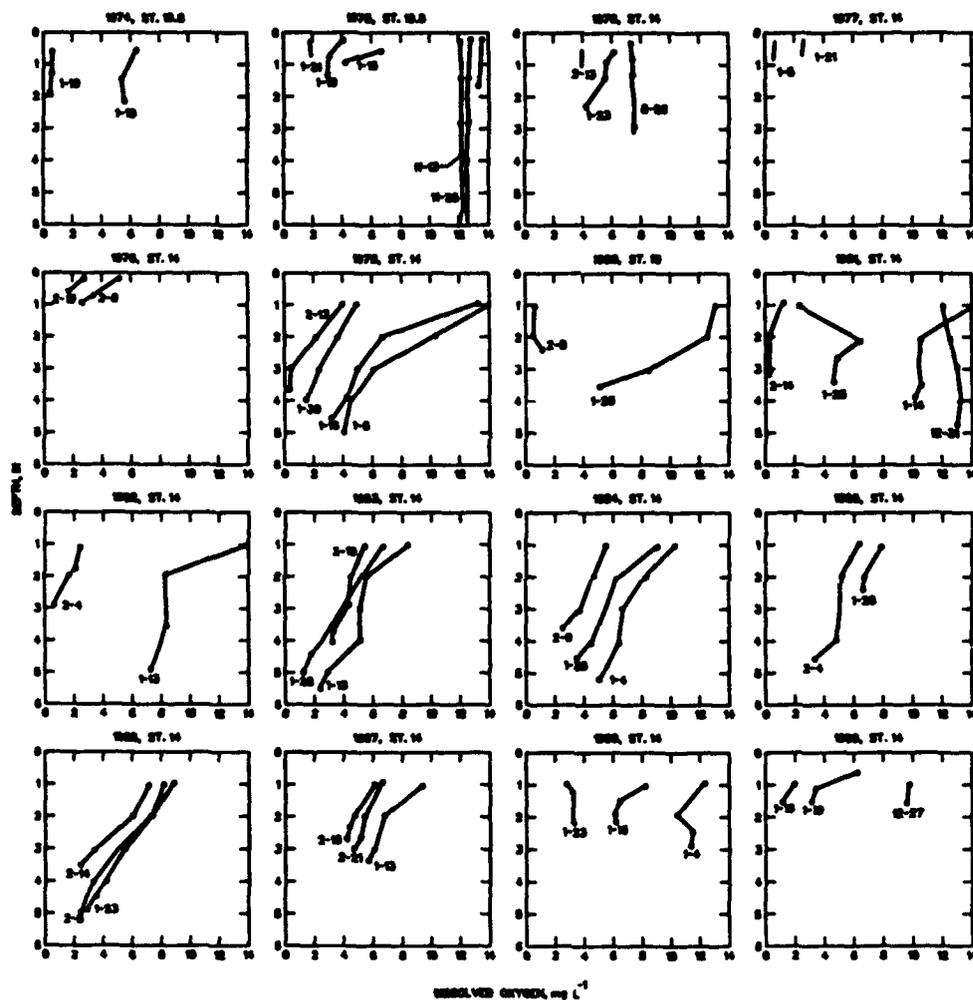
Figure 34. Vertical variations in dissolved oxygen over time at stations located in the headwaters of the reservoir
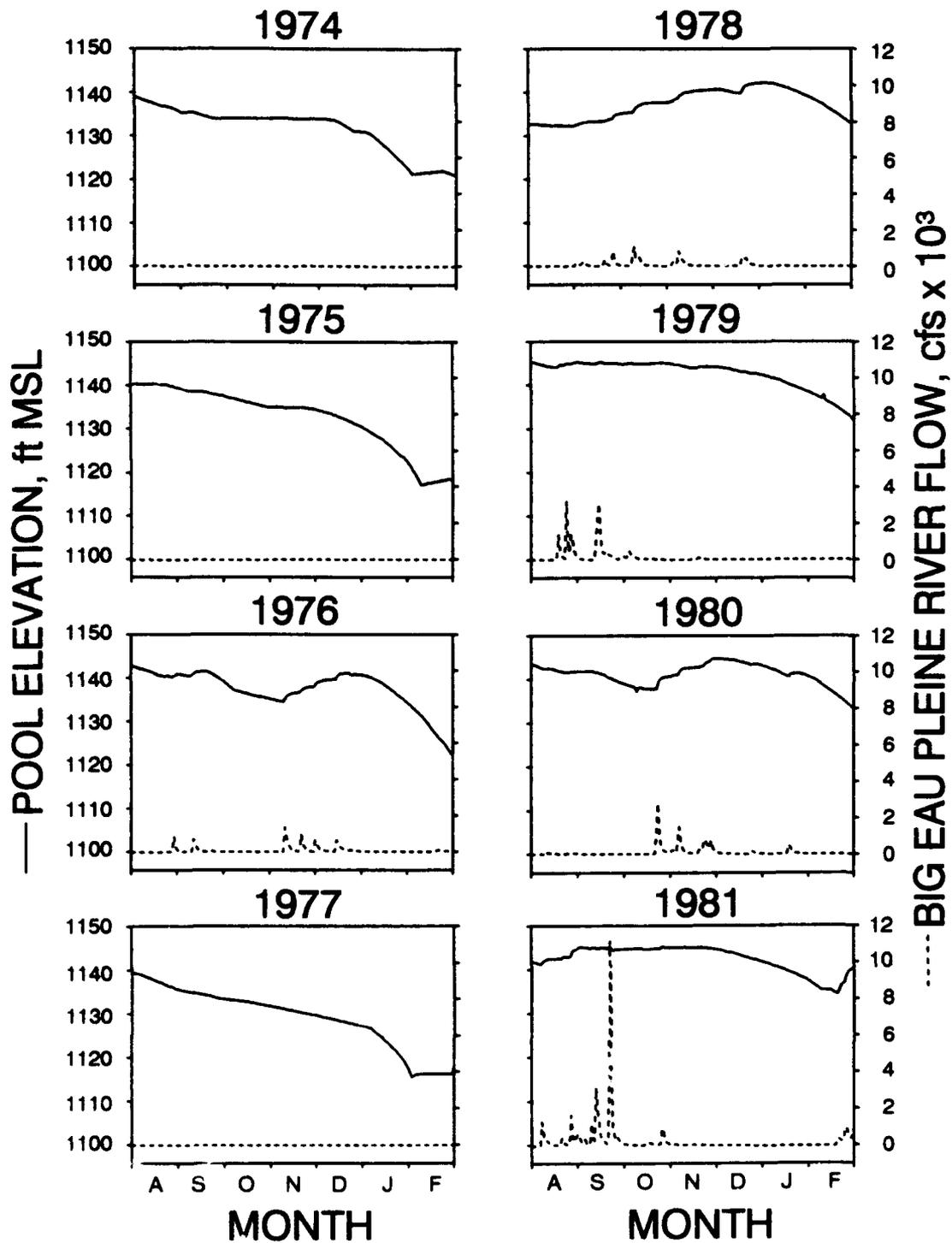
Figure 35. Variations in daily pool elevation and flows from the Big Eau Pleine River during August through February over different years (Continued)
