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Dynamics of an estuarine ecosystem – The Chesapeake Bay experience: statistical approaches and water quality patterns

Water quality
Monitoring
Statistics
Trends
Flow

Qualité de l'eau
Surveillance
Statistique
Tendance
Flux

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ABSTRACT

A long-term water quality monitoring program has been established in the Virginian waters of the Chesapeake Bay. To date, over eight years of data have been analyzed to characterize spatio-temporal patterns and long-term trends in water quality. Complementary multivariate statistical procedures were employed to define spatial and seasonal patterns, while a series of non-parametric trend analyses were used for determining overall, site-specific, and season-specific long-term trends for water quality variables in the tributaries and mainstem of the Bay. Particular attention was focused on determining the effect of river flow on the trends, because flow rates in some of the tributaries have changed dramatically since the beginning of the monitoring program. Many of the water quality variables from the tributaries displayed strong relationships to flow. Trends for increasing nutrients could be attributed to flow effects in certain tributary regions, while in others "potential trends" for improvement in water quality were obscured by flow. Nonetheless, point source controls in the tidal fresh region of the James River apparently produced decreasing nutrient trends which persisted for the flow-corrected data. Water quality conditions in the mainstem of the lower Bay were not as greatly affected by flow. The up-bay segments displayed trends for decreasing inorganic nitrogen and ammonium, while the down-bay regions were characterized by declining trends for phosphorus. Total organic carbon and suspended solids displayed increasing trends throughout the Virginian waters of the Bay. Chlorophyll and bottom dissolved oxygen concentrations displayed no significant long-term trends, but both variables showed potential trends in the flow-corrected data sets. The ecological and management implications of major findings are discussed.

RÉSUMÉ

Dynamique d'un écosystème estuarien, la baie de Chesapeake: approche statistique et modèle de qualité de l'eau.

Un programme à long terme de surveillance de la qualité de l'eau a été mis en place en Virginie, dans la baie de Chesapeake. Les données acquises pendant plus de huit ans ont été analysées pour établir des modèles spatio-temporels et pour déterminer les tendances à long terme de la qualité de l'eau. L'analyse statistique multivariée a été appliquée pour définir les modèles; une série d'analyses des tendances non paramétriques a été utilisée pour déterminer les évolutions globales à long terme des paramètres de qualité de l'eau dans les tributaires et à l'entrée de la baie. Une attention particulière a été portée à l'effet des fleuves sur les tendances car les flux de plusieurs tributaires ont varié notablement depuis le début du programme de surveillance.

Plusieurs caractéristiques de la qualité de l'eau des tributaires sont fortement corrélées aux débits. L'augmentation des nutriments pourrait être liée aux flux dans certaines régions tributaires alos que, dans d'autres régions, des « tendances potentielles » d'amélioration de la qualité de l'eau sont masquées par les flux. Les contrôles à la source dans les eaux douces de la rivière James indiquent pourtant une diminution des nutriments qui se retrouve dans les données corrigées du flux. La qualité de l'eau à l'extrémité de la baie inférieure est moins sensible aux flux. Le bassin supérieur de la baie montre une diminution de l'azote et de l'ammoniaque inorganique, tandis que le bassin inférieur est marqué par une diminution du phosphore. Le carbone organique total et les particules en suspension augmentent en Virginie dans les eaux de la baie. Les concentrations en chlorophylle et en oxygène dissous dans la couche de fond ne présentent pas de tendance significative à long terme, mais ces deux variables montrent des tendances potentielles dans les données corrigées du flux. Les principaux résultats sont discutés avec leurs conséquences dans l'écologie et la gestion de la baie.

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INTRODUCTION

The Chesapeake Bay is the largest estuary in the United States, yet the areal extent of the Bay proper (designated herein as the "mainstem") represents only a small fraction of the total watershed of approximately 166,000 km^2. The Chesapeake Bay watershed comprises over 150 rivers, streams and creeks in six states and the District of Columbia. Approximately 90% of the total freshwater input to the Bay is contributed by six major rivers: the Susquehanna, Potomac, and Patuxent Rivers in Maryland; and the Rappahannock, York and James Rivers in Virginia (USEPA, 1983). Historically, the Chesapeake Bay has supported some of the most productive commercial fisheries in the world. It also represents a major resource to recreational and tourism industries of the region. In addition, the Chesapeake Bay contains Baltimore and Hampton Roads, two of the largest commercial seaports in the U.S., the latter also being the largest military port in the world.

