1991

Multivariate Analyses of Spatiotemporal Water Quality Patterns of Back Bay, Virginia

Raymond W. Alden III
Old Dominion University

Walter I. Priest
Back Bay Restoration Foundation

Multivariate Analyses of Spatiotemporal Water Quality Patterns of Back Bay, Virginia

Raymond W. Alden III

Applied Marine Research Laboratory
Old Dominion University, Norfolk, Virginia

and

Walter I. Priest III

Back Bay Restoration Foundation
Virginia Beach, Virginia

Abstract: An investigation employing multivariate statistical techniques was conducted to determine major spatiotemporal patterns in water quality in Back Bay, Virginia. Water quality data collected by the Virginia Water Control Board (VWCB) over the past two decades and recent data collected by the Department of Game and Inland Fisheries and the Back Bay Restoration Foundation were consolidated for statistical analysis. Unfortunately, lack of continuity in sampling regimes prevented the use of many of the site/date/variable combinations in the statistical analyses. Nonetheless, a number of water quality patterns were characterized.

Long-term trends could be evaluated for a relatively few parameters (NO_2, NH_3, TKN, conductivity, DO, and pH) for which an adequate data base existed. Trend analysis of a 16-year data base for Hell Point Creek indicated a significant decrease in ammonia concentrations (-0.011 mg 1^{-1} yr^{-1}), possibly related to changes in land use activities in the region.

The TKN concentrations in the Bay almost doubled between the 1970's and 1980's (from 1.14 mg/1 to 1.97 mg/1). Indicators of eutrophication such as high daytime dissolved oxygen and pH measurements qualitatively appeared to decrease between 1970's and 1980's throughout the Bay, but lack of spatial and/or temporal continuity in the data sets prevented direct statistical comparisons.

Distinct seasonal patterns were characterized: "summer" conditions were characterized by high temperatures but lower suspended solids load and nutrient concentrations, while the converse was true for "winter" months. "Spring" and "fall" collection periods were intermediate in these characteristics but displayed elevated volatile suspended solids and depressed phosphorus concentrations, possibly due to seasonal phytoplankton blooms.

Overall spatial patterns indicated the tributary creeks appeared to be "source areas" for elevated nitrogen and phosphorus based nutrients, while the main Bay was characterized by a high organic-rich suspended solids load. The tributary of greatest concern was Nawney Creek, which displayed elevated nutrient concentrations and appeared to influence water quality in the proximate Bay region. In summary, two major problems appear to be associated with water quality conditions in Back Bay: elevated levels of nitrogen and phosphorus based nutrient in the tributary creeks and a high suspended solids load of organic-rich particles in the Bay. The full ecological significance of these conditions cannot be determined by the present study. However, consistent and comprehensive monitoring of water quality conditions, such as has been implemented in recent years, should permit observation of long-term trends in environmental conditions in various portions of the Bay. Only in this way can the success of any management or restoration actions be judged.

Introduction

Over the past two decades, there has been concern over the apparent degradation of the Back Bay ecosystem in Virginia Beach, Virginia. A variety of environmental studies have been conducted at Back Bay, including a number of water quality investigations. The Virginia State Water Control Board (VWCB) has monitored a varying number of stations in Back Bay over the last two decades. Also, since 1986 the Department of Game and Inland Fisheries and the Back Bay Restoration Foundation have been collecting monthly water quality samples from Back Bay and its tributary streams, respectively. Although the results of most of these investigations are archived in the STORET system through the Tidewater Regional Office of the Virginia State Water Control Board, no attempts have been made to perform multivariate statistical analyses to explore major spatial and temporal patterns in the water quality of the Back Bay ecosystem since the collections began. The purpose of the present study is to evaluate the spatiotemporal coverage and compatibility of the various water quality data sets and to utilize multivariate statistical techniques to delineate any "big picture" patterns in water quality conditions.

Objectives

The following objectives were identified for the present study:

1. To screen all water quality data for spatiotemporal continuity and compatibility for use in subsequent statistical analyses;
2. To determine whether there have been any long term trends in water quality at sites for which data have been collected from the early 1970's to the late 1980's;
3. To characterize large scale temporal patterns, once spatial patterns have been taken into account:
   a) to compare water quality conditions from the 1970's to those observed in the 1980's;
   b) to delineate temporal patterns of similar water quality conditions during the periods of collections;
4. To characterize large scale spatial patterns, once temporal patterns have been taken into account:
   a) to delineate spatial patterns in water quality for the entire period of collections (1970's and 1980's);
   b) to delineate spatial patterns in water quality conditions for the more comprehensive studies conducted during the late 1980's.

Technical Approach

For simplicity of presentation, the technical approach section is organized by "tasks" that correspond directly to the objectives.

Task 1. Screening of Water Quality Data for Continuity and Statistical Compatibility

The water quality data received from STORET had to be screened in a number of ways prior to the development of multivariate statistical models. In all multivariate statistical techniques, continuity of variables measured at each of the stations over the collection period is of primary concern, since "missing values" or combinations that do not quite "match up" cause entire sample sets to be discarded by the analysis. Therefore, the data had to be visually screened through a number of plotting protocols. Plots of observation periods for each station, and water quality variables versus date by sites, as well as tables of unique listings of collection dates for each site were examined for continuity. Ultimately, a matrix was produced to display the degree of temporal continuity for the various site-variable combinations. Decisions concerning which data could be used for subsequent analyses were based upon this matrix.

For cases where exact collection dates did not "match up", a computer routine matching month by month correspondence had to be utilized. Site-variable combination not displaying sufficient continuity over time were eliminated from subsequent analyses. Additional spatiotemporal analyses were conducted on data from the more comprehensive 1980's water quality study in order to include the more extensive set of variables being collected.

Task 2. Determination of Long Term Trends in Water Quality

Environmental trend analysis over a time series represents a rather new, complex and often controversial field of study. In order to meet the assumptions of most time series based trend analyses, data must be normally distributed, be collected over an extensive time period (often a minimum of 10 years) and contain no "missing values". Since most environmental data sets generally do not fit these criteria, several new, nonparametric approaches have been recommended for water quality trend analyses (Gilbert, 1987).

In the present study, two nonparametric trend analyses were utilized. The first approach called the "Seasonal Kendall test" was developed by Hirsch et al. (1982). A more recent approach described by Hirsch and Slack (1984) takes into account autocorrelation (or serial correlation), a typical characteristic of time series data which influences the power and robustness of statistical analyses. Unfortunately, this approach can only be used for data sets containing more than 10 years of monthly observations. Therefore, for site-variable combinations with sufficient numbers of observations, both analyses were conducted.

Task 3. Characterization of Overall Temporal Patterns

In order to examine temporal patterns in Back Bay, major spatial patterns must first be taken into account statistically. Therefore, a series of complementary multivariate spatial and temporal analyses were conducted which paralleled those being used for the Chesapeake Bay Program (Alden et al., 1988; Birdsong et al., 1988). The first procedure, based upon the methods described by Williams and Stephenson (1973), allowed the calculation of classification coefficients which were used in complementary cluster analyses: 1) to cluster sites according to similarities in water quality patterns, once temporal patterns have been taken into account; and 2) to classify temporal groups displaying similar water quality patterns, once spatial patterns have been taken into account. The evaluation of dendograms produced by these analyses allowed the determination of "site groups" (sites displaying similar water quality patterns through time) and "date groups" (time periods displaying similar water quality patterns over all sites).

Prior to the analyses of the specific water quality conditions associated with the temporal patterns, any spatial effects were "removed" by subjecting the data to a multivariate analysis of variance (MANOVA) of site groups defined by the Williams and Stephenson cluster analysis. Residuals from the MANOVA were analyzed by three alternate models: 1) an *a priori* comparison of the 1970's to the 1980's water quality conditions; 2) a comparison of "date groups" defined by the cluster analysis of the 1970's and 1980's data; and 3) a comparison of "date groups" defined by the cluster analysis of the 1980's data alone. The models each involved a MANOVA and a discriminant analysis of the water quality "residuals". The discriminant analyses were used for data presentation purposes. The discriminant functions produced by these analyses can be related to the water quality variables most responsible for differences between the temporal groups. Since the MANOVA is a far more conservative test of group differences than discriminant analysis, the variable list used to "name" the discriminant axes included only variables shown to be statistically significant (a=0.01) by this analysis.

Task 4. Characterization of Overall Spatial Patterns

The spatial patterns were analyzed in an analogous manner. Two models were employed to explore major spatial patterns in water quality in Back Bay: 1) a comparison of "site groups" defined by the cluster analysis of the combined 1970's and 1980's data sets; and 2) a comparison of "site groups" defined by the cluster analysis of the more extensive 1980's data set. Prior to the analyses, MANOVAs were conducted to "correct" for date groups defined by the cluster analysis. The residuals from this step were analyzed by the MANOVA/discriminant analysis procedures to compare site groups.

Results

Task 1. Screening of Water Quality Data for Continuity and Statistical Compatibility

A total of 19 water quality variables were sampled at 17 stations throughout the Back Bay ecosystem. Only 12 of the stations were sampled into the 1980's. Unfortunately, many of the site-variable combinations were not very consistent over time (Table 1). In fact, less than 5% of all possible site-variable combinations displayed year round continuity throughout the study period from the 1970's through the 1980's. These combinations (NO_2, NH_3, TKN, DO, conductivity, and pH at station HPC001.46) were used for time series trend analysis (Task 2).

Other subsets of data were screened and assembled for the other spatiotemporal analyses (Tasks 3-4). For each analysis, data sets had to be established which had spatial and temporal continuity and few missing values. For the temporal and spatial analyses involving data from 1970's and 1980's, only three variables (TKN, NH_3, and NO_2) from eight stations were available for analysis. For the temporal and spatial analyses of the 1980's data, ten variables (temperature, TKN, NH_3, NO_2, NO_3, OPO_4, TP, volatile suspended solids, and fixed suspended solids) at 12 stations were available for analysis.

The data also had to be screened for inconsistencies in designation of "below detection limit" (BDL) values. The STORET coded many values which were BDL with a code of "K" beside a number which varied from one sample to another. In order to standardize these values for statistical analyses, the Virginia Division of Consolidated Laboratory Services was contacted to determine a standardized detection limit for each variable. All values coded with the BDL coding were converted to the appropriate standardized detection limits.

Task 2. Determination of Long Term Trends in Water Quality

The results of the long term trend analysis of water quality at station HPC001.46 are presented in Table 2. Of the water quality variables, only ammonia had a significant trend, decreasing approximately 0.011 mg/l per year. This trend represents an approximate decline of 7.4% of the median value per year (Fig. 1). In the early 1970's, ammonia values were sporadically quite high (>1.00 mg/l). By the late 1970's, the ammonia values were consistently found at low levels, often below detection limits. None of the other water quality parameters displayed significant trends. Nitrates were not monitored consistently at this station in the 1970's, so it cannot be established whether the lower ammonia concentrations translated to reduced nitrate levels.

Task 3. Characterization of Overall Temporal Patterns

The results of the cluster analyses that simultaneously classified dates into date groups and sites into site groups according to similarities in water quality patterns from the 1970's to the 1980's (NO_2, NH_3, TKN only) are presented in Figures 2 and 3, respectively.

The results of the cluster analyses of the 1980's water quality data (temperature, TKN, NH_3, NO_2, NO_3, OPO_4, TP, TOC, volatile suspended solids, and fixed suspended solids) are presented in Figures 4 and 5. For interpretation purposes, mean values and standard errors for each site group-date group combination are presented in Figures 6 to 8 for the 1970's/1980's data set, and Figures 9 to 16 for the 1980's data set. Details concerning the composition and water quality characteristics of the date groups and site groups will be discussed in this section and in the following section.

The Williams and Stephenson (1973) method produces information concerning the relative importance of temporal and spatial factors. Table 3 presents values that Williams and Stephenson (1973) term the "mean variances per comparison". These values are somewhat analogous to eigenvalues and represent the relative amount of the variance in each data set that can be attributed to temporal effects, spatial effects or the spatial-temporal interaction. In the 1970's/1980's data analysis, the temporal and spatial effects appeared to be quite important to the overall patterns in the data, representing 30% and 61% of the variance, respectively. The interaction value, which Williams and Stephenson (1973) term "noise" when the magnitude is small, accounted for less than 10% of the variance. The analyses of the 1980's water quality data produced similar results. Temporal effects accounted for 35% of the variance, while 58% of the variance was attributable to spatial effects. The spatiotemporal interaction accounted for only 7% of the variance, Thus, it appears that spatial effects account for nearly twice as much of the variance as temporal effects, regardless of whether the 1970's and 1980's data sets were analyzed together or the 1980's data were analyzed alone.

The first analysis of temporal patterns involved a comparison of the 1970's water quality conditions with those from the 1980's, once the spatial patterns had been taken into account. The residuals of a MANOVA of site groups defined by the cluster analysis for selected water quality variables (TKN, NH_3, NO_2) were analyzed for the MANOVA/discriminant analysis protocol comparing these conditions for the two decades. Only TKN concentrations significantly differed between the two decades, increasing from an average of 1.14 ± 0.30 mg/1 in the 1970's to an average of 1.97 ± 0.41 mg/1 in the 1980's.

The temporal patterns were further explored through an analysis of the date groups of similar water quality conditions indicated by the cluster analysis. The dendogram for the temporal effects for the 1970's/1980's data set indicated four major date groups, once site effects were taken into account (Fig. 2). Date group 1 (DG-1) encompassed the majority of the sampling dates (a total of nearly 70 collection periods). Date group 2 (DG-2) represented a few winter/spring collection dates in 1975, 1976, 1987, and 1988. Date group 3 (DG-3) was composed of most of the collection periods in 1986 and 1987, as well as a few summer/fall collections from 1988. The MANOVA/discriminant analyses indicated that, across all sites, DG-3 tended to have higher TKN values, while DG-2 tended to exhibit higher NH3 concentrations (Fig. 17). The two periods composing DG-4 displayed elevated but highly variable NO_2 concentrations and low NH_3 concentrations. These patterns can be confirmed in Figures 6 to 8, if one looks at overall concentration patterns along the x-axes and mentally "averages" the values across the site groups.

The dendogram of the temporal groups of the 1980's data alone indicated three major date groups (Fig. 4). Date group 1 (DG-1) was a "summer" group, consisting of collections made during the late spring and summer of 1986 and the summers of 1987 and 1988. Date group 2 (DG-2) was a group that contained mostly fall and spring collection dates. Date group 3 (DG-3) consisted of collection periods from the winter of 1987, February of 1988 and March and April of 1989.

The results of the MANOVA/discriminant analyses of site- corrected temporal effects are presented in Figure 18. Each of the date groups were characterized by certain water quality conditions. The "summer" data group (DG-1) had higher temperatures; and lower fixed suspended solids (indicative of sediment particles), NH_3 concentrations and NO_3 concentrations. On the other hand, the "winter" group (DG-3) displayed lower temperatures, a higher sediment load (higher fixed suspended solids concentrations), and higher NH_3 and NO_3 concentrations. The "spring-fall" group (DG-2) was intermediate in these water quality conditions. It was distinct from the other groups in displaying slightly higher volatile suspended solids (indicative of carbon-rich particles such as phytoplankton cells, detritus particles, humus particles, etc.), and lower total phosphorus concentrations.

Task 4. Characterization of Overall Spatial Patterns

As noted in the previous section, spatial patterns (i.e. between-site variation) accounted for approximately twice the "explained" variance in the water quality data as the temporal patterns. Figure 3 displays the dendogram for spatial effects in the 1970's/1980's data set. There were three site groups formed by the eight sites for which common variables (TKN, NH_3, NO_2) were collected. Site group I (SG-I) consisted of a single site (WNC003.65) in West Neck Creek (Fig. 19). Site group II (SG-II) represented sites in the mouths of Muddy Creek (MDY000.00) and Hell Point Creek (HPC000.00), as well as two sites in the eastern portion of Back Bay (Sand Bay-BKY006.48; and Shipps Bay- SHB000.57). The third site group (SG-III) consisted of sites located in three tributary creeks along the northern and western borders of Back Bay: Hell Point Creek (HPC001.46), Beggars Bridge Creek (BBC000.76), and Nawney Creek (NWN000.00).

The results of the MANOVA/discriminant analyses of the site groups are presented in Figure 20. Site group II tended to display elevated levels of TKN relative to SG-I, with SG-III being intermediate and somewhat more variable in TKN concentrations (see Fig. 6). Site group III tended to display higher NH_3 levels relative to the other site groups, particularly during the winter/early spring date group (DG-2) which may have been subject to increased storm activity (see Fig. 7).

The three site groups defined by the cluster analysis of the more comprehensive water quality data set collected in the 1980's are presented in the dendogram in Figure 5. In this analysis, the first site group (SG-I) consisted of most of the tributary creek sites: West Neck Creek (WNC003.65), a tributary of the North Landing River, Beggars Bridge Creek (BBC000.76), Muddy Creek (MDY000.00), Hell Point Creek (HPC001.46), and a site described as "Drum Point", off the mouth of Nawney Creek (BKY006.37) (Fig. 21). The two sites located at Nawney Creek formed the second site group (SG-II). The sites forming SG-III were for the most part, located in Back Bay: Hell Point Creek (HPC000.00), Shipps Bay (SHB000.57), Sand Bay (BKY006.48), "Off Pellitory Point" (BKY003.17), and "North of Buckle Island" (BKY000.99). Despite the fairly large geographic spread of the "main-Bay" sites, the similarities in overall water quality conditions were quite high and the separation from the other two site groups quite evident.

The results of the MANOVA/discriminant analyses characterizing significant differences in water quality conditions between the site groups are presented in Figure 22. As with the date group patterns, the reader may visually confirm these spatial patterns in Figures 9 to 16, which display mean values for each of the variables found to be significant by the analyses of the various site group/date group combinations. The major separation between the groups was between SG-II and SG-III: SG-II had higher concentrations of nutrients such as phosphorus (both TP and OPO_4), and nitrogen (NO_3 and NH_3); while SG-III had lower levels of these nutrients but higher levels of suspended solids (both volatile and fixed suspended solids, particularly during the "winter" date group when storm activities probably tended to stir the sediments). Site group I had intermediate levels of the nutrients, but tended to have somewhat lower concentrations of TKN than the other site groups.