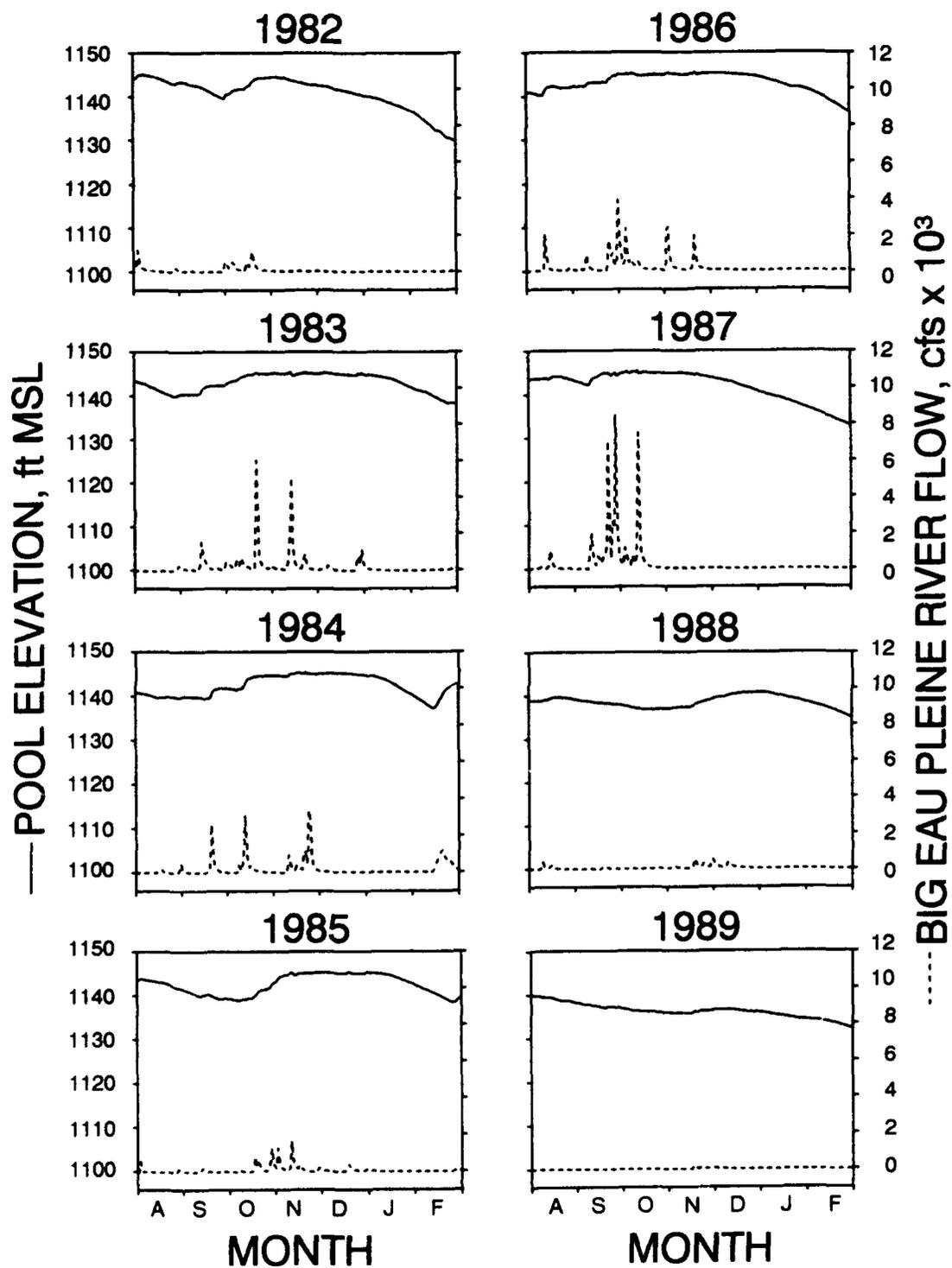
Figure 35. (Concluded)
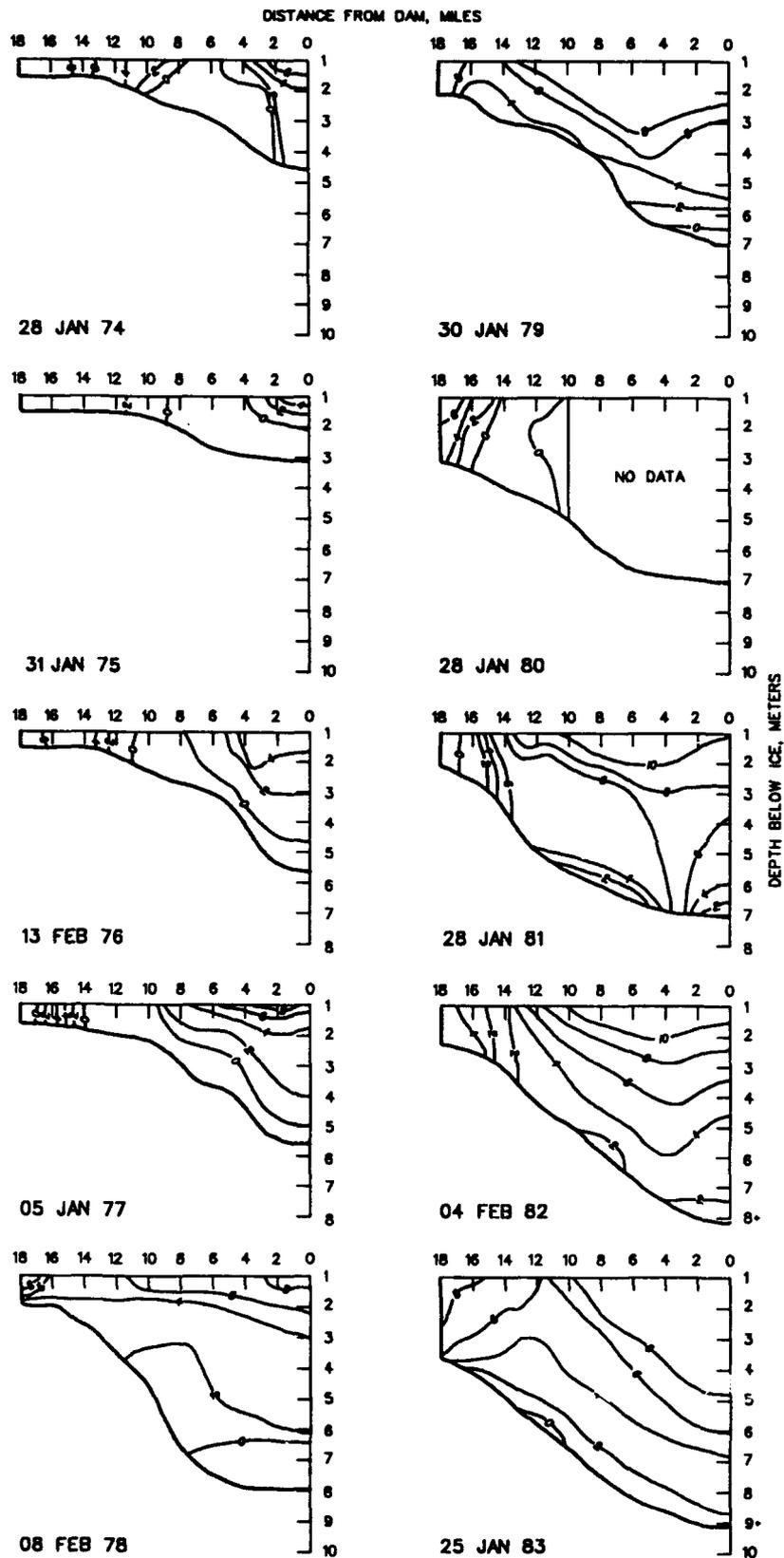
Figure 36. Longitudinal and vertical variations in dissolved oxygen contours (mg L^{-1}) during late January-early February over different years (Continued)