Environmental conditions in the Chesapeake Bay and its major tributaries have deteriorated significantly over the past half century (USEPA, 1983). Rapidly expanding urban development and agricultural activities in the watershed have introduced excessive nutrient loads to the Bay, leading to a state of cultural eutrophication (*i.e.* excessive algal blooms) in many regions. These anthropogenic changes are generally believed to be detrimental to the structure of Bay food webs, as well as to the long-term maintenance of commercially and recreationally important shellfish and finfish stocks. In addition, the eutrophic conditions are believed to lead to low dissolved oxygen conditions in bottom waters when excessive amounts of organic matter associated with the algal blooms accumulate in the deeper regions of the mainstem Bay. The regions of the mainstem Bay that suffer from hypoxic or anoxic conditions during the summer months are believed to have expanded significantly between the 1960's and 1980's. This areal expansion of low oxygen conditions is also believed to represent a major threat to the productivity of the Bay's living resources.

In 1984, concerns over the declining health of the Bay led to the implementation of the Chesapeake Bay Program (CBP) by the United States Environmental Protection Agency, the Commonwealths of Virginia and Pennsylvania, the State of Maryland, and the District of Columbia. One of the major components of the CBP was a comprehensive monitoring program which was designed to:

1) characterize the spatial patterns of water quality and living resources;

2) characterize seasonal patterns of water quality and living resources;

3) detect long-term trends in environmental conditions;

4) determine relationships between living resources and water quality conditions.

The overall goal of the Chesapeake Bay Monitoring Program (CBMP) was to allow environmental managers to determine the effectiveness of management actions and/or to determine which regions of the Bay continue to deteriorate, and, therefore warrant greater management attention. Thus, the CBMP allows scientists and managers to "take the pulse" of the ecological health of the Bay in order to determine long-term management strategies.

This article provides an overview of the statistical approaches and general findings of the water quality component of the CBMP in the Commonwealth of Virginia. The focus of this case study will be on objective 3, long-term trends, but examples of the approaches to objectives 1 and 2, the spatio-temporal characterizations, will also be presented. Discussions of the findings of analyses of phytoplankton and benthic biological communities are presented in companion articles by Marshall and Alden (1997) and Dauer (1997), respectively.

MATERIALS AND METHODS

Water quality data analyzed

Water quality collections have been made throughout the Chesapeake Bay and its tributaries since June of

1984. Virginia's portion of the CBMP for water quality includes 27 stations in the lower Bay Main Stem and 31 stations in the three major tributaries (Fig. 1). Water quality collections have been made at these stations 18-20 times per year: twice per month from March through October and once per month from November through February from 1984-1988; and thereafter, twice per month from April through September and once per month October through March. Details of the analytical methods for the CBMP have been presented elsewhere (USEPA, 1992, 1994). The water quality variables that were used for statistical analysis (and abbreviations used in tables and figures) included: temperature (TEMP), salinity (SAL), dissolved oxygen (DO), Secchi depth (SECCHI), total suspended solids (TSS), total organic carbon (TOC), dissolved ammonium (NH4), total nitrogen (TN), dissolved inorganic nitrogen (DIN), total phosphorus (TP), dissolved inorganic phosphorus (DIP), silicic acid (SI), and chlorophyll a (CHLA). All variables were analyzed separately for surface (1 m below surface; abbreviations designated with a "S" prefix) and bottom (1 m above bottom; abbreviations designated with a "B" prefix) depths except for Secchi depth, and dissolved oxygen, which was analyzed statistically only for the bottom depth. The same variables were analyzed for the data sets from the tributaries, except that only surface chlorophyll a measurements are collected in the tributary monitoring program.