Discussion

The success of multivariate statistical techniques in analyzing environmental data is highly dependent upon the continuity of the collection regime. On the other hand, programs such as the environmental monitoring that has occurred in Back Bay over the past two decades often depend upon the opportunistic acquisition of data of various sorts from many different sources. Such data sets require much screening to eliminate site-time-variable combinations that are not compatible with the remaining data. Subjective decisions often must be made to determine which sites or collection periods are "close enough" to have the appropriate degree of continuity. Variables, sites, dates, or even entire data sets must often be discarded because they do not meet even these subjective criteria. All of these circumstances were encountered to some degree in the assessment of the Back Bay water quality data. Nonetheless, a number of patterns have emerged from the multivariate analyses. These patterns will be discussed along with more qualitative evaluations of some of the data which could not be used in the analyses. A positive observation that emerged from the screening phase of the assessment was that the water quality data sets collected in the late 1980's have far greater continuity over the site-time- variable combinations than those collected earlier. If the data collection can be maintained over the long term, comprehensive trend analyses similar to those being targeted for the Chesapeake Bay Monitoring Program could become a reality for Back Bay.

The major long-term trend at the single Hell Point Creek site with a sufficient data base for time series trend analysis was a decrease in ammonia concentrations. The trend represented an average decrease of 7.4% (0.01 mg/1/1) of the median concentration (0.15 mg/1) per year. It is believed that discharges from an animal feed lot and a small sewage treatment plant may have produced sporadically high (>1.00 mg/1) levels of ammonia. These were brought under control by the late 1970's, leading to a decrease in ammonia levels. The watershed has since been converted from agricultural and woodland to large residential subdivisions.

The Williams and Stephenson cluster analyses of both the 1970's/1980's data sets combined and the 1980's data set alone indicated that spatial effects (i.e. site to site patterns) accounted for twice as much of the "explained" variance in the water quality as temporal effects. The spatial-temporal interaction term proved to represent only a small portion of the variance, indicating that site groups did not tend to exhibit opposite patterns within the date groups (i.e. there appeared to be a continuity of temporal patterns for the site groups).

In comparing water quality for the 1970's with that of the 1980's, only TKN displayed a significant difference, increasing in the 1980's. However, it should be emphasized that only TKN, NH_3 and NO_2 could be included in the analysis, due to lack of continuity in the remaining parameters. The elevation of TKN concentration in the 1980's was more or less confirmed in the MANOVA/discriminant analyses of date groups formed by cluster analysis of the same data set. The date groups representing much of the 1980's (particularly 1986 and 1987) displayed significantly higher TKN concentrations than the other groups. An examination of the raw data strongly suggests that the TKN concentrations have increased in the main Bay (Fig. 23a) but that the pattern in the tributary (creeks) data set was less distinct, due to sporadically high TKN concentrations in the 1970's at the Hell Point Creek site which moderated during the late 1970's (Fig. 23b). The concentrations of TKN in the 1980's average between 1.5 mg/1 and 2.5 mg/1 for most of the site group-date group combinations. These concentrations are quite high. As a point of comparison, the Virginia Water Control Board (VWCB) at one time used a concentration of 0.9 mg/1 TKN as a "reference level" against which to compare the quality of Virginian's waters in the 305b Water Quality Inventory reports (VWCB, 1976). This level was selected to act as a "reference" to determine whether an ecosystem was over-enriched in nitrogen as a potential long term nutrient load. Although no water quality criteria have been established for TKN, and even the use of a "reference level" was dropped from 305b reports in the late 1970's (VWCB, 1978), the TKN concentrations in Back Bay appear to be quite high. However, ammonia (NH_3),which often constitutes the major component of TKN, did not appear to be elevated (usually, <0.5 mg/1) for most site group-date group combinations displaying high TKN levels (Figs. 6, 7, 10, and 11). Therefore, it is believed that the observed TKN concentrations represent organically bound nitrogen, probably in the form of detritus particles, organic-rich suspended sediments, or phytoplankton biomass.

Marshall (1988) has reported that the phytoplankton communities have become less eutrophic since the 1970's, so phytoplankton blooms would not appear to be responsible for the persistently elevated TKN concentrations in the 1980's. More likely explanations revolve around other changes pointed out by Marshall (1988): changing land use patterns including increasing agricultural activities and housing developments; increasing turbidities in Back Bay; and loss of submerged aquatic vegetation. Suspended solids concentrations were not measured in the 1970's, but the TKN trends may reflect the increased suspended solid load of organic-rich sediments and detritus due to the changing land use activities in the Back Bay watershed during the two decades.

Ammonia concentrations tended to be highest during the winter/early spring months, reaching high concentrations (>1 mg/1) in some of the tributary creeks (HPC001.46 in the 1970's NWN000.00 in the 1980's, see Fig. 24). The concentrations of ammonia in the main Bay, while exhibiting the same seasonal patterns, never exceeded 1.0 mg/1. The water quality criteria for ammonia are dependent on specific pH and temperature conditions, so it is impossible to make definitive statements concerning the potential for ammonia toxicity in the tributaries without much more detailed case by case assessments. However, the 1976 305b Report (VWCB, 1976) indicated that only a small percentage (< 10%) of all water quality observations in the major river basins in Virginia exceeded the "reference level" of 0.89 mg/1. Perhaps levels above 1 mg/1 should be considered to be "elevated" as a potential nutrient source, with toxicity becoming an issue when concentrations greatly exceed that level, particularly under conditions of high pH and temperature. During the 1980's, the ammonia concentrations generally exceeded 1 mg/1 during the winter/early spring months *only* at Nawney Creek sites, probably due to agricultural runoff (Fig. 24).

The analyses of the short-term temporal (seasonal) patterns of water quality in the 1980's indicated three date groups. The "summer" date group tended to have higher temperatures, but lower suspended solids and nutrients. The "winter" date group had lower temperatures, but higher suspended sediment and nutrient loads. The "spring/fall" date groups displayed elevated volatile solids and depressed phosphorus concentrations relative to the other groups, possibly due to seasonal blooms of various phytoplankton species (Marshall, 1988).

The spatial patterns in water quality dominated the "explained variance" in the multivariate analyses. In other words, geographic patterns in water quality in Back Bay and its tributaries overshadowed short-term or even long-term temporal trends by a margin of 2 to 1. The overall spatial pattern that appears to emerge is that the main Bay sites tend to have higher suspended solid and organic nitrogen (TKN) loads than the tributaries, but the tributary waters tend to be enriched in nutrients, both nitrogen (NH_3 and NO_3) and phosphorus (TP and OPO_4). Thus, it appears that the tributary creeks, particularly Nawney Creek act as source areas for nutrients, probably due to agricultural and residential runoff, while the main Bay waters tend to be enriched in organic-rich suspended particles, probably plant detritus, sediments, or both. The portion of the suspended solid load that appears to be associated with inorganic suspended sediment particles (fixed suspended solids) tend to reach maximum concentrations during the winter months when wind and storm activities probably keep the shallow Bay waters stirred up. However, the organically-rich suspended solids (i.e. fine humus particles and detritus) tend to be relatively elevated (generally >20 mg/1; see Fig. 15) throughout all seasons. Whether the turbid waters of the Bay are due to its action as a "sink" or reservoir for sediments carried by runoff from land being developed for agricultural and residential use in the watershed, or due to the loss of sediment stabilization by the dwindling submerged aquatic vegetation in the Bay cannot be determined from monitoring data. In fact, it cannot be stated with complete certainty that the natural condition for a shallow, wind-driven system such as Back Bay is not to exhibit the suspended solid load observed in the 1980's. Measurements of suspended solids and turbidity in the main Bay were not started until the 1980's, so it is difficult to substantiate the suspected trend of increasing suspended solid loads in the system. However, the observed increase in organically bound nitrogen (TKN) in the Bay does indirectly suggest that organic-rich suspended solids concentrations have increased over the past two decades.

It may prove useful to classify the levels of various water quality parameters measured in the Bay during the 1980's relative to 305b "reference levels" (VWCB, 1976), as has already been done for TKN and ammonia. Among the nutrients, average nitrate concentrations for Nawney Creek sites (SG-II) for winter months (DG-3) exceeded the reference level of 0.9 mg/1 (Fig. 12). In fact, this reference level was exceeded by factors of 2-3 during certain collection periods at sites in Nawney Creek (Fig. 25b). The other creeks had somewhat elevated levels of nitrates, but "peak" concentrations observed during the 1970's tended to moderate during the 1980's, particularly in Hell Point Creek and Beggars Bridge Creek (Fig. 25b). Nitrate concentrations at the main Bay sites did not exceed the reference level, although sites BKY006.37 and BKY003.47 did display the most elevated nitrate concentrations during this period, possibly reflecting their proximity to the Nawney Creek "source" area (Fig. 25a).

Average concentrations of OPO_4 exceeded the "reference level" of 0.1 mg/1 at Nawney Creek sites (SG-II) during all seasons (Fig. 13). The OPO4 concentrations at these sites often exceeded the reference level by factors of 2-3 or more (Fig. 26b). The reference level was exceeded occasionally at other creek sites (Fig. A26b), as well as the two main Bay sites (BKY006.37 and BKY003.47) in closest proximity to Nawney Creek (Fig. 26a).

Total suspended solids (fixed plus volatile suspended solids) exceeded the reference level of 80 mg/1 at the main Bay sites (SG-III) during the winter months (DG-3) and much of the spring/fall collections (DG-2) (see Figs. 15, 16, 27a, and 27b). Peak concentrations of suspended sediments at sites BKY003.47 and BKY006.37 exceeded this level by factors of 2-3, presumably during winter "storm" events (Fig. 27a).

The pH readings which were quite elevated in the main Bay waters (often measuring 9-10 pH units, exceeding the reference level of 9) during the 1970's appeared to moderate (readings of 7-8 units) during the 1980's (Fig. 28a). This trend could be due to a decrease in primary production, either of submerged aquatic vegetation, or phytoplankton, or both. Although dissolved oxygen readings were not taken in the 1980's, high (probably supersaturated) oxygen concentrations were observed during the 1970's, tending to substantiate the speculation that elevated pH readings during that decade were due to high levels of primary productivity. Neither pH nor dissolved oxygen measurements were taken consistently at all of the tributary creek sites during the 1980's, so no speculation can be made concerning the patterns of these parameters in these areas.

Finally, salinity measurements in Back Bay have been taken for the STORET data set only since mid-1987. Since seawater pumping operations have ceased, it has been speculated (Marshall, 1988) that salinities in Back Bay should decrease over time. Although it is difficult to detect a significant long-term trend with only two years of data, the patterns may suggest that salinities may be decreasing (i.e. spring lows for 1987 were lower than 1988; see Fig. 28b). Of course, the spring of 1989 was quite wet, so only a more extended data base will confirm whether a long-term trend for decreasing salinities is, in fact, in progress.

Literature

Alden, R.W. III, R.M. Ewing, and S.W. Sokolowski. 1988. Lower Chesapeake Bay Mainstem Water Quality Monitoring Program. Final Report to Virginia Water Control Board. 84 pp.

Birdsong, R.S., H.G. Marshall, R.W. Alden III, and R.M. Ewing. 1988. Lower Chesapeake Bay Mainstem Plankton Monitoring Program for 1986-87. Final Report to Virginia Water Control Board.

Gilbert, R.O. 1987. *Statistical Methods for Environmental Pollution Monitoring*. VanNostrand Reinhold Co., New York. 320 pp.

Green, R.H. 1979. *Sampling Design and Statistical Methods for Environmental Biologists*. John Wiley and Sons, Inc., New York. 257 pp.

Hirsch, R.M., J.R. Slack, and R.A. Smith. 1982. Techniques of trend analysis for monthly water quality data. Water Resources Research 18: 107-121.

Hirsch R.M. and J.R. Slack. 1984. A nonparametric trend test for seasonal data with serial dependence. Water Resources Research 20(6): 727-732.

Marshall, H.G. 1988. Seasonal phytoplankton composition and abundance patterns in Back Bay, Virginia. Final Report to The Virginia Commission of Game and Inland Fisheries. 40 pp.

Virginia Water Control Board. 1976. Water Quality Inventory (305(b) Report) *Virginia*. Report to EPA Administrator and Congress. Information Bulletin 526. VWCB, Richmond, VA. 361pp., 2 Appendices.

Virginia Water Control Board. 1978. Water Quality Inventory (305(b) Report) *Virginia*. Report to EPA Administrator and Congress. Information Bulletin 542. VWCB, Richmond, VA. 98pp.

Williams, W.T. and W. Stephenson. 1973. The analysis of three-dimensional data (sites x species x times) in marine ecology. J. Exp. Mar. Biol. Ecol. 11: 207-227.

Acknowlegements

This study has been supported by a grant from the Back Bay Restoration Foundation through funds provided by the Virginia Environmental Endowment. We would like to acknowledge the substantial technical efforts of John Seibel and the staff of the Applied Marine Research Laboratory Computer Section: John Kressel, Cheryl Hess, and Michael Ehret. The study would not have been possible without their dedicated efforts in the areas of data acquisition, reduction and management; multivariate statistical analyses; and computer graphics. We also would like to express appreciation to Rita Hidalgo who provided the technical support required for the preparation of this report.

We would also like to acknowledge the efforts of Mitchell Norman and Ron Southwick of the Department of Game and Inland Fisheries and Bill Scott and Sean Priest of the Back Bay Restoration Foundation who collected the samples that provided much of the data analyzed in this report and Walter Priest who was the project manager for the Foundation.

The efforts of Robert F. Jackson and his staff of the Virginia State Water Control Board in organizing the sampling program and providing interim data reports are greatly appreciated.

Table 1. Matrix displaying qualitative degree of continuity in water quality data sets from Back Bay.

Station	TEMP	TOTAL RESID	SSVOL	SSFIX	AMMONIA	NITRITE	NITRATE	TKN	TP	ORTHO	TOC	SALIN	pH	TURBY	COND	DO	FECCOL	BOD_5	SECCHI
WNC003.65	A	A	A	A	A	A	A	A	A	A	B	NS	F	C	D	F	A	F	NS
	A	F	F	F	A	A	B	A	F	F	F	NS	A	F	F	A	F	E	NS
SHB000.57	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	F	F	NS	B
	G	F	F	F	G	G	H	G	F	F	F	F	G	F	F	G	G	NS	F
NWN001.84	A	A	A	A	A	A	A	A	A	A	B	NS	NS	C	D	NS	NS	NS	NS
	F	F	F	F	F	F	F	F	F	F	F	NS	NS	F	F	NS	NS	NS	NS
NWN000.00	A	A	A	A	A	A	A	A	A	A	B	NS	F	C	B	F	F	NS	NS
	G	F	F	F	G	G	H	G	F	F	F	NS	G	F	F	G	G	NS	NS
MDY000.00	A	A	A	A	A	A	A	A	A	A	B	NS	F	D	B	F	F	F	NS
	G	F	F	F	G	G	H	G	F	F	F	NS	G	F	F	G	G	D	NS
HPC001.46	A	A	A	A	A	A	A	A	A	A	B	B	A	D	A	A	A	A	NS
	A	D	F	F	A	A	B	A	F	F	F	F	A	F	F	A	A	E	NS
HPC000.00	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	F	F	F	B
	G	F	F	F	G	G	H	G	F	F	F	F	G	F	F	G	G	D	F
BKY006.48	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	F	F	NS	B
	F	F	F	F	G	G	H	G	F	F	F	F	G	F	F	G	G	NS	F
BKY006.37	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	NS	NS	NS	B
	F	F	F	F	F	F	F	F	F	F	F	F	F	F	G	MS	MS	MS	F
BKY003.47	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	NS	NS	NS	B
	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	NS	NS	NS	F
BKY000.99	A	A	A	A	A	A	A	A	A	A	B	B	A	B	B	NS	NS	NS	B
	F	F	F	F	F	F	F	F	F	F	F	F	F	F	F	NS	NS	NS	F
BBC000.76	A	A	A	A	A	A	A	A	A	A	B	NS	F	C	B	F	F	F	NS
	A	F	F	F	A	A	B	A	F	F	F	NS	A	F	F	A	A	E	NS

Legend (top half of box = sampled in 1980; bottom half of box = sampled in 1970):

A = sampled regularly
B = sampled regularly, but with 1 large gap
C = sampled once
D = sampled a few times
E = sampled many times with significant gaps
F = not sampled during time period
G = sampled during summer only
H = sampled during summer only, but with 1 large gap
NS = never sampled

Table 2. Results of the long term trend analysis of water quality at station HPC001.46. The probability (p) values for the overall trends are shown for nonparametric models unadjusted and adjusted into units.

Variable	Median Value	Trend Slope (Units/Year)	P-Value Unadjusted	P-Value Adjusted	Significant "Seasonal" Trend Slopes (Units/Year)	Month	P-Value
TKN	1.500 mg/1	0.018	0.058	0.292	-0.100	Jan.	0.021
					0.108	Sep.	<0.001
NH3	0.150 mg/1	0.011	<0.001	0.008	-0.108	Jan.	0.001
					-0.041	Mar.	0.031
					-0.022	Apr.	0.043
					-0.010	May	0.026
					-0.024	Jun.	0.026
NO_2	0.010 mg/1		0.096	0.100	—	—	—
DO	8.9 mg/1		0.12	0.10	—	—	—
Temp	18°C		0.065	0.143	—	—	—
Cond	3023 mohms		0.385	0.581	—	—	—
pH	7.1		0.972	0.976	—	—	—

Table 3. Mean variance per comparison values for the 1970 and 1980 water quality data sets. Values in parentheses represent the percentage that each represents of the total "explained" variance.