DISTANCE FROM DAM, MILES

25 JAN 84

31 JAN 89

28 JAN 85

30 JAN 90

23 JAN 86

02 FEB 87

NO DATA

31 JAN 88

DEPTH BELOW ICE, METERS
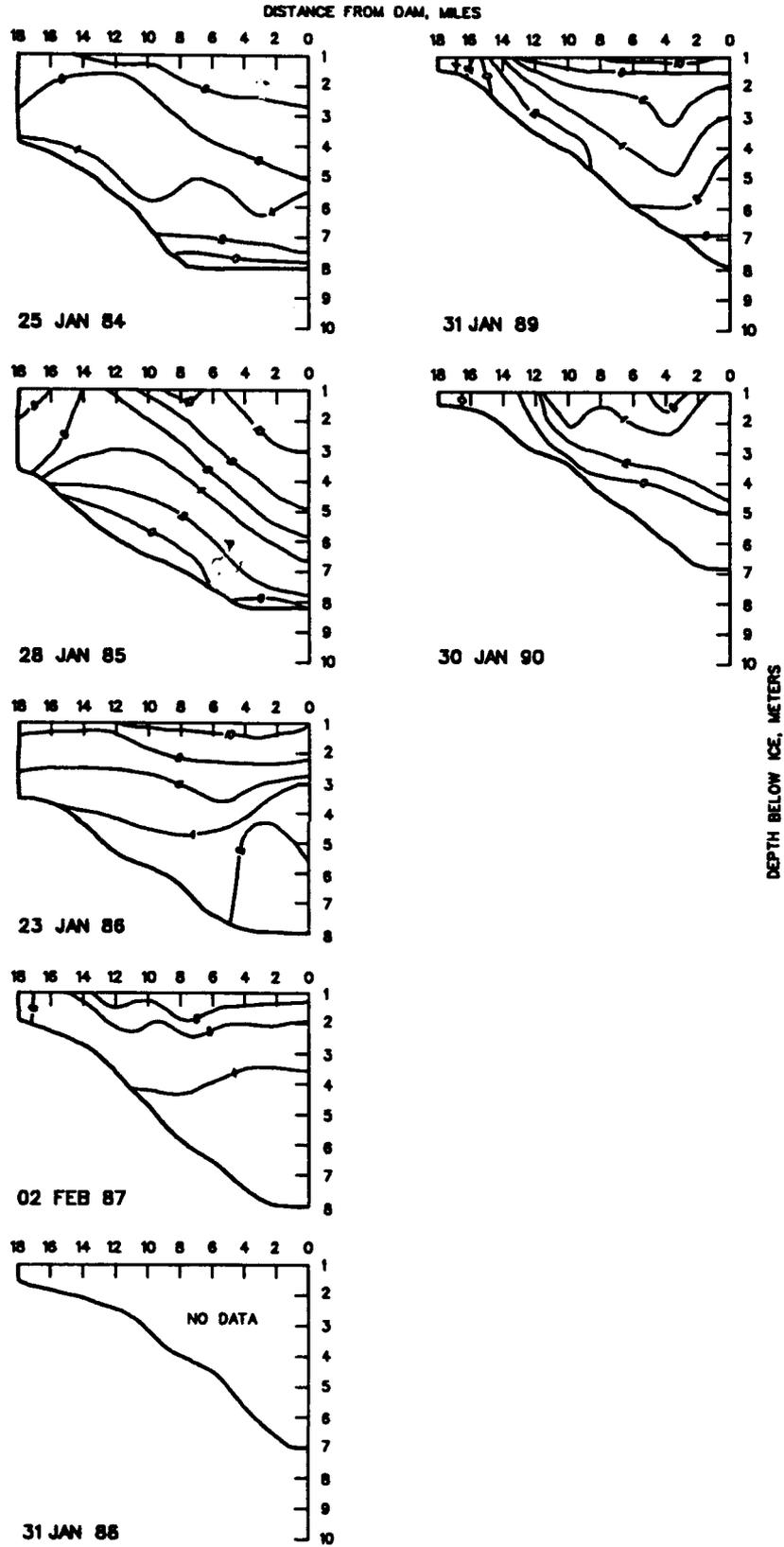
Figure 36. (Concluded)
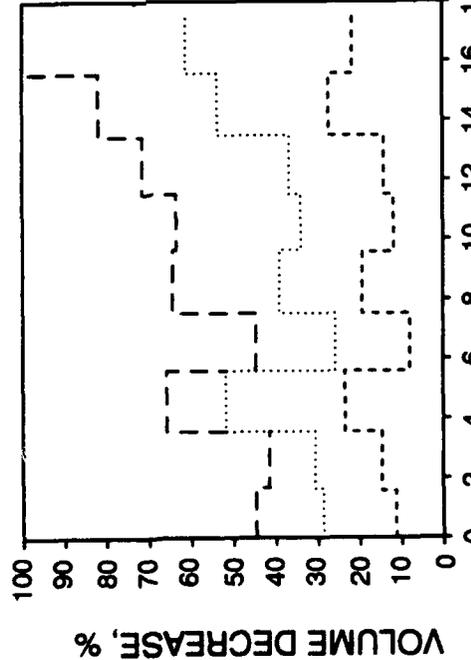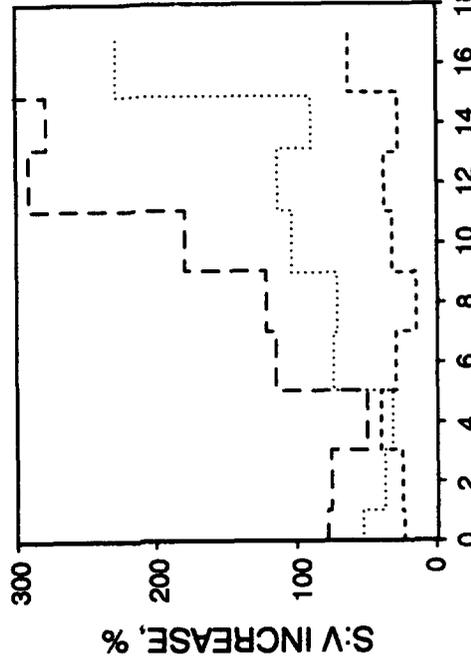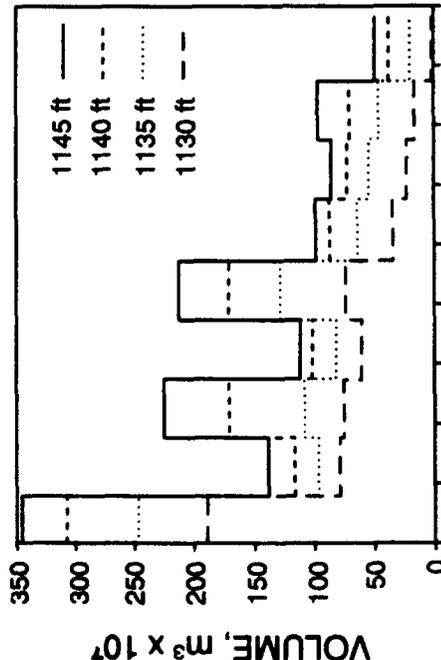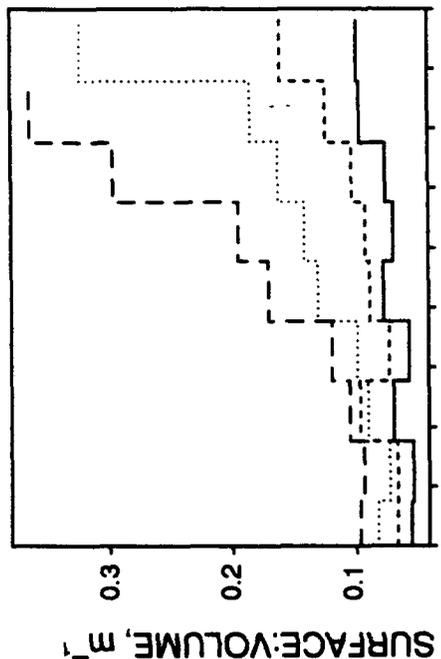
Figure 37. Longitudinal variations in water volume, percent decrease in water volume, reservoir surface-to-volume ratio, and percent increase in the reservoir