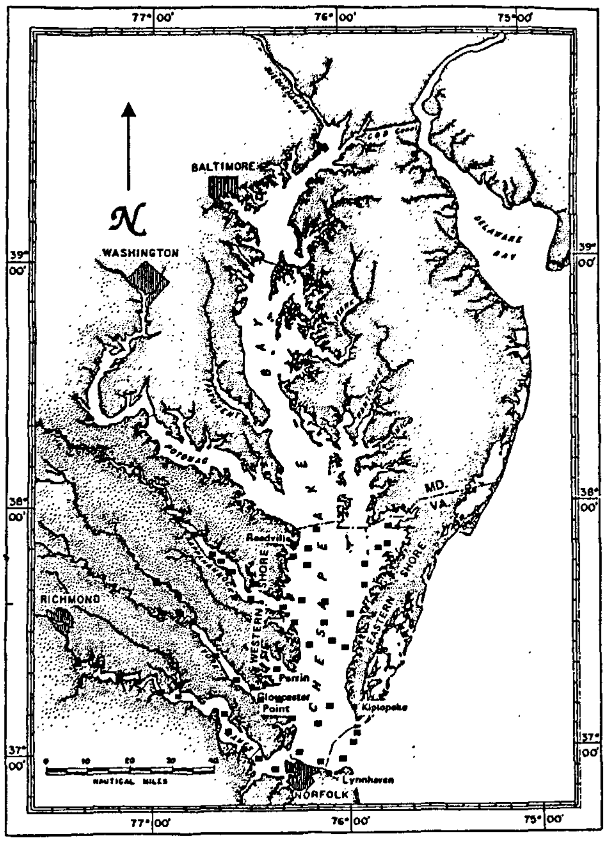

Figure 1

Map of Chesapeake Bay with location of monitoring stations in Virginia.

Statistical analyses

Spatio-temporal analyses

A series of complementary multivariate statistical techniques were employed to explore spatio-temporal patterns of water quality. The analyses were designed to identify regions with similar water quality patterns, as well as seasonal or other short-term temporal patterns in water quality. The first series of the procedures were based upon methods described by Williams and Stephenson (1973). This approach allowed the calculation of classification coefficients which were used in two cluster analyses: the classification of collection periods (sampling events designated herein as "cruises") by water quality similarities, once spatial patterns have been taken into account; and the clustering of sites by water quality similarities, once temporal patterns have been taken into account. This technique not only allowed the calculation of "cruise groups" and "site groups" of similar water quality conditions, but also produced information concerning the relative importance of the overall temporal and spatial effects. The analysis produces values analogous to eigenvalues that Williams and Stephenson (1973) term the "mean variances per comparison". These values represent the relative amount of the variance in a data set that can be attributed to spatial effects, temporal effects, or the spatial-temporal interaction.

Once spatial and temporal groups were defined, two additional analyses were used to explore the specific water quality conditions responsible for differences defined by the cluster analyses. In order to correct for either the spatial or temporal effects prior to examining the other effect, multivariate analyses of variance (MANOVAs) were conducted on unit deviate standardized water quality data employing either the site or cruise groups as the independent class variable, and the residuals were output for statistical evaluation. The residuals from these analyses were subjected to discriminant analysis and MANOVA (SAS, 1990). The discriminant analysis was used for data presentation purposes, by producing 95 % confidence ellipses of each site or cruise group on axes representing the two principal discriminant functions. These discriminant functions can be related to the combination of water quality variables most responsible for the differences between the groups. Since the MANOVA is a far more conservative test of group differences (*i.e.* less subject to Type I error) than discriminant analysis, it was used as a means of confirming significant differences between groups. In addition, the univariate tests associated with the MANOVA were used to confirm the loadings from the discriminant analyses before the discriminant functions were named. Only variables that loaded heavily on a discriminant function and were shown to display statistically significant differences ($\alpha = 0.01$) between groups separated by the function were included on axis labels. The sequence of variable names in the axis labels represent the degree of loading, while the arrows represent the direction of the effects.

A second type of statistical approach was taken to explore temporal patterns of select water quality variables. The residuals from MANOVAs that corrected for spatial effects were analyzed by nonlinear regression analyses. These analyses employed sine and cosine transformations of time and interactions between these transformations and dummy variables for each year to fit periodic and aperiodic (*i.e.* year-specific) temporal patterns. A linear trend variable was introduced into the model first, so that all subsequent analyses were on detrended data. The remaining time variables were introduced in a stepwise fashion (the inclusion criterion for forward selection was a probability of 0.15 for the F-value of the variable). The regressions were weighted by the inverse of the variances calculated for the spatially corrected data from each collection period. The predicted values and 95 % confidence limits for the models were plotted in various combinations to gain insight into relationships between short-term temporal patterns of the variables.