	Variance Attributable To:		
Nature of Comparison	Spatial Effects	Temporal Effects	Spatial-Temporal Interaction
1970 & 1980 data	4.50 (61)	2.22 (30)	0.70 (9)
1980 data only	8.82 (58)	5.39 (35)	1.10 (7)

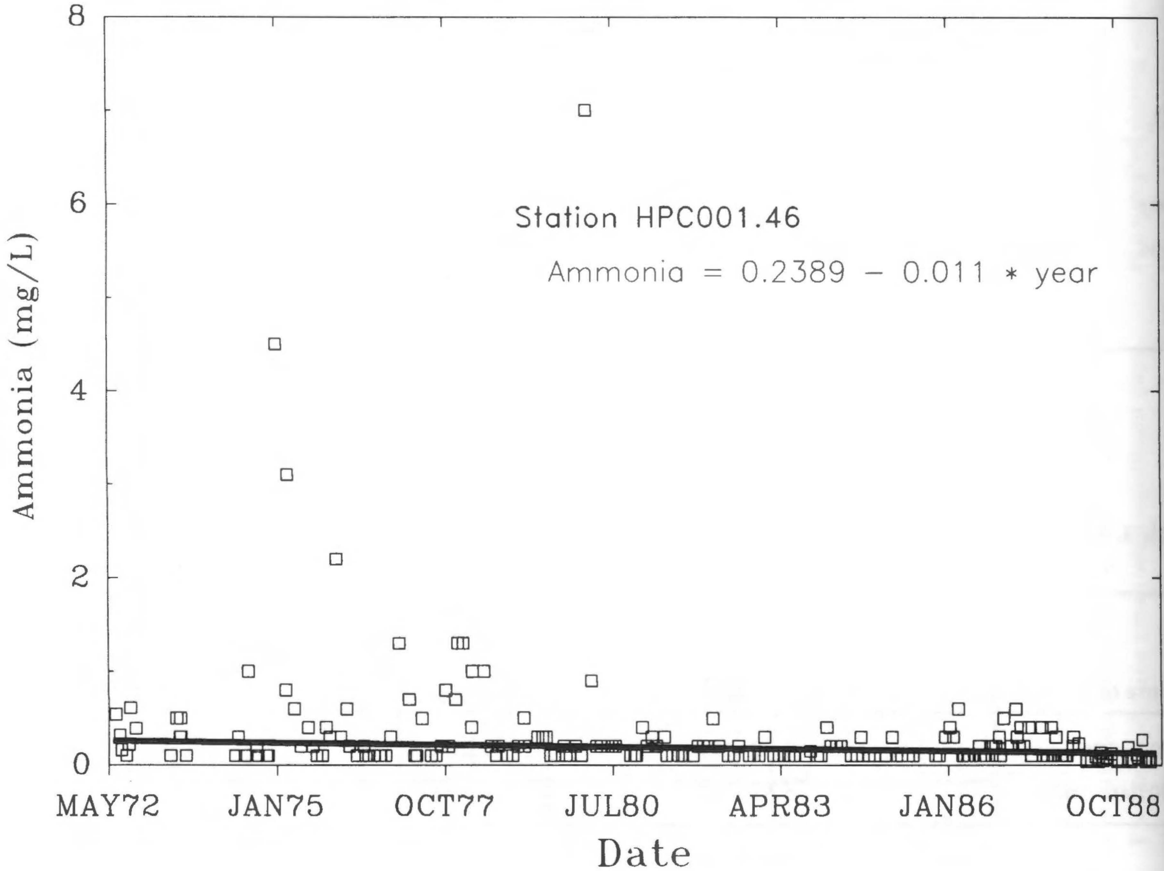


Figure 1. Ammonia concentrations (mg/1) versus date of collection for Hell Point Creek site HPC001.46. The line represents the trend detected by the seasonal Kendall test for serially correlated data.

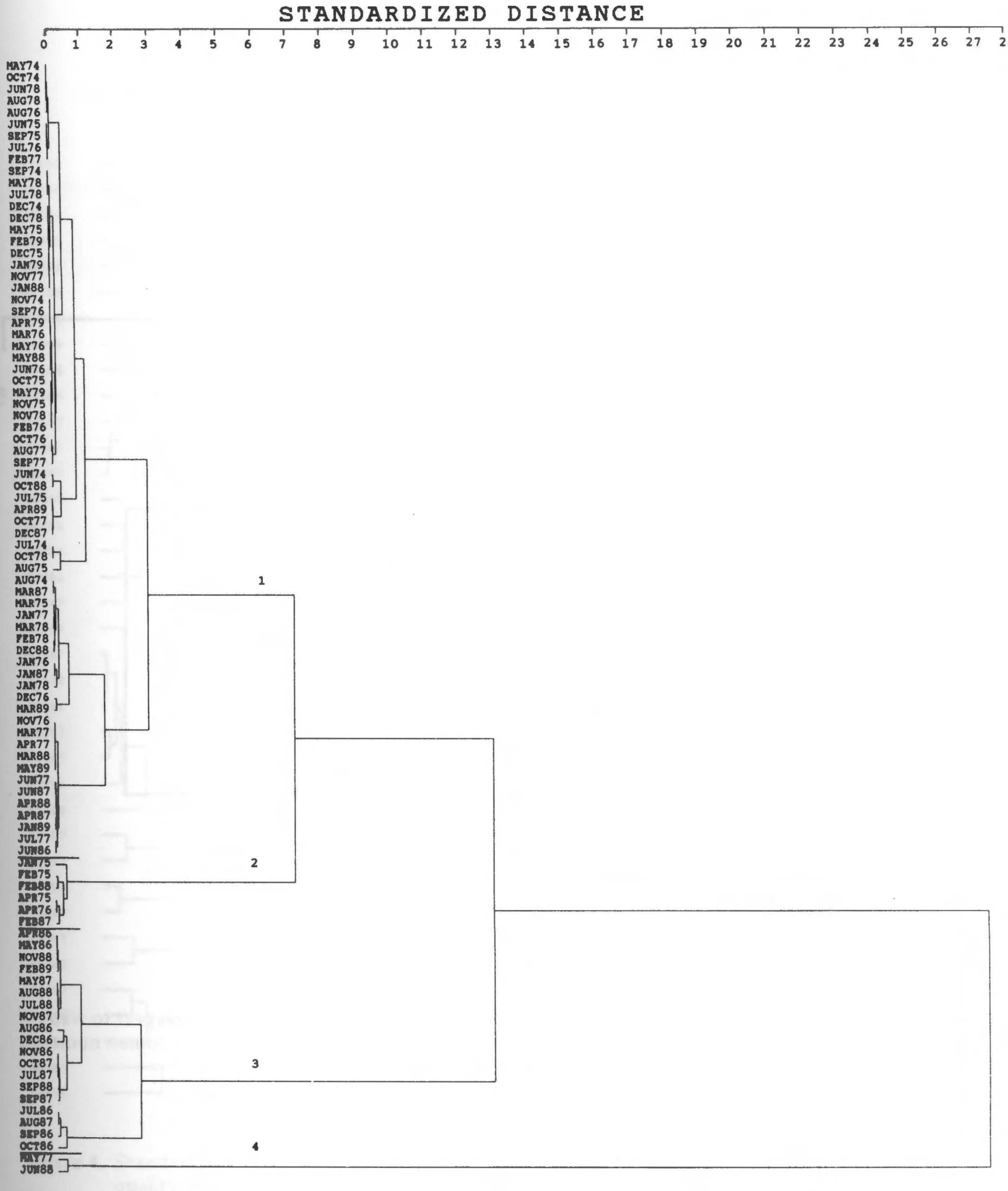


Figure 2. Standardized distance dendogram for classification of temporal patterns with respect to water quality conditions for the 1970's and 1980's (spatial effects removed). The arabic numbers designate date groups.

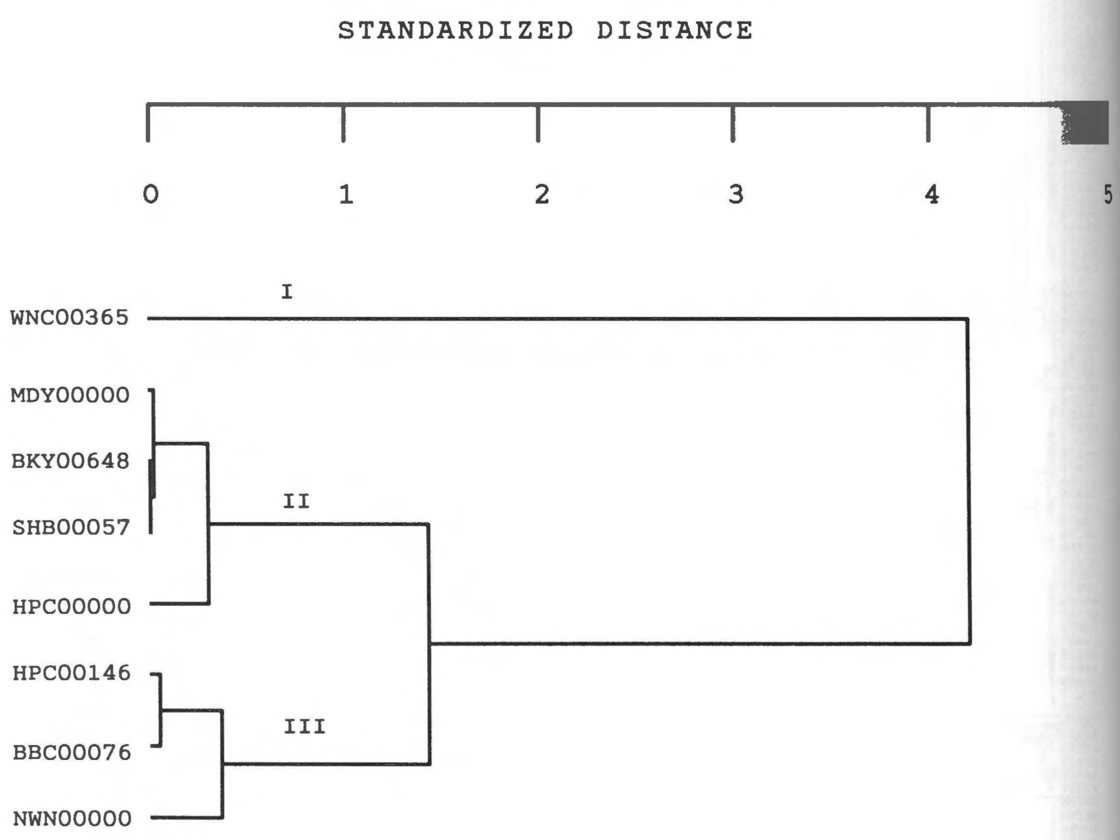


Figure 3. Standardized distance dendogram for classification of spatial patterns with respect to water quality conditions for the 1970's and 1980's (temporal effects removed). The roman numerals designate site groups.

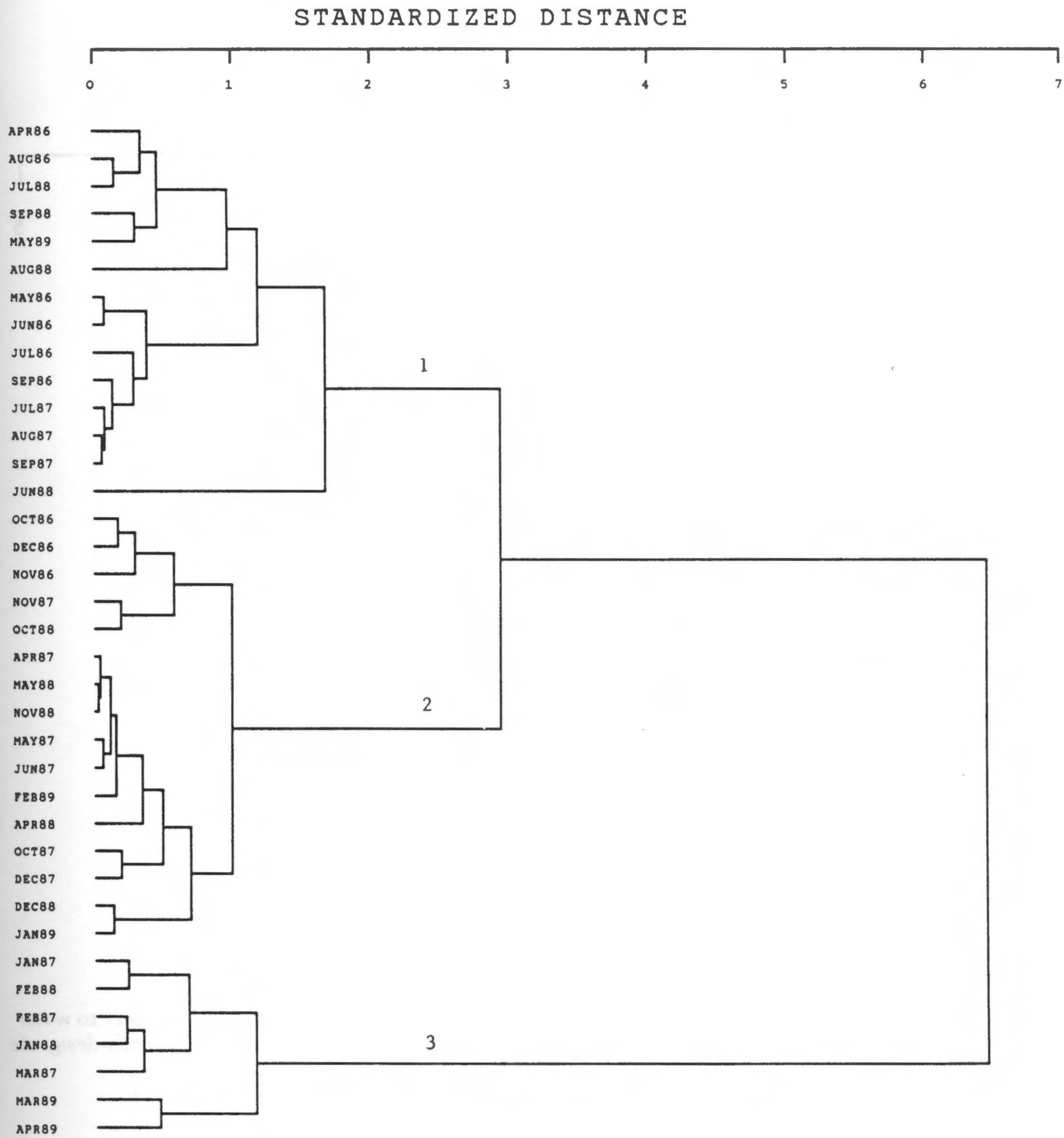


Figure 4. Standardized distance dendogram for classification of temporal patterns with respect to water quality conditions for the 1980's (spatial effects removed). The arabic numbers designate date groups.

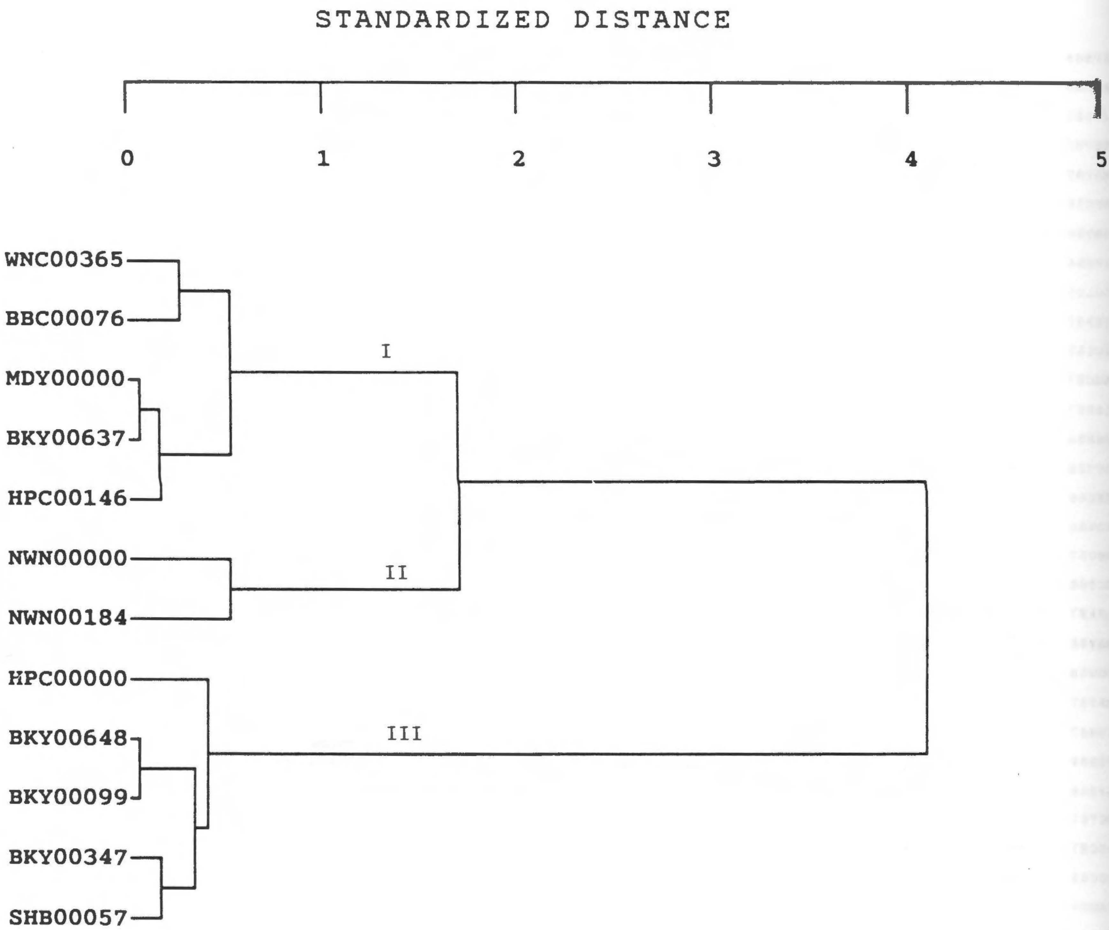


Figure 5. Standardized distance dendogram for classification of spatial patterns with respect to water quality conditions for the 1980's (temporal effects removed). The roman numerals designate site groups.