surface-to-volume ratio at increments of 5-ft intervals below normal pool elevation (i.e. 1,145 ft MSL)
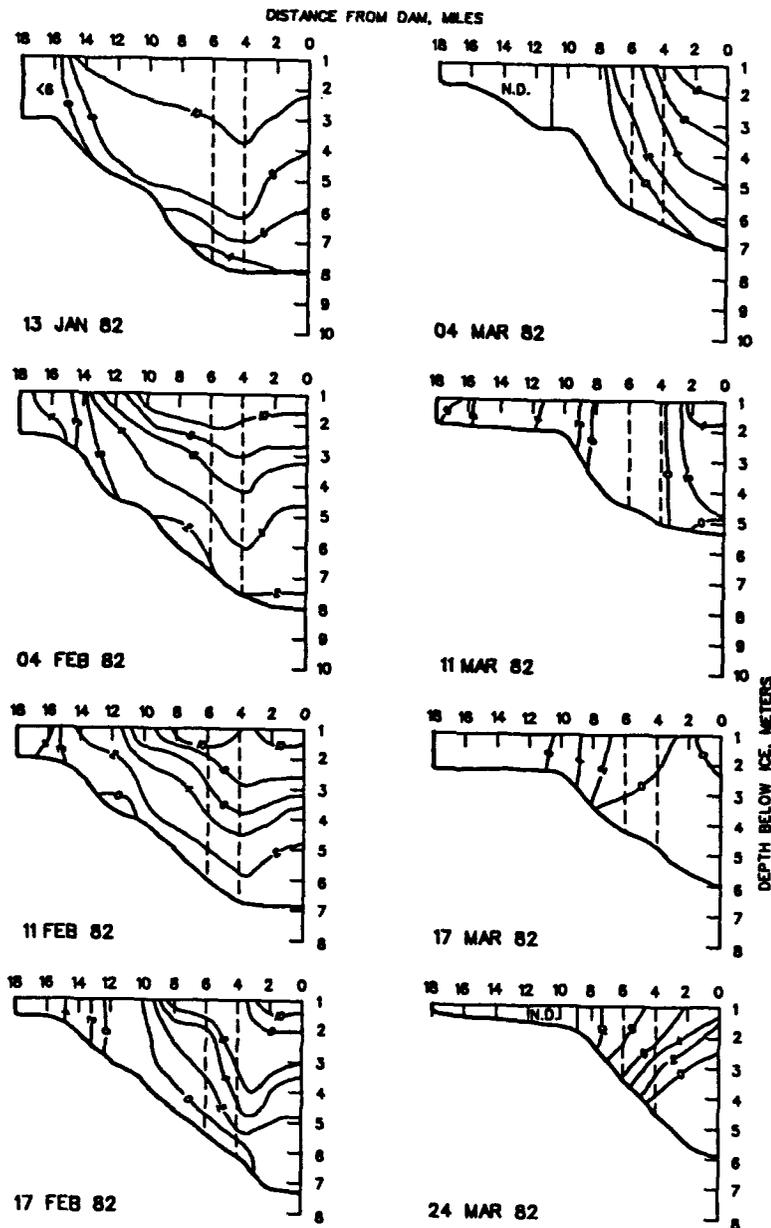
Figure 38. Longitudinal and vertical variations in dissolved oxygen (mg L⁻¹) over time during the winter of 1982. Dashed lines represent regions of influence of the aeration systems
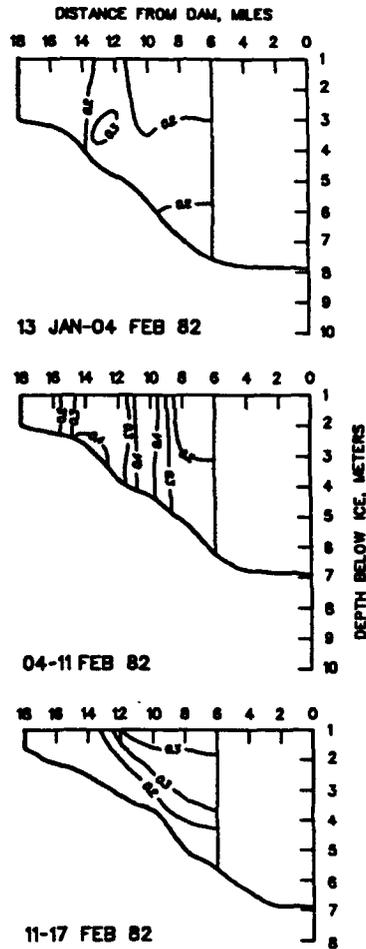
Figure 39. Longitudinal and vertical variations in dissolved oxygen depletion rates (mg L^{-1} d^{-1}) over time during the winter of 1982. Dissolved