Long-term trend analyses

The long-term trends in water quality were analyzed by a series of powerful nonparametric trend tests. The overall trends were analyzed by a seasonal intra-block sign test based on the Kendall Tau statistic (designated as the "Seasonal Kendall" test) described by Hirsch *et al.* (1982) and the aligned rank test (designated as the "Sen's Tau" test) described by Sen (1968). The trends unique to certain seasons, to certain sites, or to the interaction of sites and seasons were analyzed by a 2-way χ^2 protocol (designated as the "Van Belle and Hughes" test) described by Van Belle and Hughes (1984). The critical test level of $\alpha = 0.01$ was used for all tests. The median slopes of significant trends were determined by Seasonal-Kendall slope estimators (Gilbert, 1987). An earlier power study (Alden *et al.*, 1991) indicated that these non-parametric tests were quite powerful and robust, even when data violated most of the assumptions of parametric time-series (e.g. data displaying autocorrelation, spatial dependence of errors, heterogeneity of variances, and/or non-normal distributions; time series with non-uniform sampling intervals; data that are censored by detection limits; missing data; etc.). Moreover, the tests could be run easily on large numbers of variable-region combinations without excessive data manipulations. Hirsch *et al.* (1991) have reviewed these methods and the reasons for their use with long-term water quality data sets.

The trend analyses were run for regions of the Bay or tributaries which were shown to display similarities in water quality patterns (*i.e.* the site groups identified in the previously described analyses). Due to changes in river flow of the major tributaries which were observed during the course of the eight year study, the effects of flow on each of the water quality variables were quantified. For variables displaying a significant relationship to flow in any given region, trend analyses were conducted on the raw data and on the data set with the flow effects removed. Thus, the overall influence of flow on the long-term trends can be identified.

The evaluation of flow effects involved the estimation of flushing times for regions of the tributaries or mainstem Bay, followed by a series of nonlinear regression models which were conducted to determine the relationship between each water quality variable and the flushing rates. Flushing time calculations were based on the "fraction of fresh water" method described by various investigators (e.g. Ketchum, 1950; Dyer, 1973; Pilson, 1985). The equation for the calculation of flushing times for each of the were as follows:

$$T = Q/R \qquad (1)$$

where Q is the total amount of freshwater in the segment of the estuary and R is the estimated average flow into the segment. Flow estimates provided monthly by the U.S. Geological Survey (USGS) for various segments of the Chesapeake Bay (based upon daily fall-line discharge data from the major tributaries to the Bay and the estimation methods of Bue, 1968) were used to calculate 2-month rolling average flow rates (R), where mean values were determined for flow data from the month of collection and the preceding month. The Q values were calculated as follows:

$$Q = fv \qquad (2)$$

where f is the fraction of freshwater in the segment and v represents the total volume of the segment. Segment volumes were obtained from estimates provided by Cronin and Pritchard (1971). The f values are calculated as follows:

$$f = (S_1 - S_2/S_1) \qquad (3)$$

where S_2 is the average salinity in the segment and S_1 is the bottom salinity of the next seaward segment.

Data for each of the water quality variables were regressed against the reciprocal of the flushing times (*i.e.* the flushing rates) of each salinity regime of each tributary using a series of regression models developed by Smith *et al.* (1982) for the U.S. Geological Survey (USGS) NASQAN Program. The statistically significant ($p < 0.01$) regression model with the highest R^2 value was employed to correct for flow effects. To correct for flow effects, the residuals from the selected regression model were standardized to the grand mean of the raw data from the salinity regime segment being analyzed. Water quality data from the mainstem Bay were analyzed in a similar manner, with the segmentation being defined by the two regions for which USGS flow data are available (Bue, 1968): Segment C being designated as the "up-bay" region of the Virginian waters; and Segment D being designated as the "down-bay" region. Trend analyses were conducted on the grand mean-centered residuals from the selected regression models. Thus, trend results were assessed for two sets of water quality data, identified as either "uncorrected", or "corrected" for flow effects.

RESULTS

Spatio-temporal patterns

The Williams and Stephenson cluster analyses indicated that the variance in the mainstem water quality data

Table 1

Percentages of total explained variance in the water quality data sets that were attributable to spatial and temporal effects and the spatio-temporal interaction. The percentages were based upon the mean variance per comparison values calculated by the cluster analysis method of Williams and Stephenson (1973).