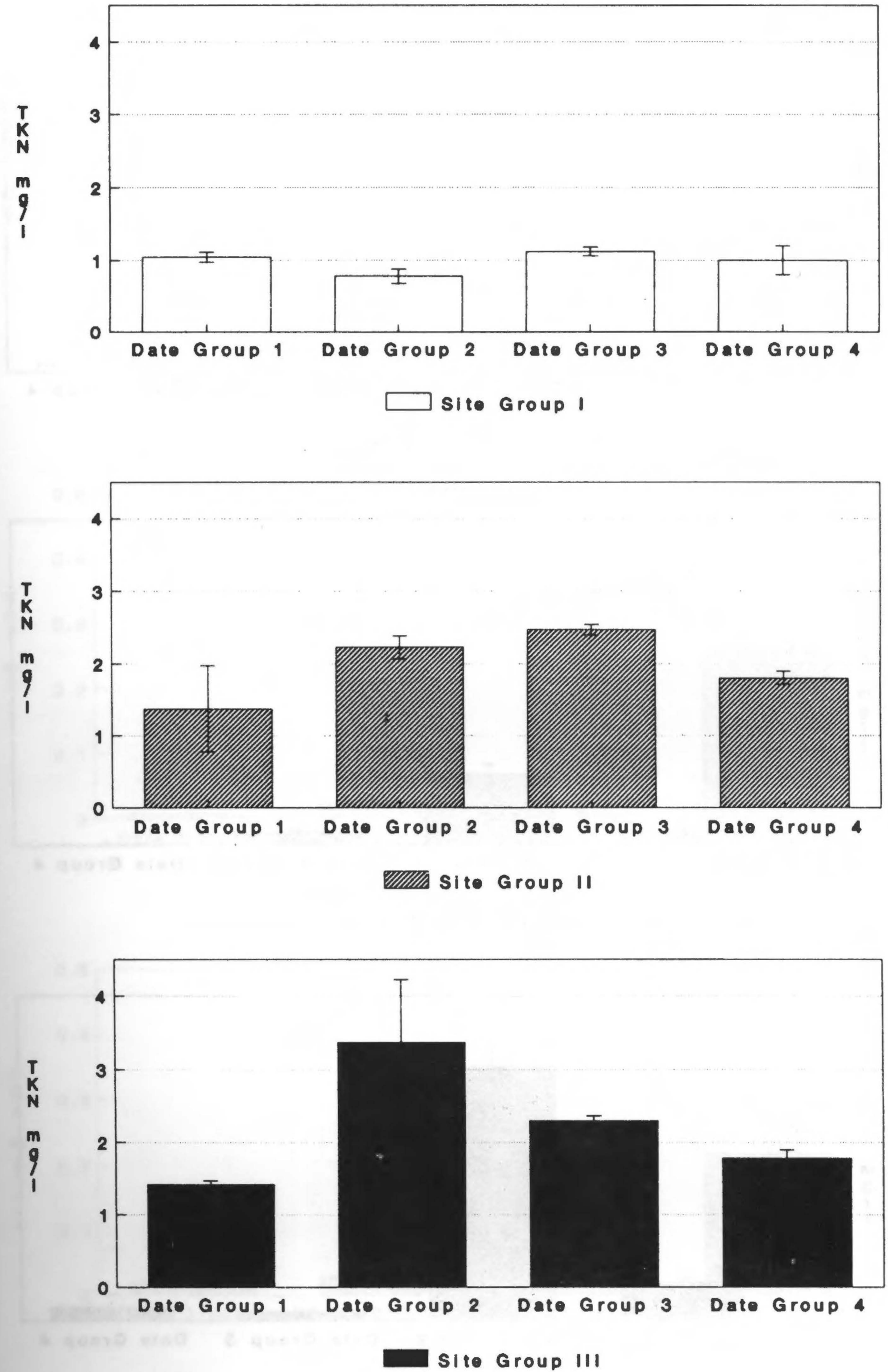


Figure 6. Mean concentrations of total Kjeldahl nitrogen (mg/1) for site group-date group combinations resulting from cluster analysis of the 1970's and 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

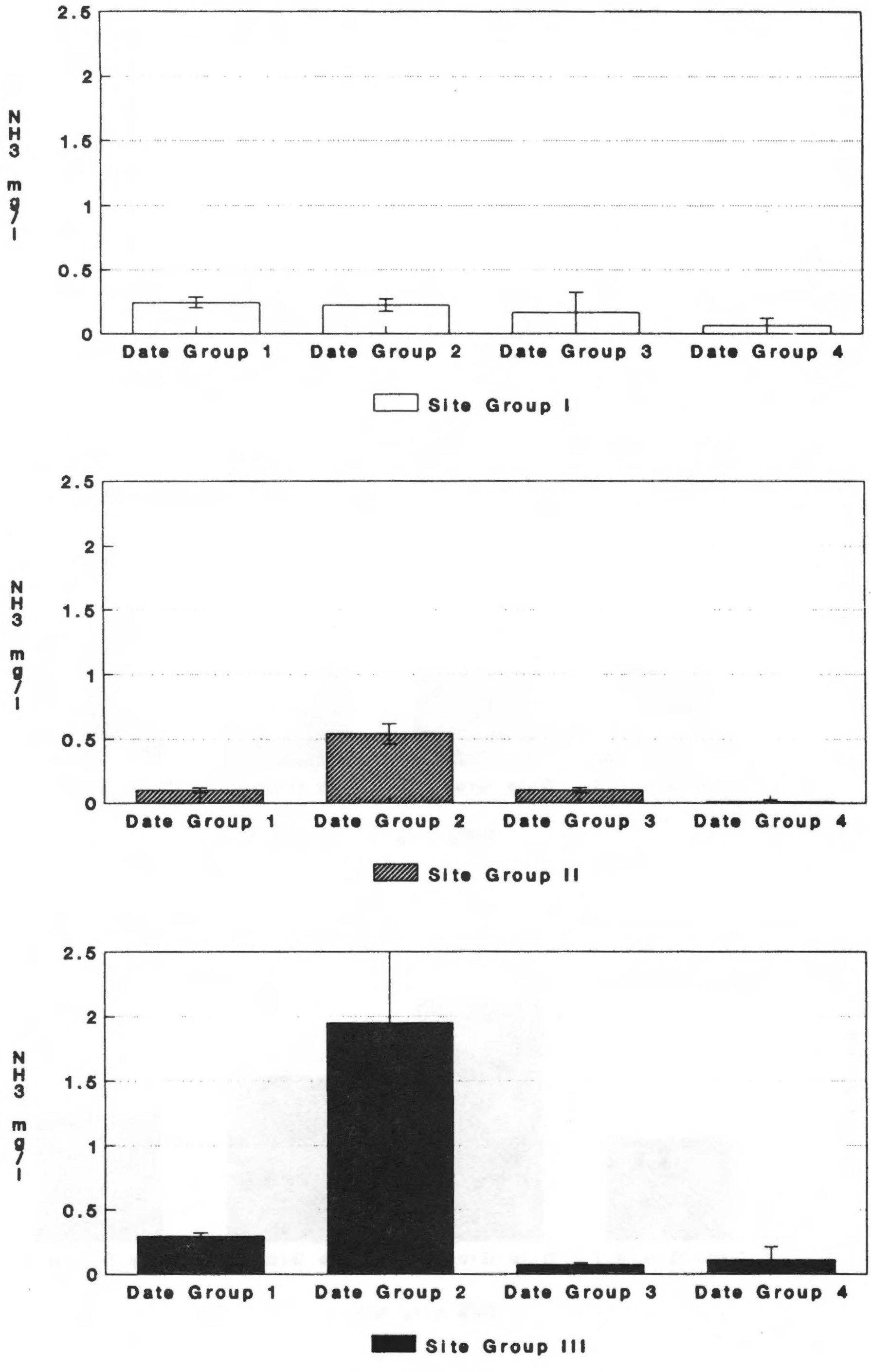


Figure 7. Mean concentrations of ammonia (mg/1) for site group-date group combinations resulting from cluster analysis of the 1970's and 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

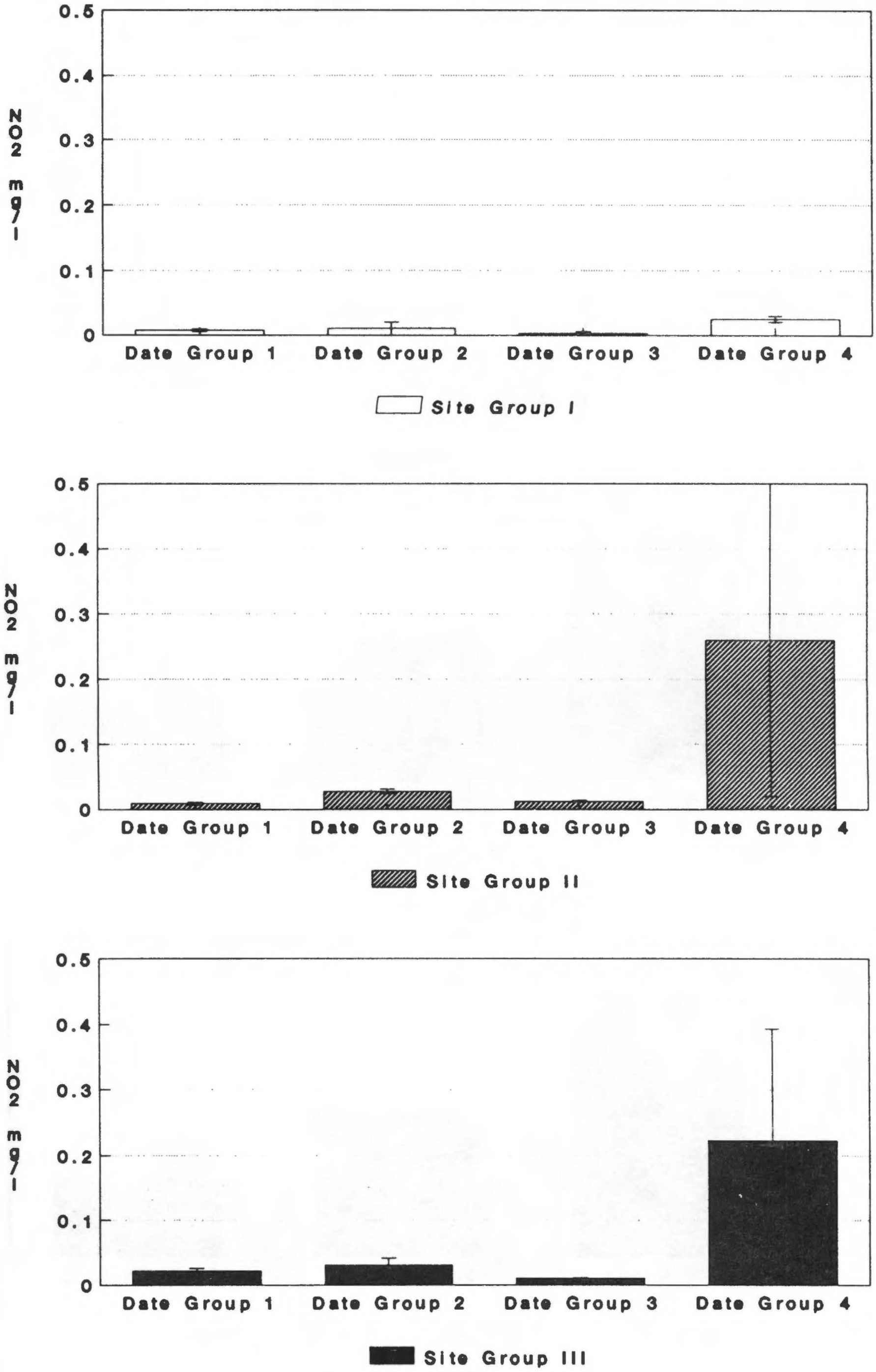


Figure 8. Mean concentrations of nitrite (mg/1) for site group-date group combinations resulting from cluster analysis of the 1970's and 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

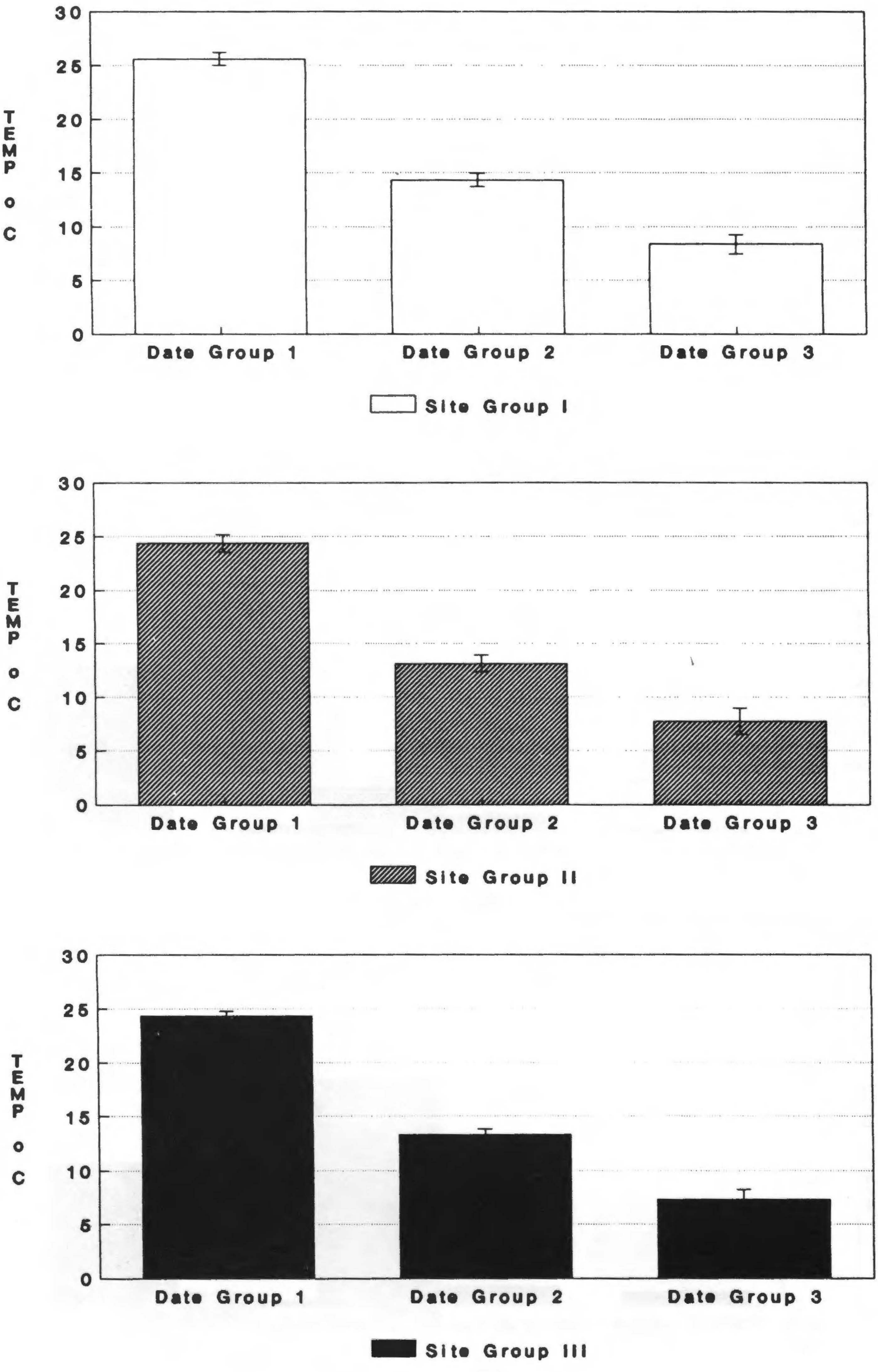


Figure 9. Mean concentrations of temperature (°C) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

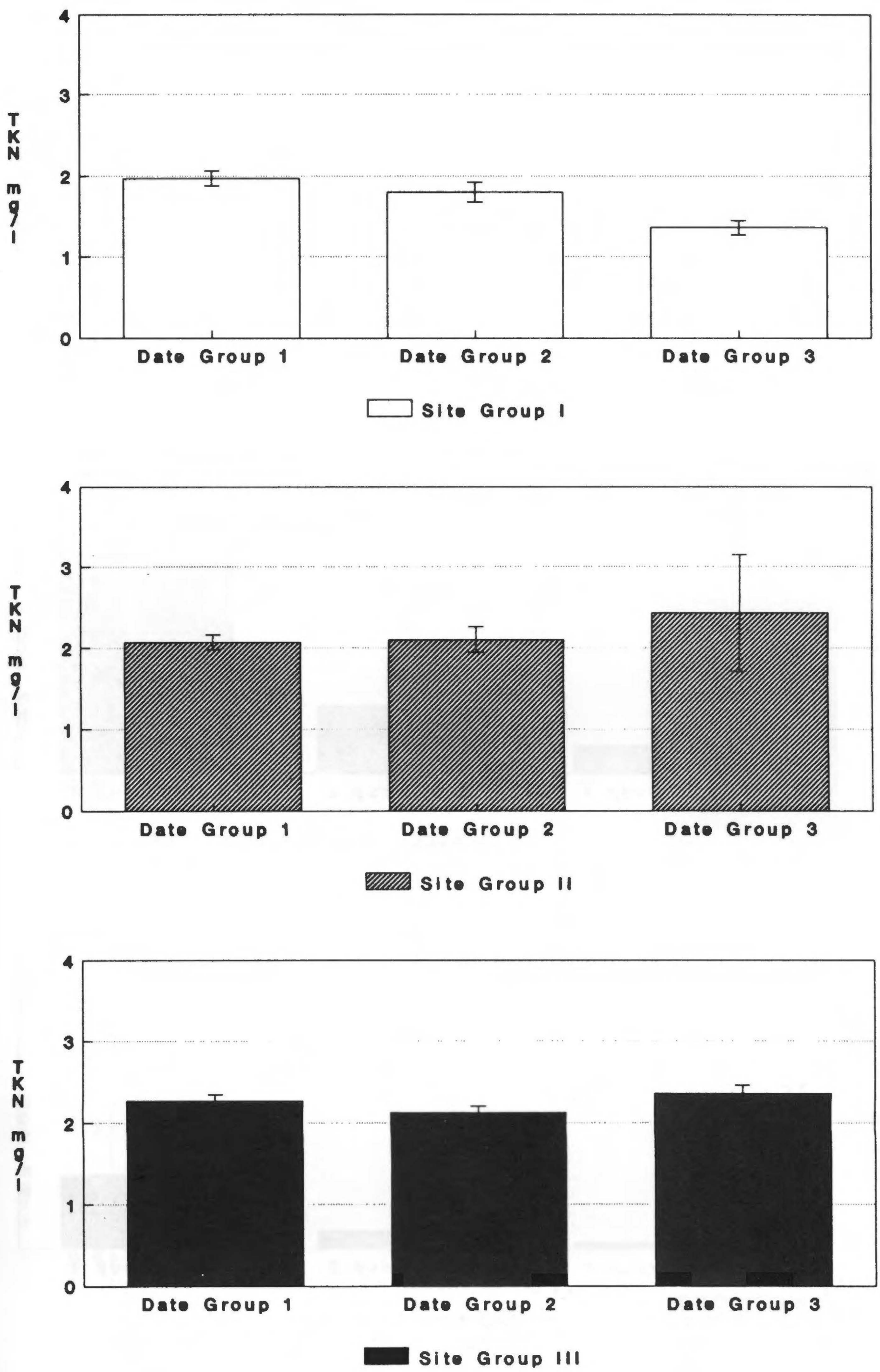


Figure 10. Mean concentrations of total Kjeldahl nitrogen (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