oxygen depletion rates were not determined for the region of aeration below RM 6
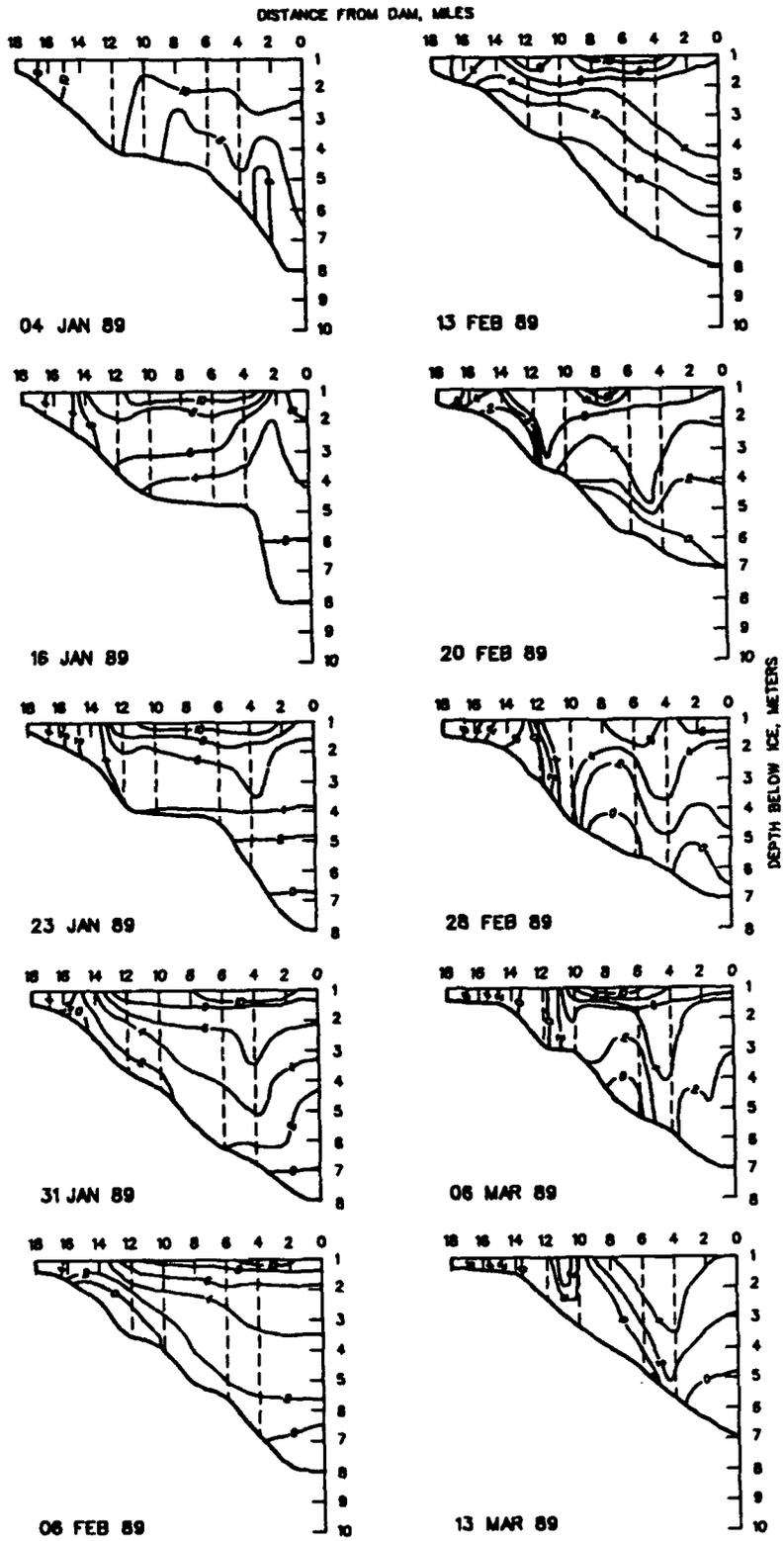
Figure 40. Longitudinal and vertical variations in dissolved oxygen (mg L⁻¹) over time during the winter of 1989. Dashed lines represent regions of influence of the aeration systems
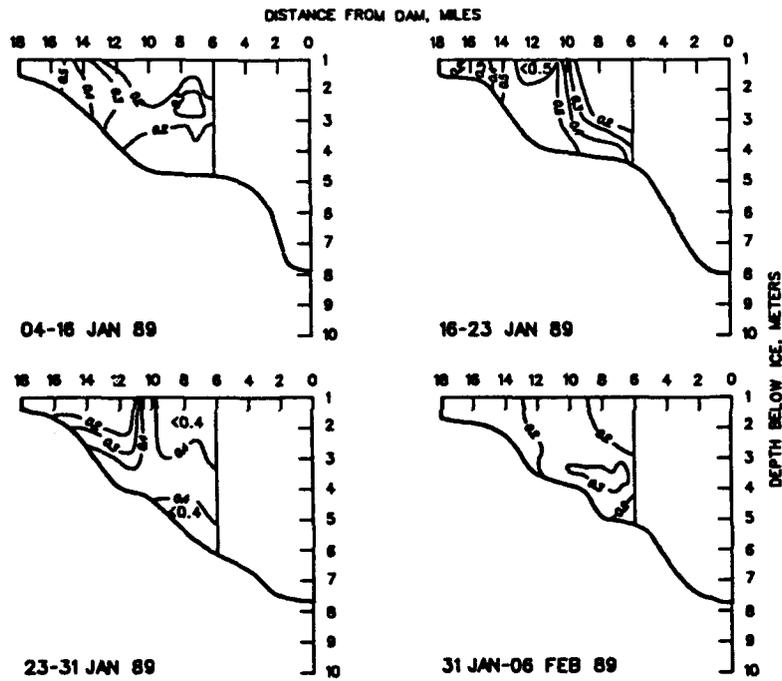
Figure 41. Longitudinal and vertical variations in dissolved oxygen depletion rates (mg L^{-1} d^{-1}) over time during the winter of 1989. Dissolved oxygen depletion rates were not determined for the region of aeration below RM 6