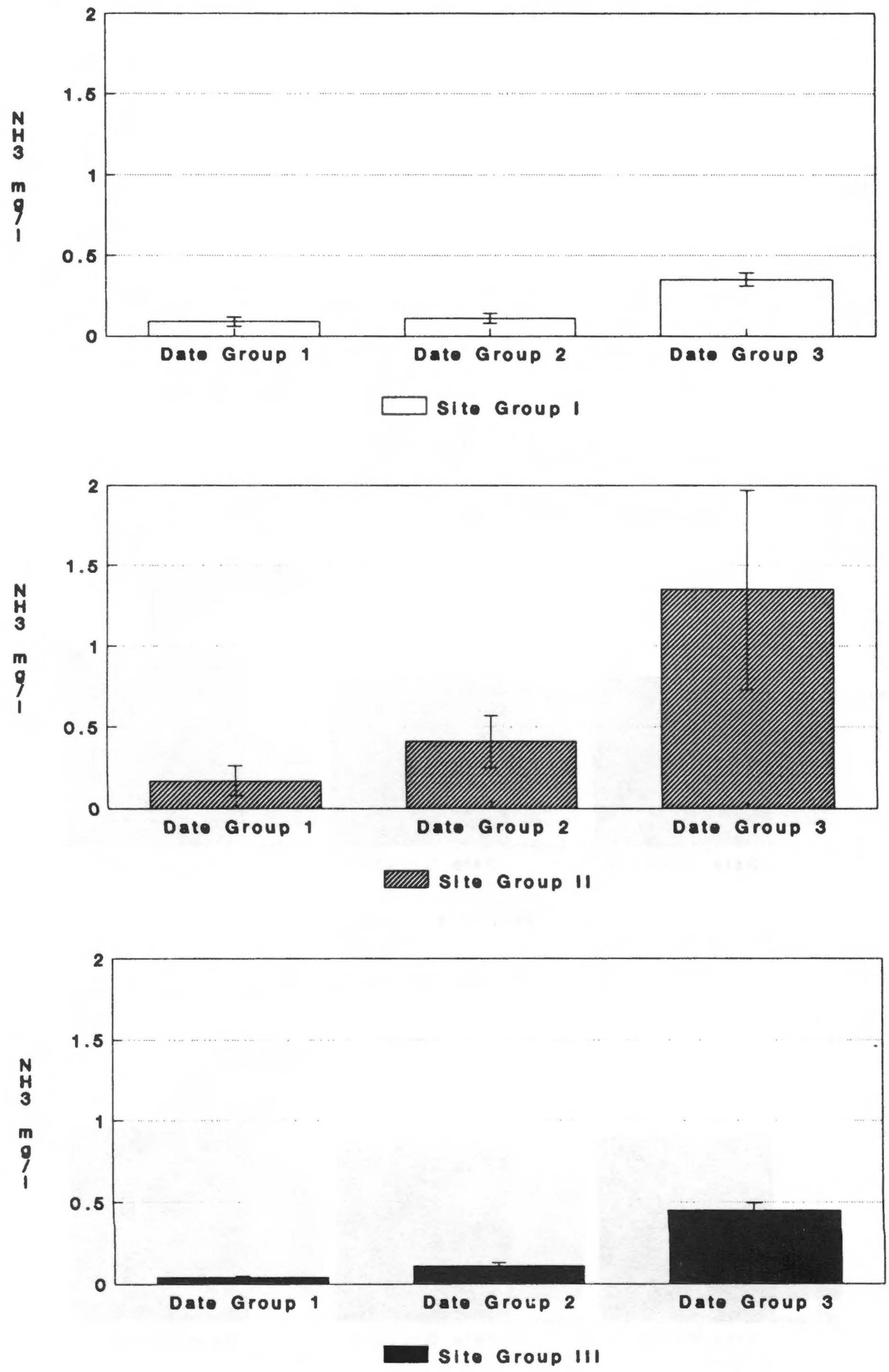


Figure 11. Mean concentrations of ammonia (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

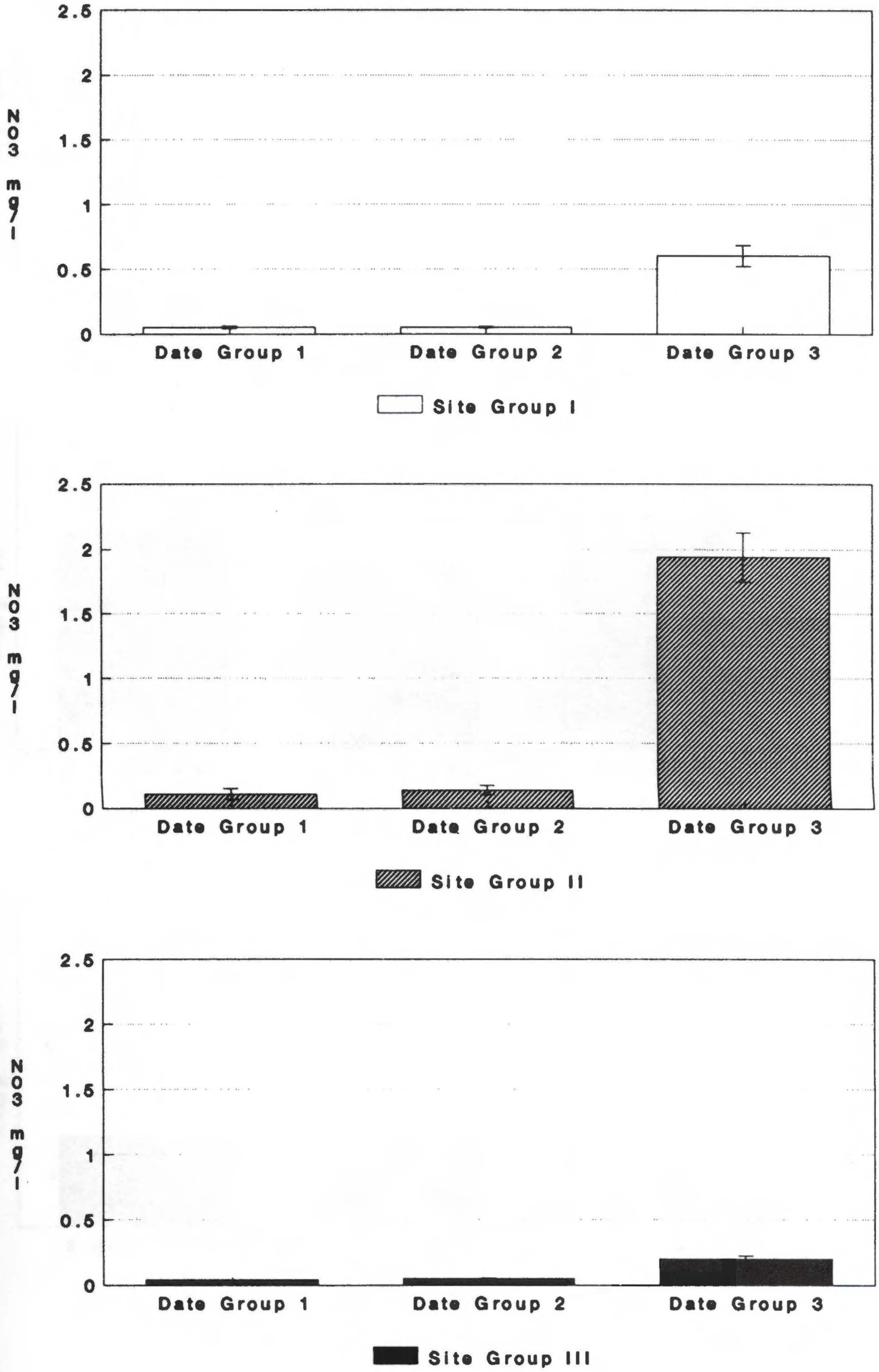


Figure 12. Mean concentrations of nitrate (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/– one standard error of the mean.

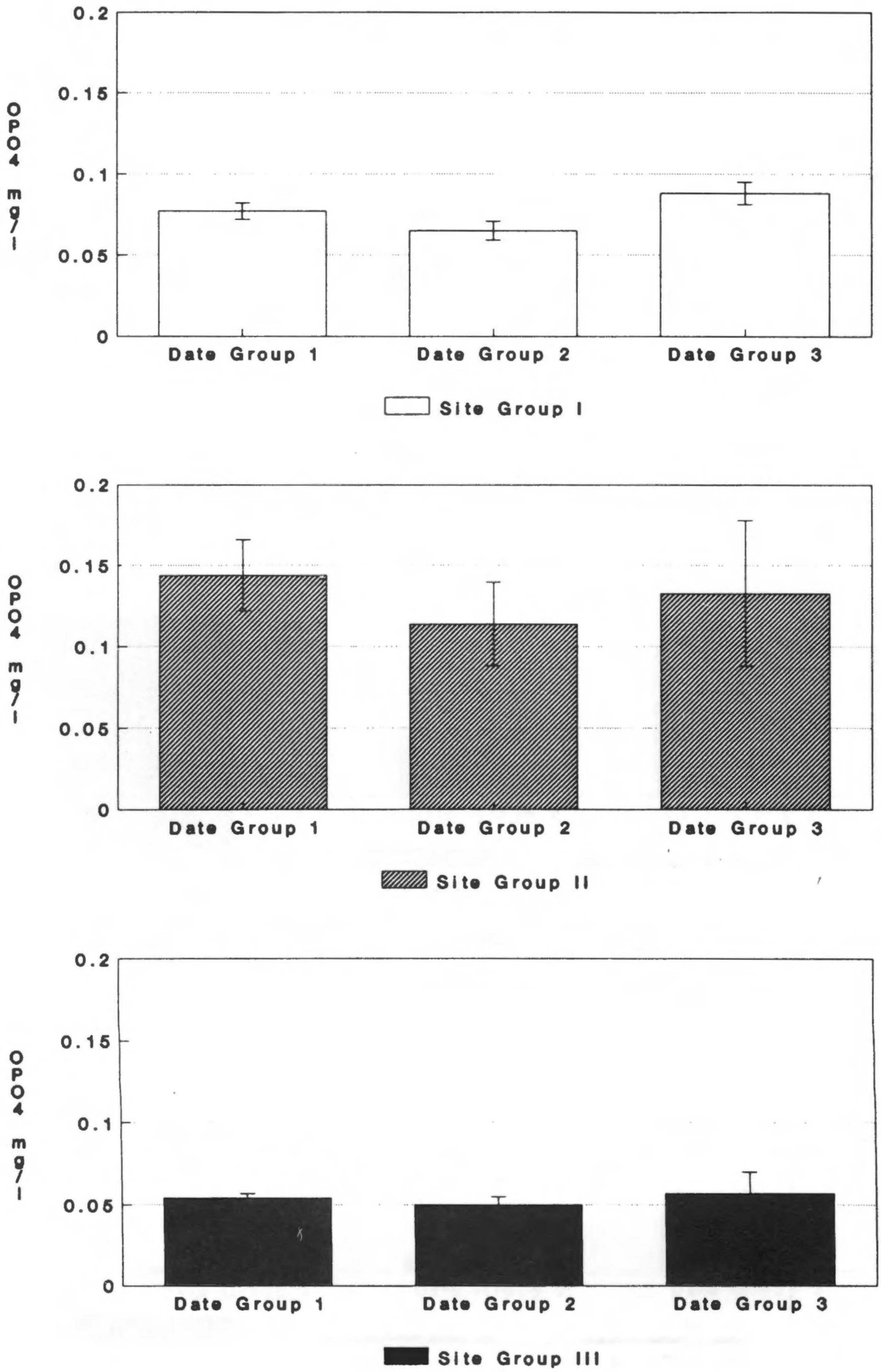


Figure 13. Mean concentrations of orthophosphates (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/ - one standard error of the mean.

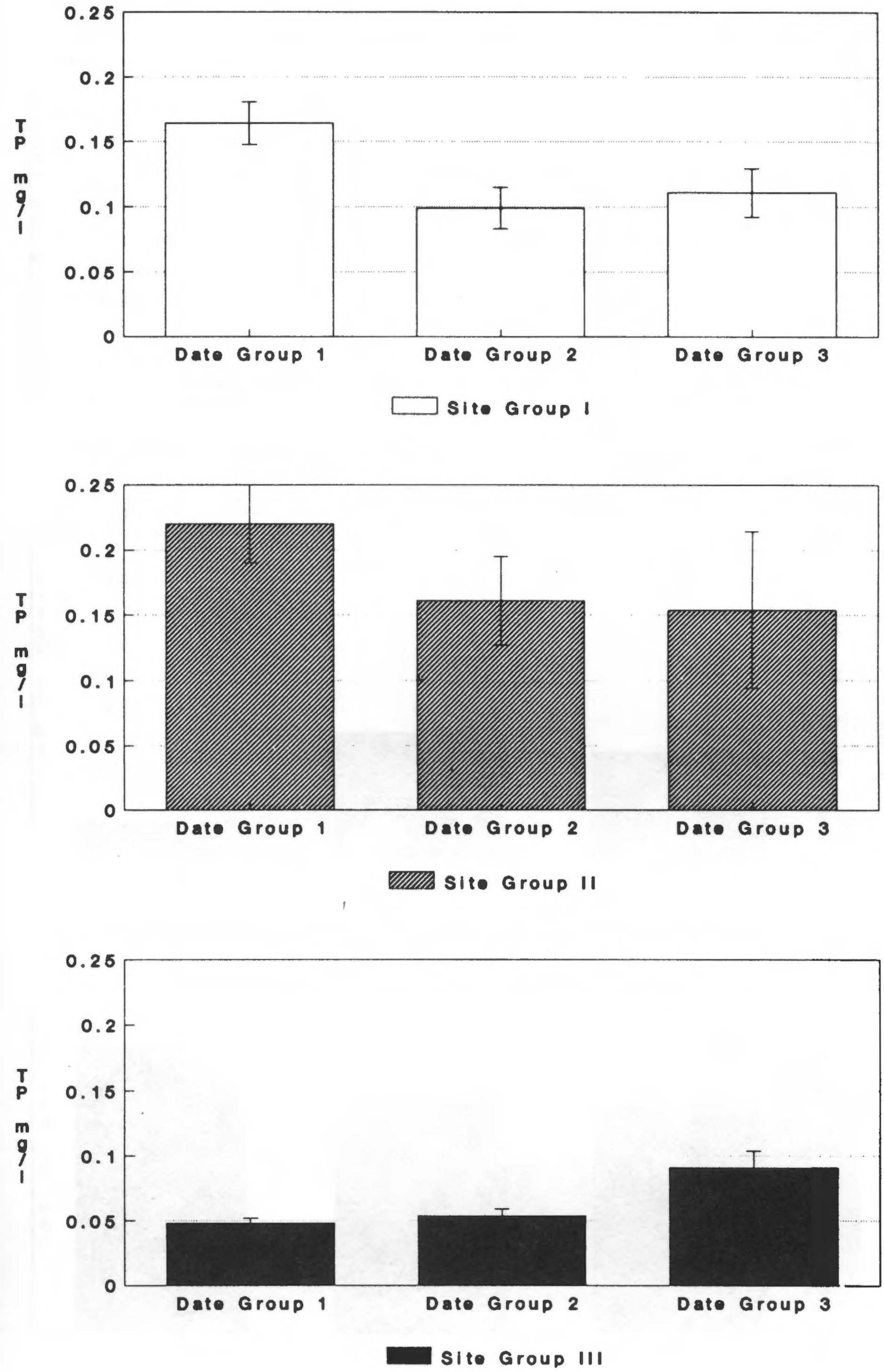


Figure 14. Mean concentrations of total phosphorus (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/ – one standard error of the mean.

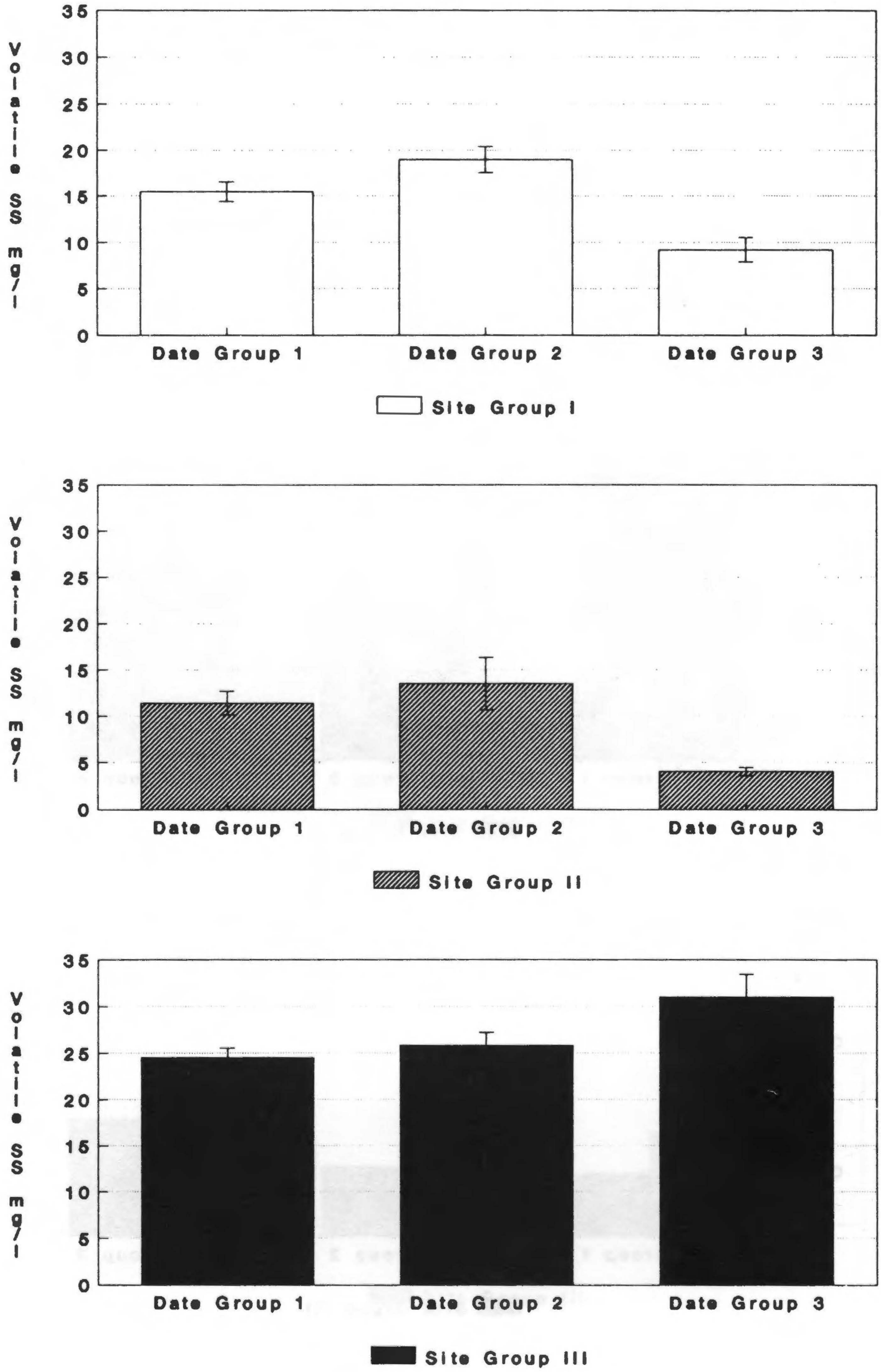


Figure 15. Mean concentrations of volatile suspended solids (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/- one standard error of the mean.

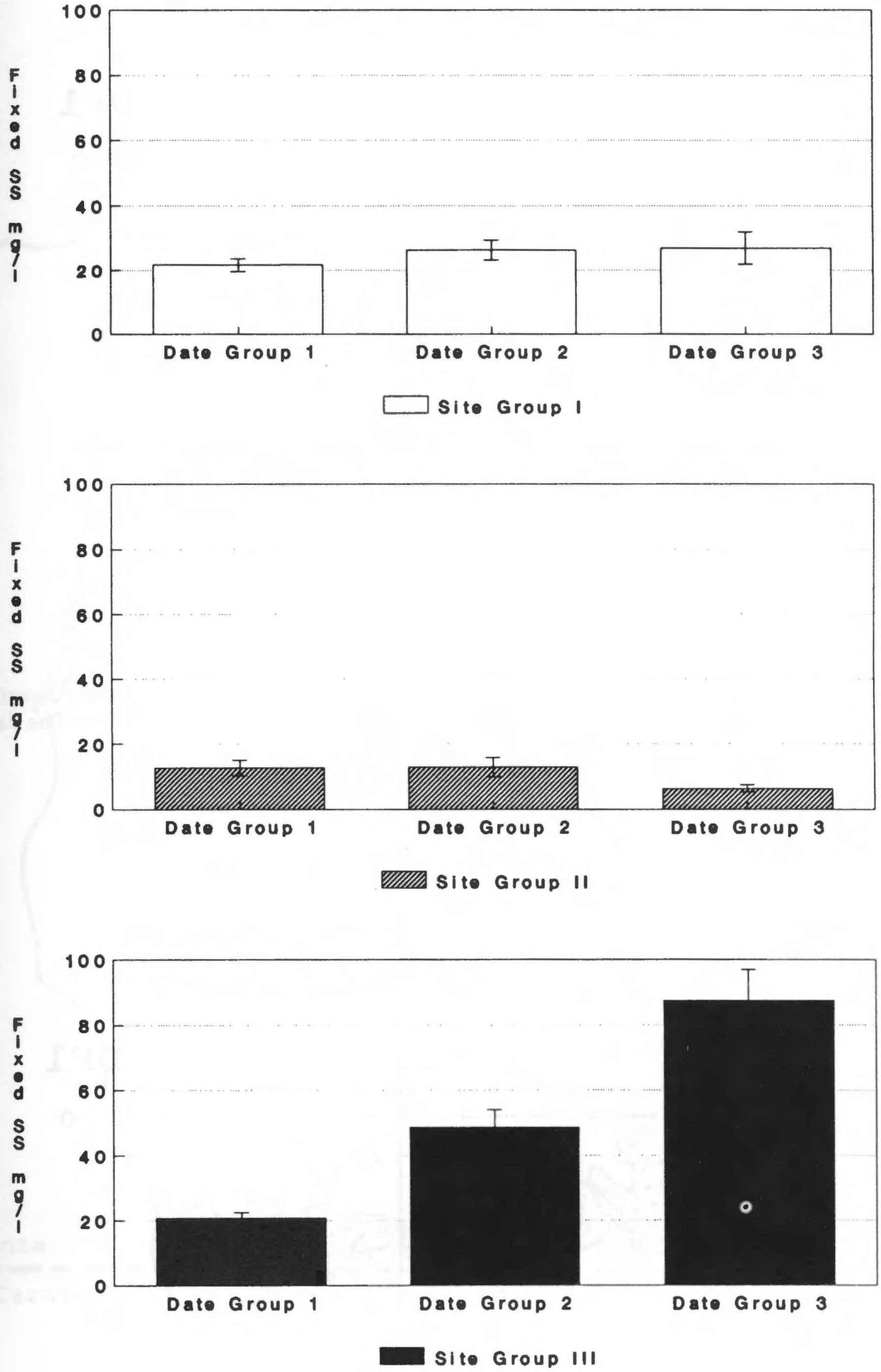


Figure 16. Mean concentrations of fixed suspended solids (mg/1) for site group-date group combinations resulting from cluster analysis of the 1980's water quality data. The vertical bars represent +/– one standard error of the mean.

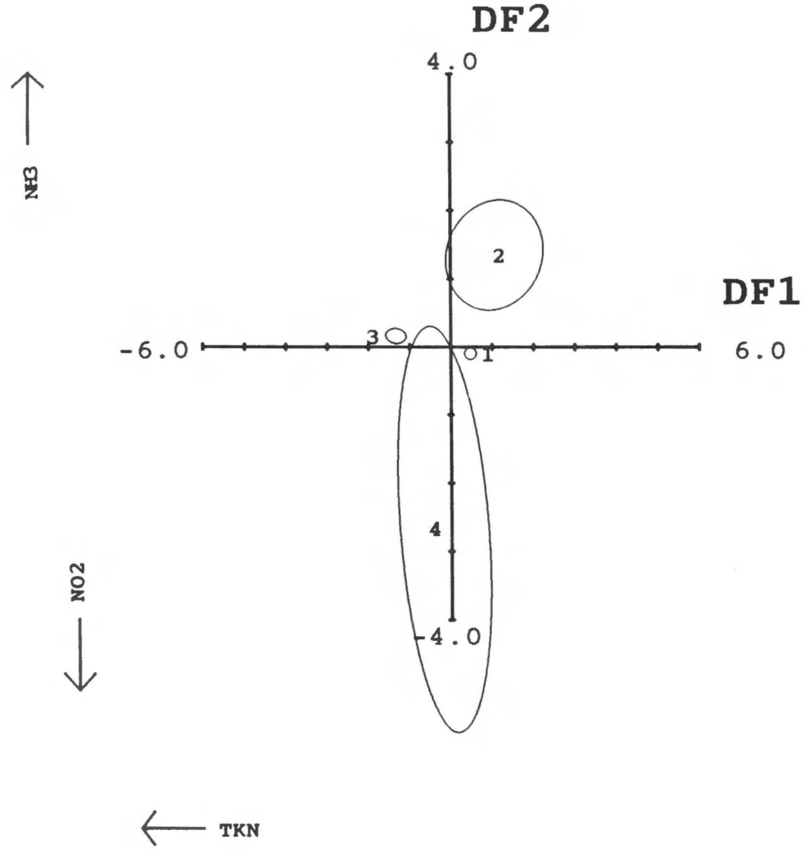


Figure 17. Confidence ellipses (a=0.05) for canonical discriminant scores of functions describing temporal differences in water quality conditions in the 1970's and 1980's. The date groups are those defined in Figure 2.

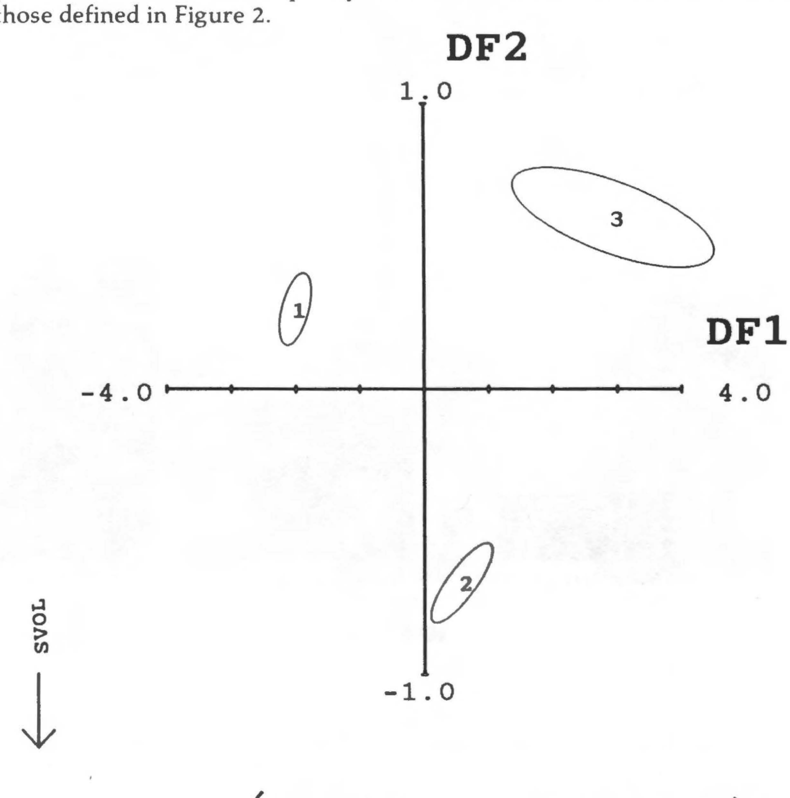


Figure 18. Confidence ellipses (a=0.05) for canonical discriminant functions describing temporal differences in water quality conditions in the 1980's. The date groups are those defined in Figure 4.

#	STATION	DESCRIPTION
1	5BWNC003.65	WEST NECK CREEK
2	5BMDY000.00	MOUTH OF MUDDY CREEK
3	5BHPC001.46	HELL POINT CREEK
4	5BHPC000.00	MOUTH OF HELL POINT CREEK
5	5BBBC000.76	BEGGARS BRIDGE CREEK
6	5BNWN001.84	MAWNEY CREEK ROAD BRIDGE
7	5BNWN000.00	MOUTH OF MAWNEY CREEK
8	5BBKY006.37	SOUTH OF DRUM POINT, OFF MOUTH OF MAWNEY CREEK
9	5BBKY003.47	OFF PELLITORY POINT
10	5BBKY000.99	NORTH OF BUCKLE ISLAND
11	5BBKY003.61	BACK BAY
12	5BBKY006.48	SAND BAY
13	5BBKY008.40	BUCK ISLAND BAY
14	5BSHB000.57	SHIPPS BAY, EAST
15	5BSHB001.15	SHIPPS BAY, WEST
16	5BXAJ001.01	NORTH BAY, LOWER
17	5BXAJ000.53	NORTH BAY, UPPER

NOTE: 'P' Designates Phytoplankton Station
All others are Water Quality Stations

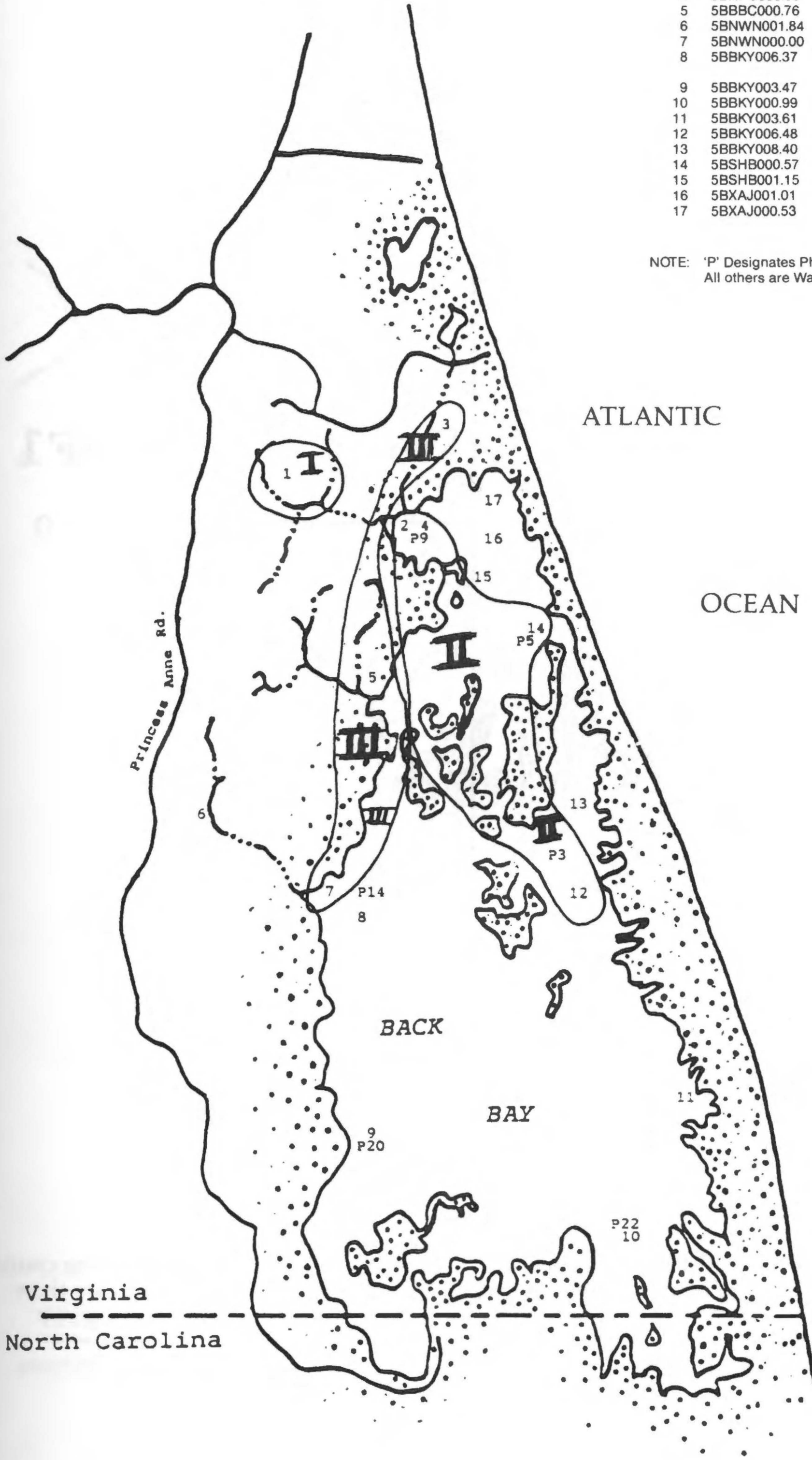


Figure 19. Map of Back Bay study area displaying collection sites and groups of sites displaying similar water quality patterns during the 1970's and 1980's. The site groups are those defined in Figure 3.