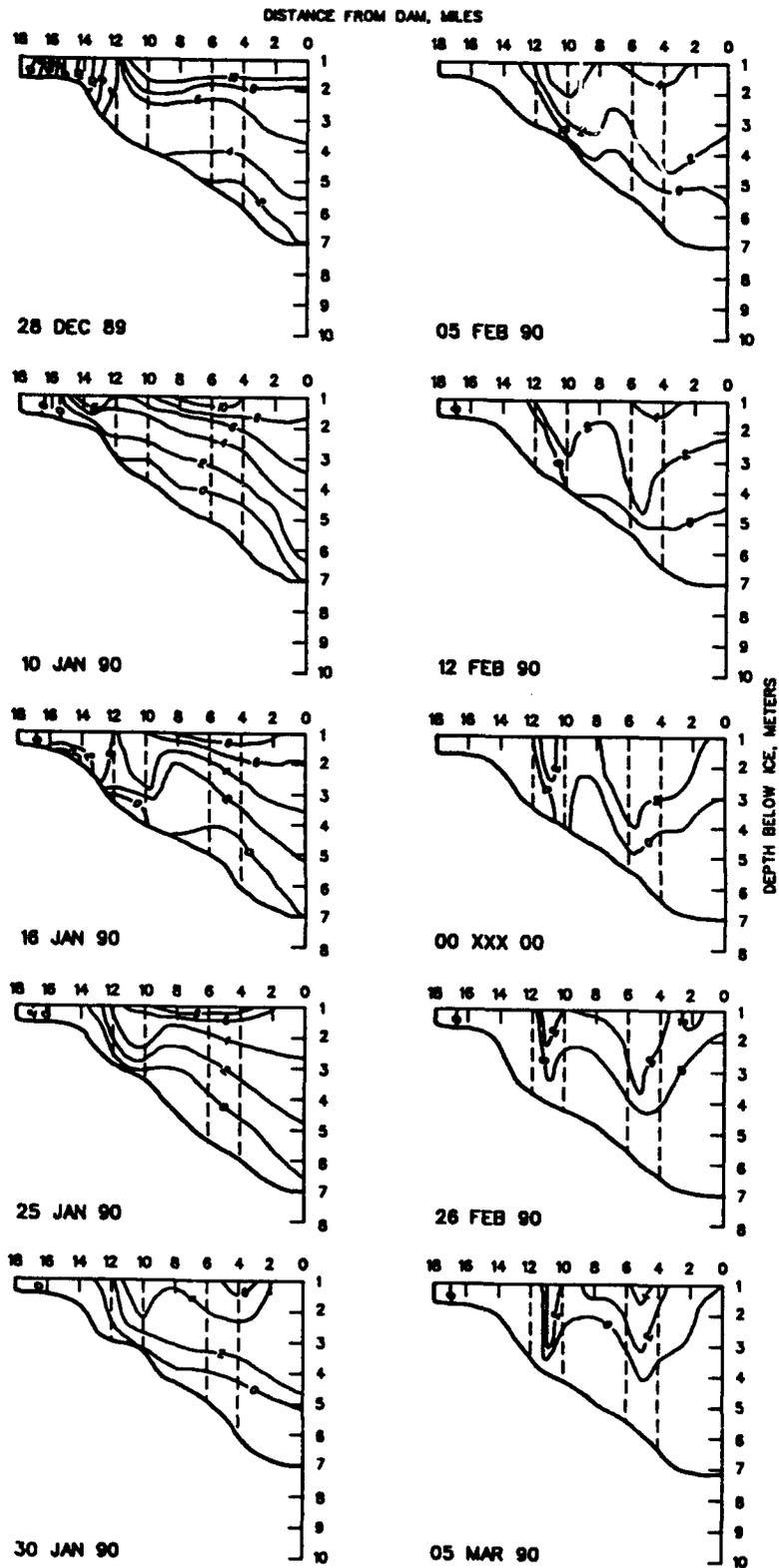
Figure 42. Longitudinal and vertical variations in dissolved oxygen (mg L^{-1}) over time during the winter of 1990. Dashed lines represent regions of influence of the aeration systems
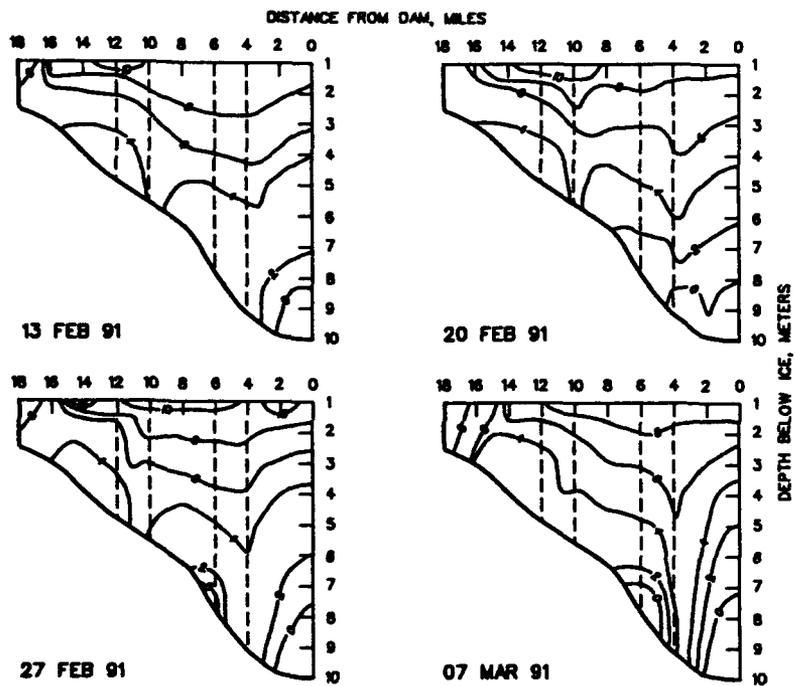
Figure 43. Longitudinal and vertical variations in dissolved oxygen ($mg\ L^{-1}$) over time during the winter of 1991. Dashed lines represent regions of influence of the aeration systems

Figure 44. Longitudinal and vertical variations in chlorophyll $\underline{a}$, dissolved organic carbon, ammonium-N, soluble reactive phosphorus, chemical oxygen demand, soluble iron, and soluble manganese on 10 January and 15 February 1990 (Continued)

DISTANCE FROM DAM, MILES

CHEMICAL OXYGEN
DEMAND, mg L⁻¹

CHEMICAL OXYGEN
DEMAND, mg L⁻¹

SOLUBLE Fe, mg L⁻¹

SOLUBLE Fe, mg L⁻¹

SOLUBLE Mn, mg L⁻¹

SOLUBLE Mn, mg L⁻¹

DEPTH BELOW ICE, METERS

10 JAN 90

15 FEB 90

Figure 44.   (Concluded)

APPENDIX A: ANALYTICAL METHODS, BIG EAU PLEINE RESERVOIR

WATER COLUMN DEPTH

Method: Depth sounding
Detection Limit: 0.01 m
Equipment: Brass sounding chain (Wildlife Supply Co., Saginaw, MI)

WATER TEMPERATURE

Method: Thermistor thermometer
Detection Limit: 0.1 °C
Equipment: In situ - Hydrolab Surveyor II water quality monitor (Hydrolab, Inc., Austin, TX) or YSI Model 57 D.O./Temperature Meter (Yellow Springs Instruments, Yellow Springs, OH); Laboratory - National Institute of Standards and Technology (NIST), formerly National Bureau of Standards, certified thermometer
Calibration: NIST certified thermometer

DISSOLVED OXYGEN

Method: Membrane electrode
Detection Limit: 0.1 mg L^{-1}
Equipment: In situ - (see WATER TEMPERATURE)
Calibration: Iodometric titration or air calibration
Reference: APHA (1985)[*]

pH

Method: Electrometric
Detection Limit: 0.1 pH units
Equipment: In situ - (see WATER TEMPERATURE); laboratory - Beckman Expandomatic IV pH meter (Beckman Instruments, Fullerton, CA)
Calibration: Standardization per manufacturer's guidelines with pH 4, 7, and/or 10 buffer solutions
Reference: APHA (1985)[*]
Sample Handling: Laboratory - samples analyzed immediately after collection

SPECIFIC CONDUCTANCE

Method: Electrometric
Detection Limit: 1 μmhos/cm, corrected for temperature to 25 °C
Equipment: In situ - (see WATER TEMPERATURE); laboratory - YSI Model 32 Conductivity Meter (Yellow Springs Instruments, Yellow Springs, OH)
Calibration: Standardization per manufacturer's guidelines with KCl solutions

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[*] References cited in Appendix A are included in References listed at the conclusion of the main text.