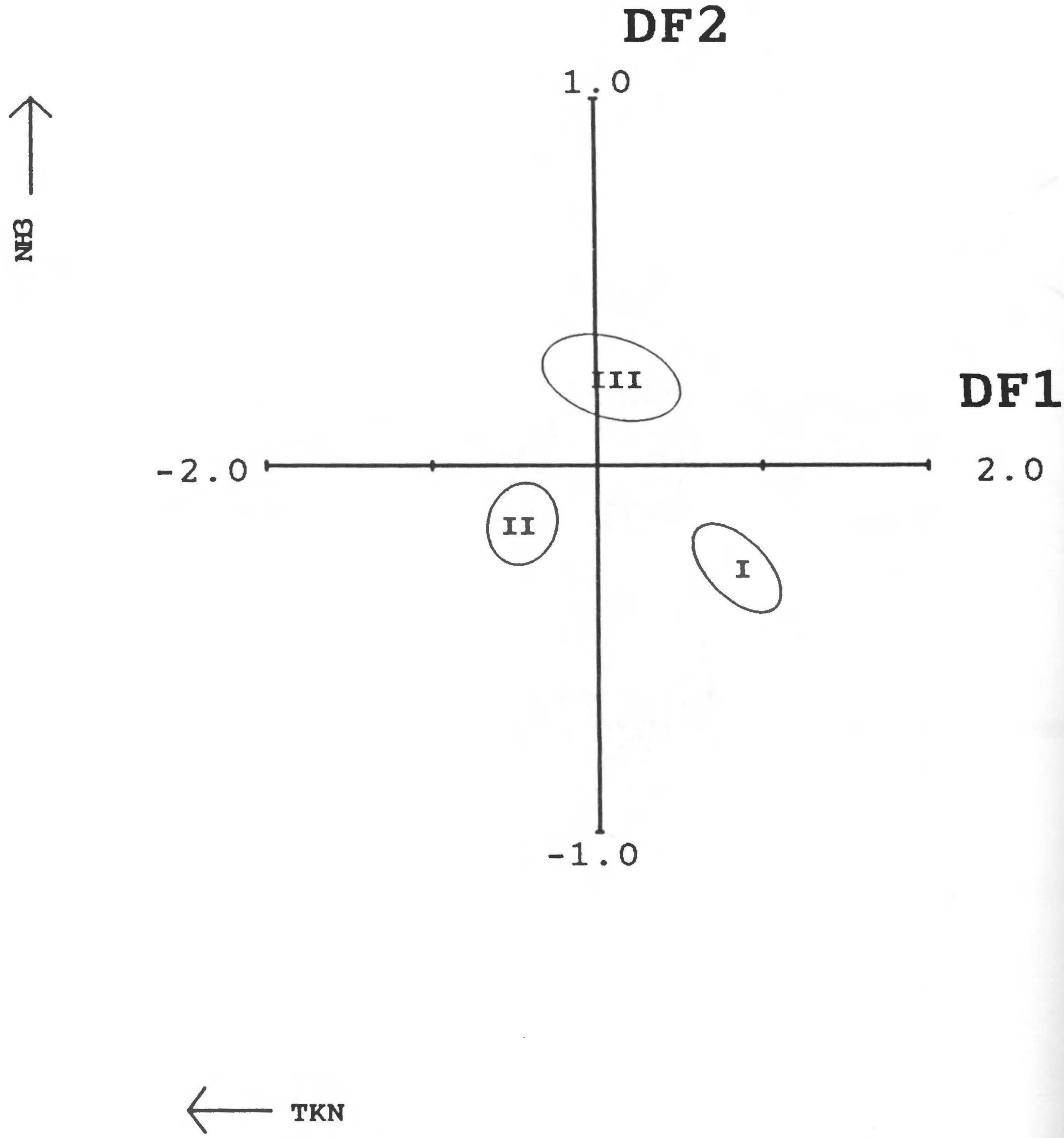


Figure 20. Confidence ellipses (a=0.05) for canonical discriminant scores of functions describing spatial differences in water quality conditions in the 1970's and 1980's. The site groups are those defined in Figure 3.

#	STATION	DESCRIPTION
1	5BWNC003.65	WEST NECK CREEK
2	5BMDY000.00	MOUTH OF MUDDY CREEK
3	5BHPC001.46	HELL POINT CREEK
4	5BHPC000.00	MOUTH OF HELL POINT CREEK
5	5BBBC000.76	BEGGARS BRIDGE CREEK
6	5BNWN001.84	MAWNEY CREEK ROAD BRIDGE
7	5BNWN000.00	MOUTH OF MAWNEY CREEK
8	5BBKY006.37	SOUTH OF DRUM POINT, OFF MOUTH OF MAWNEY CREEK
9	5BBKY003.47	OFF PELLITORY POINT
10	5BBKY000.99	NORTH OF BUCKLE ISLAND
11	5BBKY003.61	BACK BAY
12	5BBKY006.48	SAND BAY
13	5BBKY008.40	BUCK ISLAND BAY
14	5BSHB000.57	SHIPPS BAY, EAST
15	5BSHB001.15	SHIPPS BAY, WEST
16	5BXAJ001.01	NORTH BAY, LOWER
17	5BXAJ000.53	NORTH BAY, UPPER

NOTE: 'P' Designates Phytoplankton Station
All others are Water Quality Stations

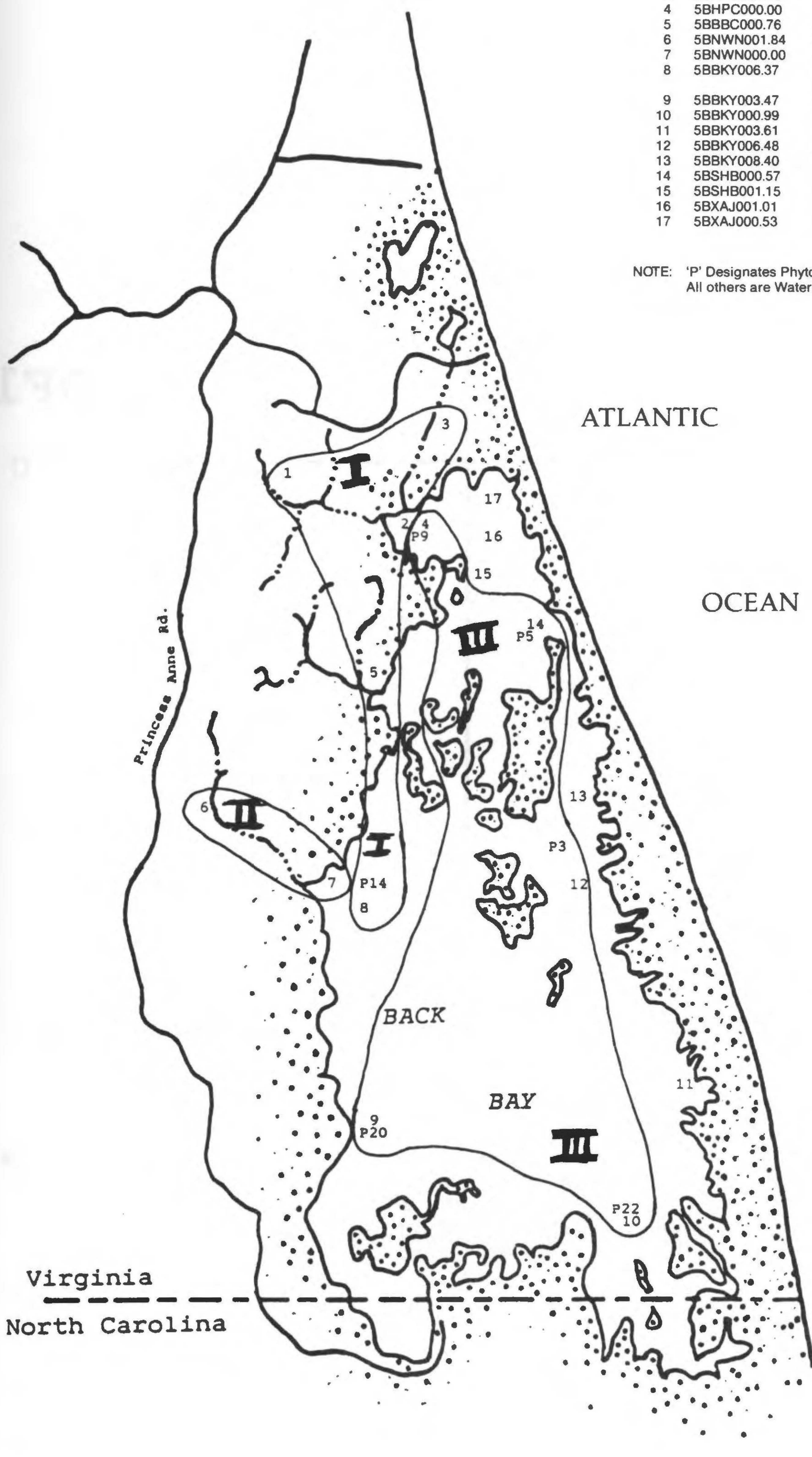


Figure 21. Map of Back Bay study area displaying collection sites and groups of sites displaying similar water quality patterns during the 1980's. The site groups are those defined in Figure 5.

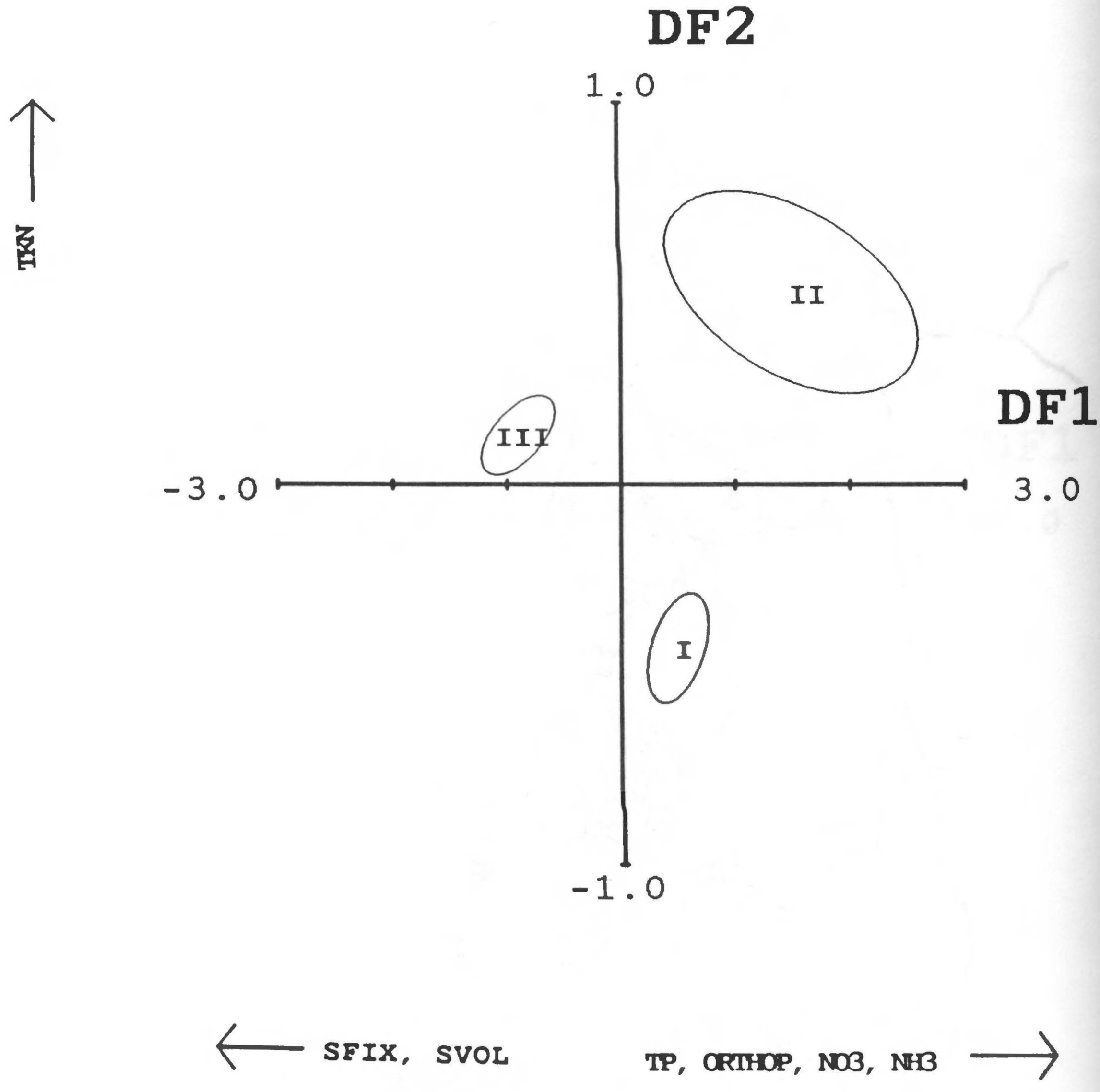


Figure 22. Confidence ellipses (α=0.05) for canonical discriminant scores of functions describing spatial differences in water quality conditions in the 1980's. The site groups are those defined in Figure 5.

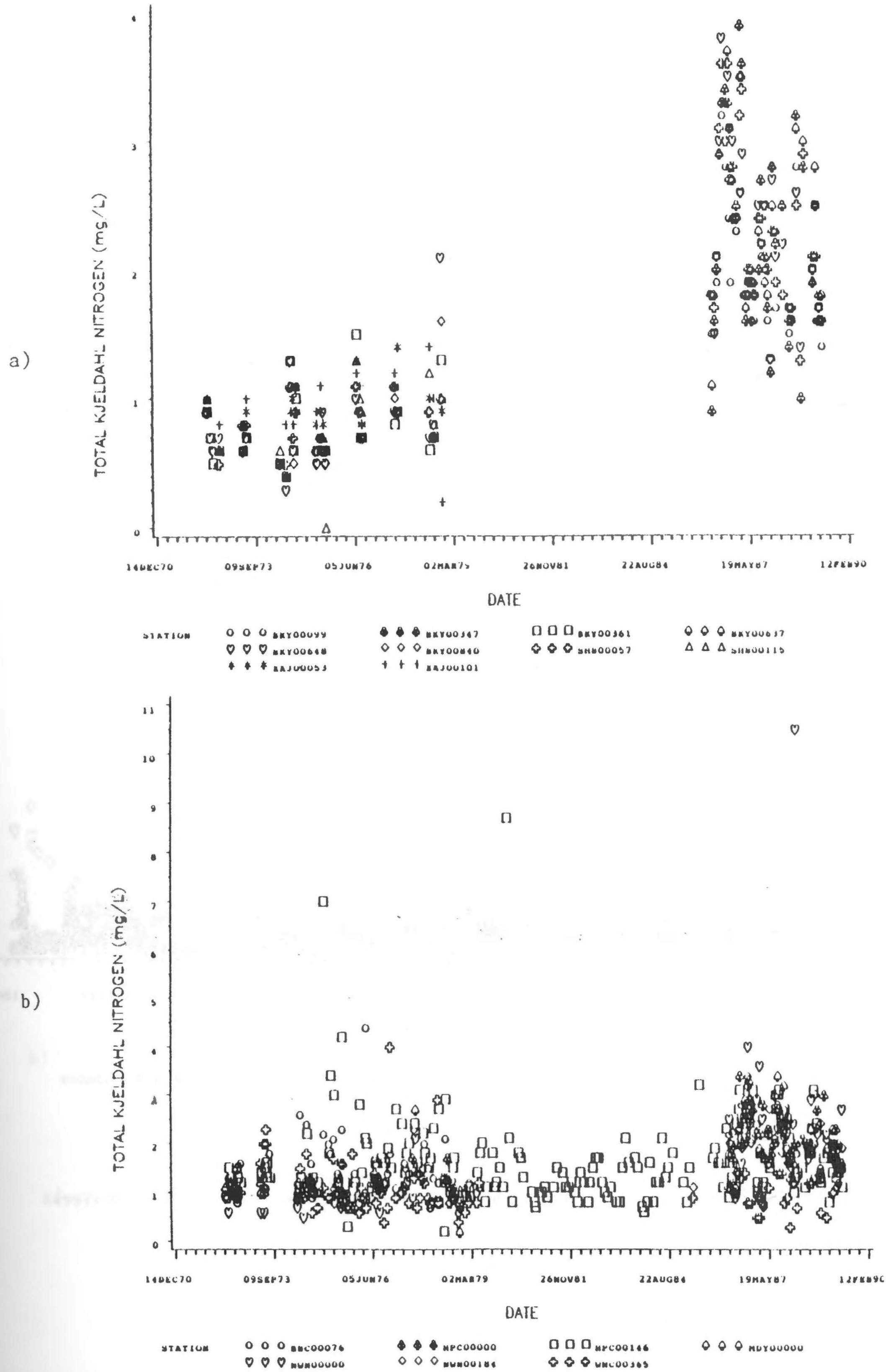


Figure 23. Scatterplots for Total Kjeldahl Nitrogen concentrations (mg/l) over time: a) main Bay sites; and b) tributary creeks.

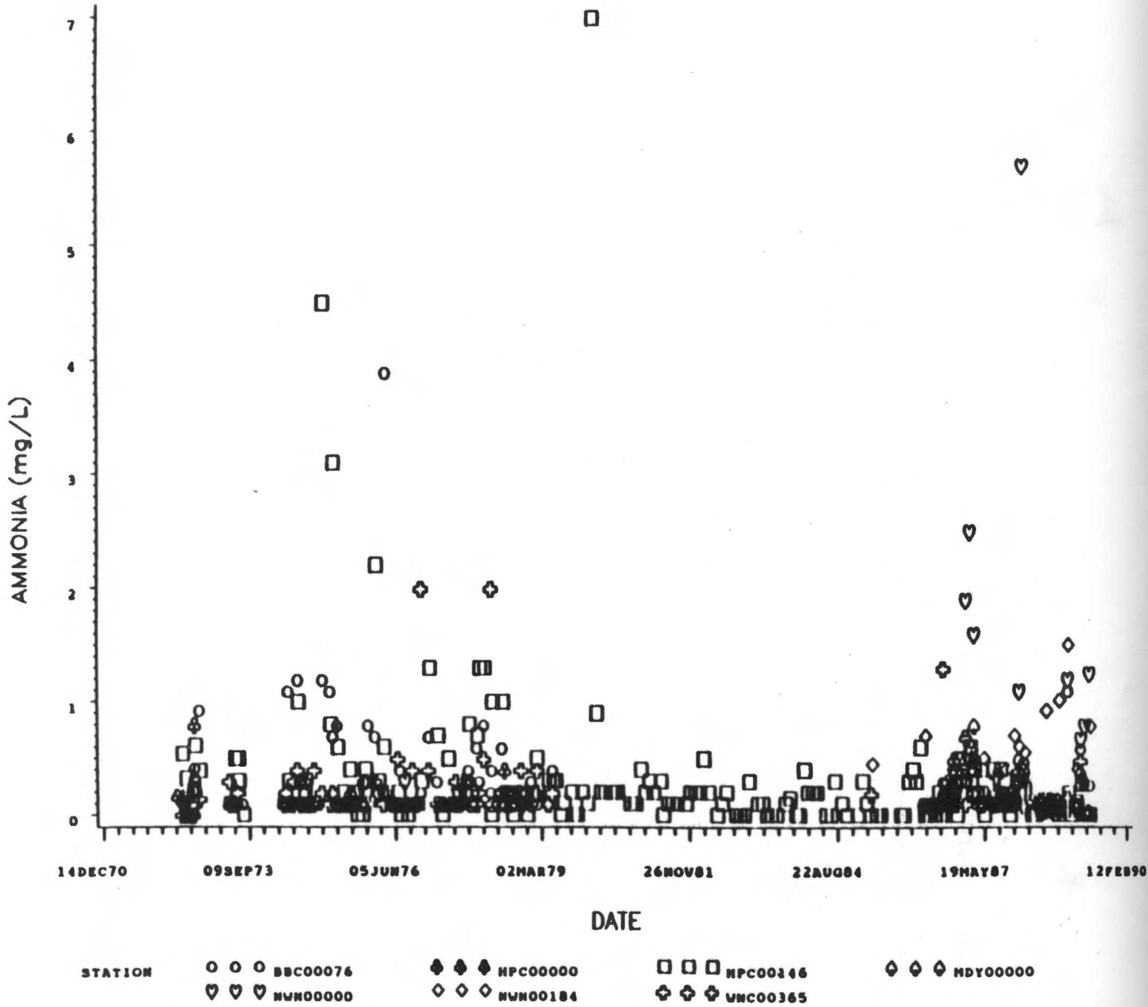
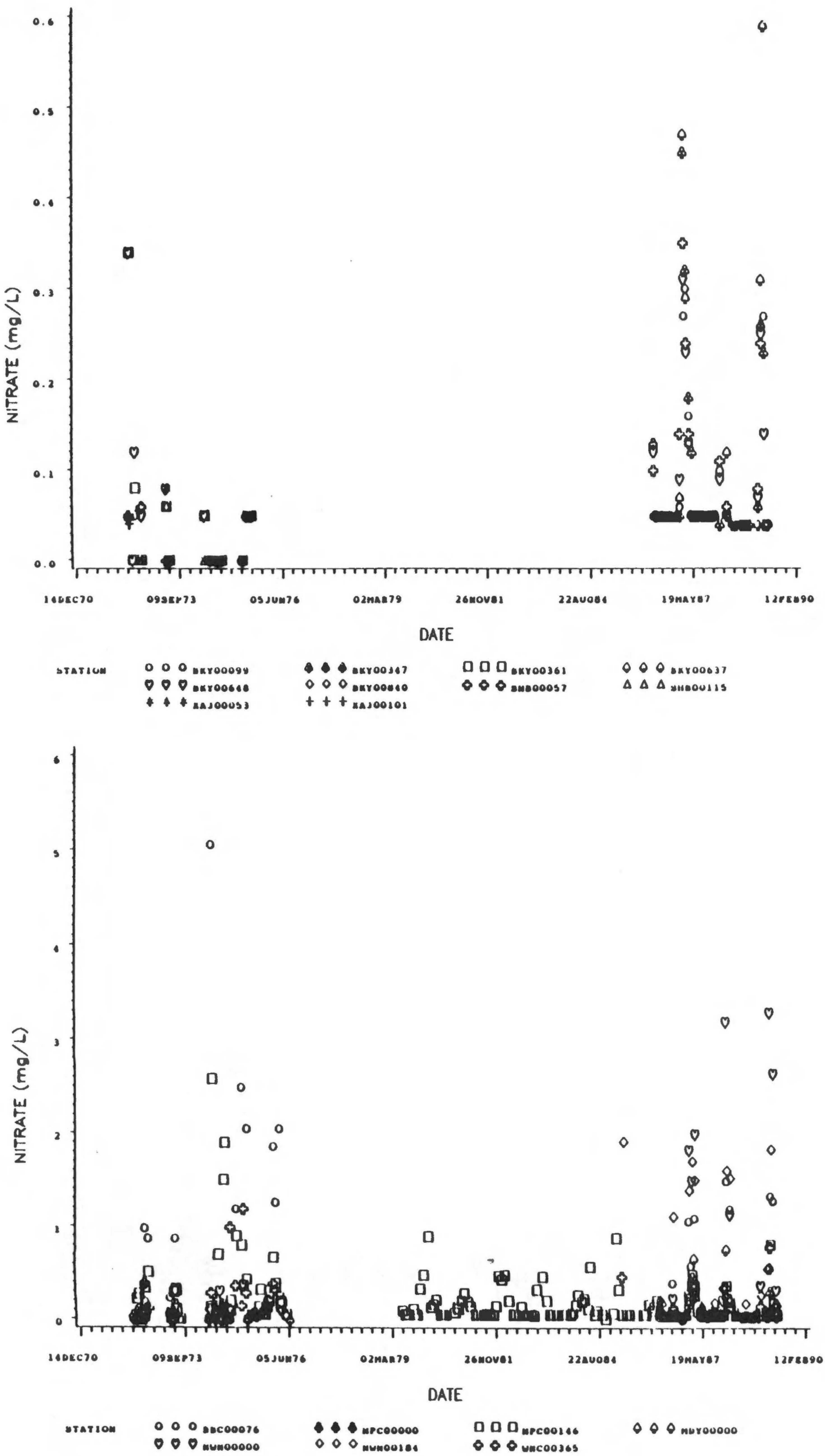


Figure 24. Scatterplot for ammonia concentrations (mg/l) over time for tributary creeks.

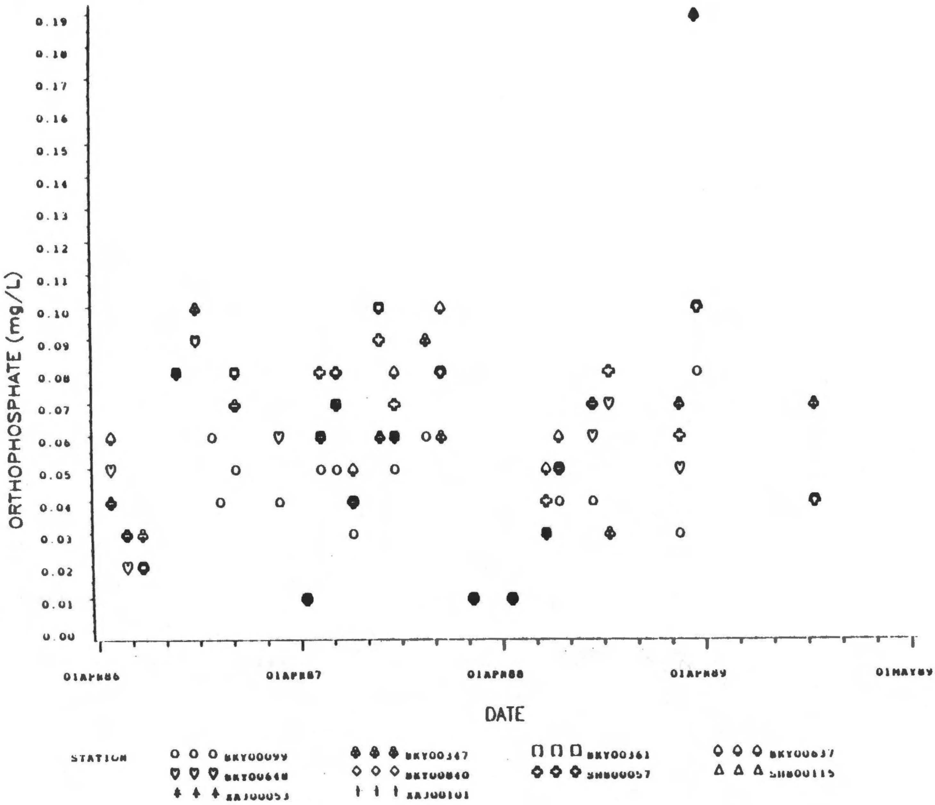
a)



b)

Figure 25. Scatterplots for Nitrate concentrations (mg/l) over time: a) main Bay sites; and b) tributary creeks.

a)



b)

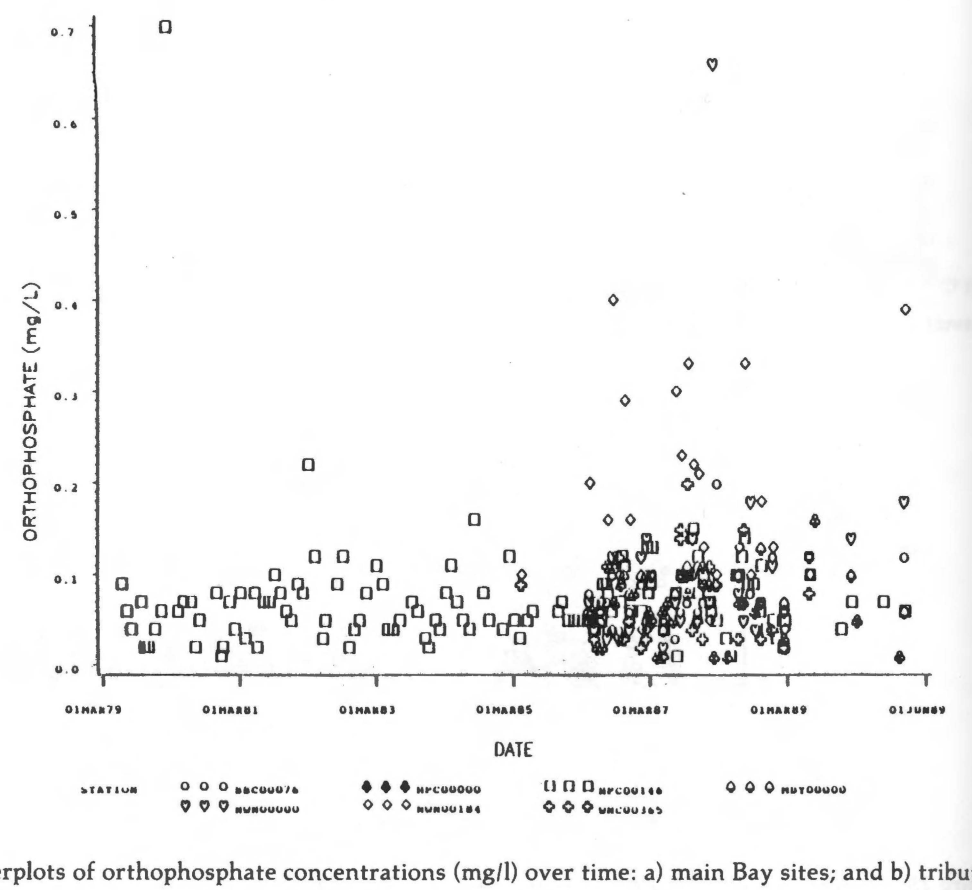


Figure 26. Scatterplots of orthophosphate concentrations (mg/l) over time: a) main Bay sites; and b) tributary creeks.

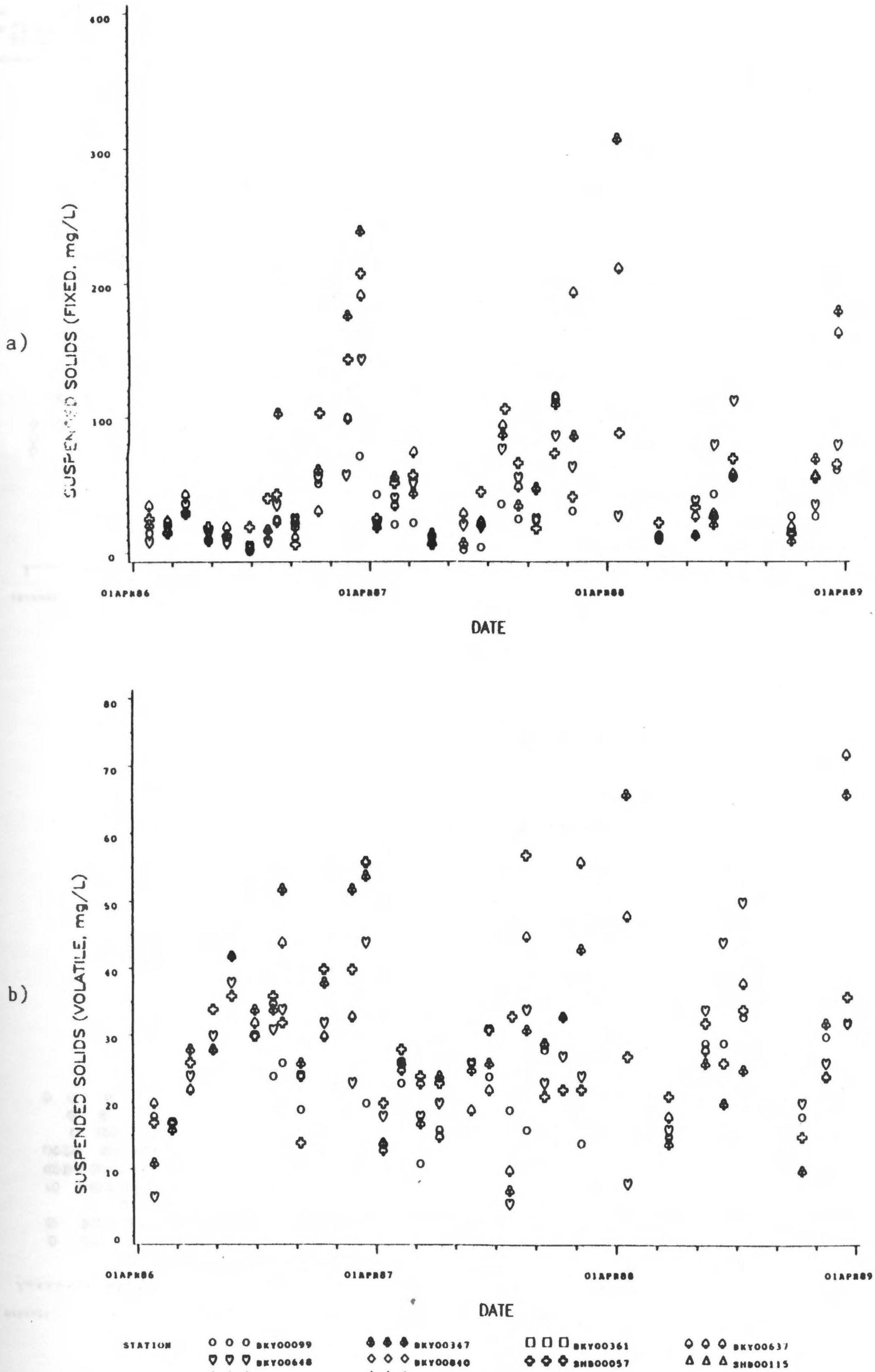


Figure 27. Scatterplots for suspended solids concentrations (mg/l) over time: a) fixed suspended solids; and b) volatile suspended solids.

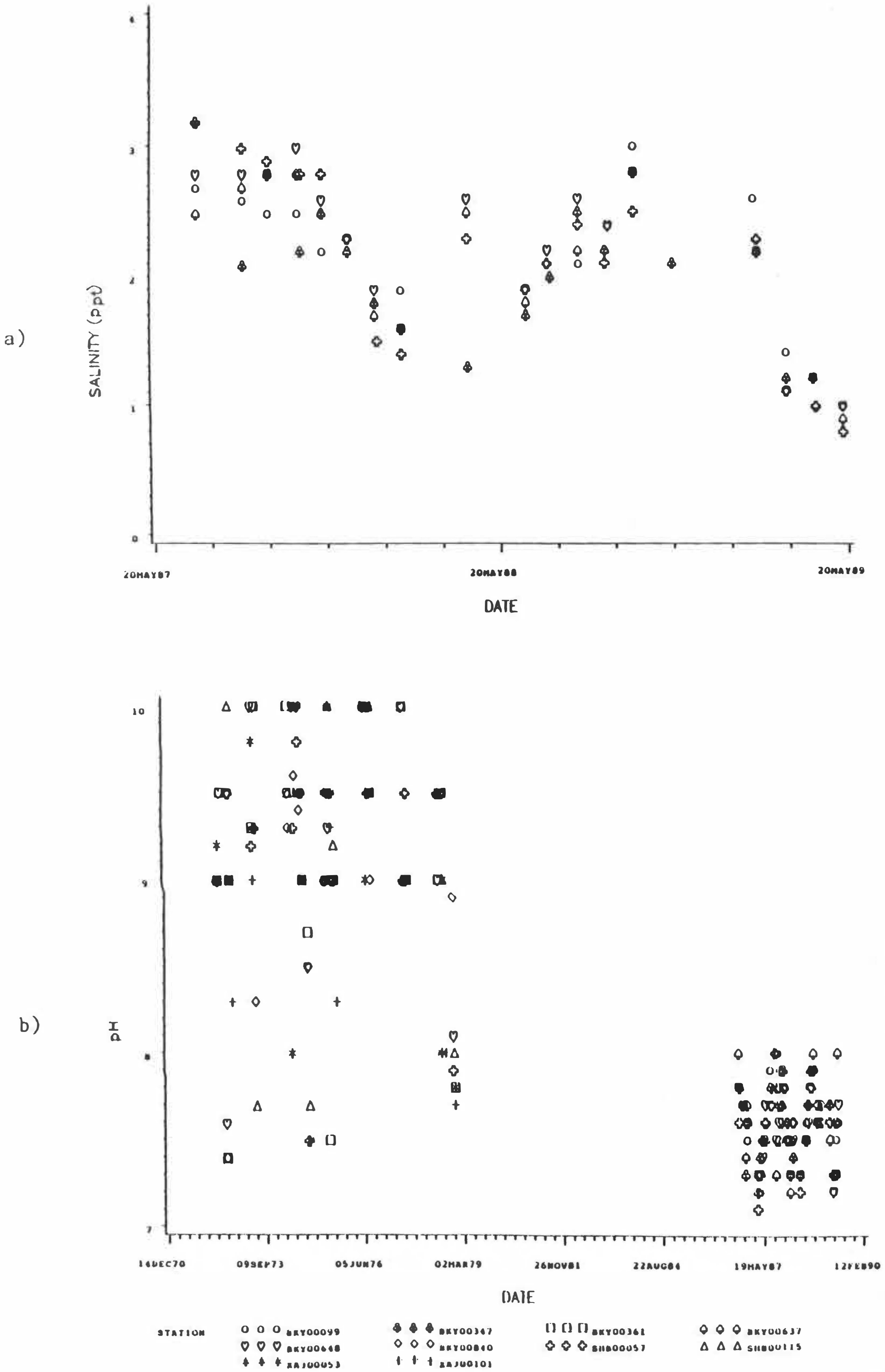


Figure 28. Scatterplots of salinity (a) and pH (b) measurements over time.