A1

Reference: APHA (1985)
Sample Handling: Laboratory - samples analyzed immediately after collection

TOTAL SUSPENDED SOLIDS

Method: Gravimetric - determination of weight of material retained on a
  standard glass fiber filter dried at 103-105 °C
Detection Limit: 0.1 mg L^{-1}
Equipment: Sartorius Model 2004MP Analytical Balance (Brinkmann Instruments,
  Westbury, NY); VWR Model 1350G Drying Oven (VWR Scientific, San Francisco,
  CA)
Calibration: Balance - per manufacturer's guidelines with NIST approved
  weights; oven - NIST certified thermometer
Reference: APHA (1985)
Sample Handling: Stored in dark at 4 °C, analyzed within 72 hr

SEDIMENT MOISTURE CONTENT

Method: Gravimetric - sediment weight loss on drying at 103-105 °C
Equipment: Mettler Model AC100 Analytical Balance (Mettler Instrument Corp.,
  Hightstown, NJ); Hotpack Model 212061 Tru-Temp Oven (Hotpack Corp.,
  Philadelphia, PA)
Calibration: Balance - per manufacturer's guidelines with NIST approved
  weights; oven - NIST certified thermometer
Reference: Allen et al. (1974)
Sample Handling: Sediment held in air-tight containers at 4 °C, homogenized
  prior to analysis within 72 hr

SEDIMENT BULK DENSITY

Method: Gravimetric - determination of ratio of sediment mass to known volume
Equipment: (see SEDIMENT MOISTURE CONTENT Equipment)
Calibration: Balance - per manufacturer's guidelines with NIST approved
  weights
Reference: Allen et al. (1974)
Sample Handling: Sediment held in air-tight containers at 4 °C, homogenized
  prior to analysis within 72 hr

LOSS ON IGNITION

Method: Loss of sediment mass on combustion at 550 °C
Equipment: Mettler Model AC100 Analytical Balance (Mettler Instrument Corp.,
  Hightstown, NJ); Thermolyne Model 30400 Muffle Furnance (Sybron Industries,
  Dubuque, IA)
Calibration: Balance - per manufacturer's guidelines with NIST approved
  weights; furnace - per manufacturer's guidelines
References: Modification of Allen et al. (1974); Plumb (1981)
Sample Handling: Sediment dried at 103-105 °C ground to a fine powder in soil
  mill prior to analysis

DISSOLVED ORGANIC CARBON

Method: DOC determined by calculated difference of Combustion-Infrared analysis of Total Dissolved Carbon (TDC) at 900 °C and Dissolved Inorganic Carbon (DIC) at 180 °C on fraction which passes through a 0.45 μm membrane filter
Equipment: Beckman Model 915A Carbon Analyzer with Model 865 Non-dispersive Infrared Detector (Beckman Instruments, Fullerton, CA)
Calibration: per manufacturer's guidelines; standard curves
Reference: APHA (1985)
Sample Handling: Samples to be analyzed for DOC acidified with H_2SO_4 to pH <2, stored in glass at 4 °C, analyzed within 72 hr

CHEMICAL OXYGEN DEMAND

A. Water column
Method: Closed Reflux Reactor Digestion, Colorimetric

B. Surficial sediment
Method: Modified Closed Reflux Reactor Digestion, Colorimetric

C. Interstitial water
Method: Closed Reflux Reactor Digestion, Colorimetric

Equipment: COD Test System (Hach Co., Loveland, CO); Spectronic 20 Spectrophotomer (Baush and Lomb, Rochester, NY)
Calibration: Standard Potassium Hydrogen Phthlate curves
References: Jirka and Carter (1975); Plumb (1981); APHA (1985)
Sample Handling: Water column samples acidified to pH<2 with H_2SO_4, analyzed within 7 days. Sediment held in air tight containers at 4 °C, anaerobically subsampled for analysis within 7 days; Interstitial water anaerobically collected and acidified with H_2SO_4 to pH <2, stored at 4 °C, analyzed within 7 days

SOLUBLE REACTIVE PHOSPHORUS

Method: Automated ascorbic acid colorimetric
Detection Limit: 0.005 mg P L^{-1} (dependent upon range used in analyses)
Equipment: Technicon AutoAnalyzer II System (Bran + Luebbe Analyzing Technologies, Elmsford, NY)
Calibration: Standard curves
Reference: APHA (1985)
Sample Handling: Water samples to be analyzed for SRP filtered, stored at 4 °C, analyzed within 72 hr; Interstitial water samples filtered, analyzed immediately after collection

AMMONIUM-NITROGEN

Method: Automated salicylate-hypochlorite colorimetric
Detection Limit: 0.02 mg N L^{-1} (dependent upon range used in analyses)
Equipment: Technicon AutoAnalyzer II System (Bran + Luebbe Analyzing Technologies, Elmsford, NY)

Calibration: Standard curves
Reference: Wall et al. (1975)
Sample Handling: Water samples to be analyzed for NH_4-N acidified with H_2SO_4 to pH <2, stored at 4 °C, analyzed within 72 hr; Interstitial water samples analyzed immediately after collection

DISSOLVED IRON AND MANGANESE

Method: Direct-aspiration flame photometry
Detection Limit: 0.05 mg L^{-1}
Equipment: Perkin-Elmer Model 2380 Atomic Absorption Spectrophotometer (Perkin-Elmer Corp., Norwalk, CT)
Calibration: Standardization per manufacturer's guidelines with standard metal solutions
Reference: APHA (1985)
Sample Handling: Samples to be analyzed for dissolved iron and manganese filtered through 0.45 μm membrane filter, acidified with HNO_3 to pH <2, stored at 4 °C prior to direct-aspiration analysis

CHLOROPHYLL a

Method: Acetone extraction, spectrophotometric
Equipment: Perkin-Elmer Model Lambda 3 Spectrophotometer (Perkin-Elmer Corp., Norwalk, CT)
References: APHA (1985); Lorenzen (1967)