Data Set	Spatial Effects	Temporal Effects	Interaction
Mainstem	52%	46%	2%
James River	82%	16%	2%
York River	81%	17%	2%
Rappahannock River	82%	16%	2%

was approximately equally associated with spatial patterns (52%) and temporal patterns (46%) (Tab. 1). This relatively equal partitioning of the variance was in contrast to the relationships observed in the three tributaries, where spatial effects represented over 80% of the explained variance and temporal patterns accounted for only 16-17%. The results of the classification of mainstem water quality data indicated seven major site groups (Fig. 2). These site groups displayed geographic continuity (Fig. 3): Site group MSI (the "MS" designation is used for mainstem segments) represents the sites of the deep trench that extends northward into Maryland; MSII contains shallower sites from both the eastern and western lateral zones of the same region; MS III is a large polyhaline region including seven sites in the open Bay and one deep site in the mouth of the York River; MSIV is contains shallower sites around the mouth of the York River; MSV is a polyhaline zone near the mouth of the Bay; MSVI includes sites from the northern region of the Bay mouth; and MSVII is a deep site in the mouth of the James River. The site groups determined for the tributaries also displayed geographic continuity (Fig. 4): site groups in the lower estuarine regions of all three tributaries (JI, YI, and RI; with "J", "Y" and "R" representing the James, York and Rappahannock Rivers, respectively) are generally located in the mesohaline regions; the groups JII, YII and YIII represent the oligohaline regions; and JIII and YIII are from the tidal fresh zone (the site classified as RIII had to be dropped from subsequent statistical analysis because differences in the sampling regime and laboratory analyses used for this site have been shown statistically to affect its sensitivity as a monitoring station; Alden *et al.*, 1991). The combination of discriminant analysis and MANOVA on the data corrected for temporal effects indicated that the site groups of the mainstem Bay were well separated by water quality conditions (Fig. 5*a*). The first discriminant function (DF1) separated site groups by water quality conditions that reflect the estuarine-coastal water gradient, while DF2 generally separated groups according to depth. Site groups MSI-IV are the more "up-bay" regions which display more eutrophic conditions associated with positive DF1 scores: greater levels of nitrogen-based nutrients and silicic acid, higher organic carbon concentrations, greater chlorophyll levels, greater suspended solids loads, and bottom temperatures that are less affected by colder coastal waters. On the other hand, MSV-VII, the "down-bay" site groups, display less eutrophic conditions and have greater salinities, as reflected by their negative DF1 scores. The deeper site groups (MSI, MSIII, MSV and MSVII) were separated from the shallower regions (MSII, MSIV, and MSVI) by DF2, which indicated that the latter groups had higher levels of bottom oxygen, but the former groups had higher surface oxygen and greater concentrations of

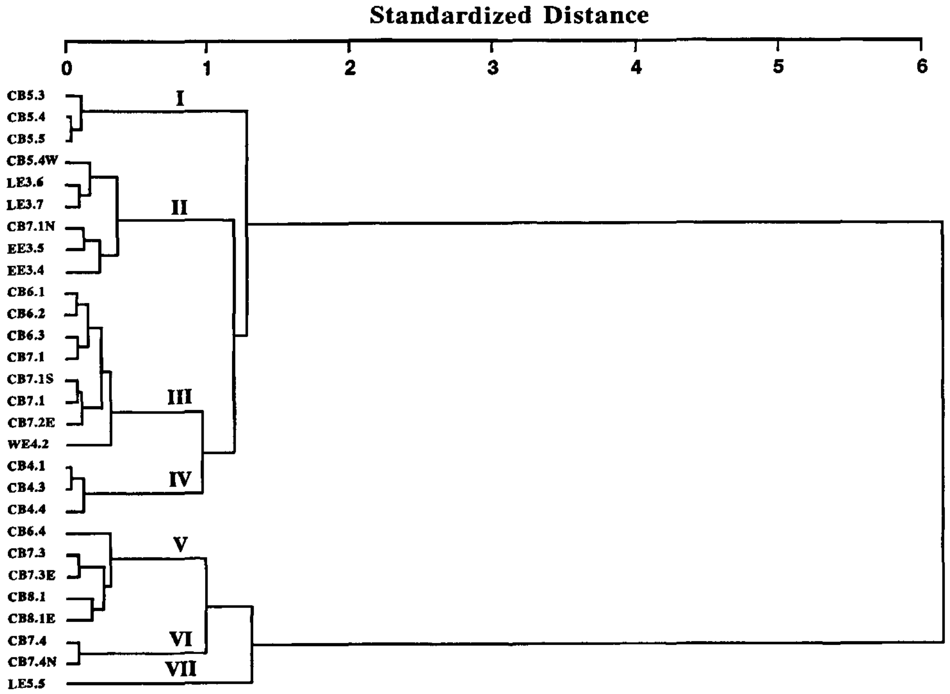

Figure 2

Standardized distance dendrogram for classification of spatial patterns of water quality in the mainstem Bay. The roman numerals designate the site groups.

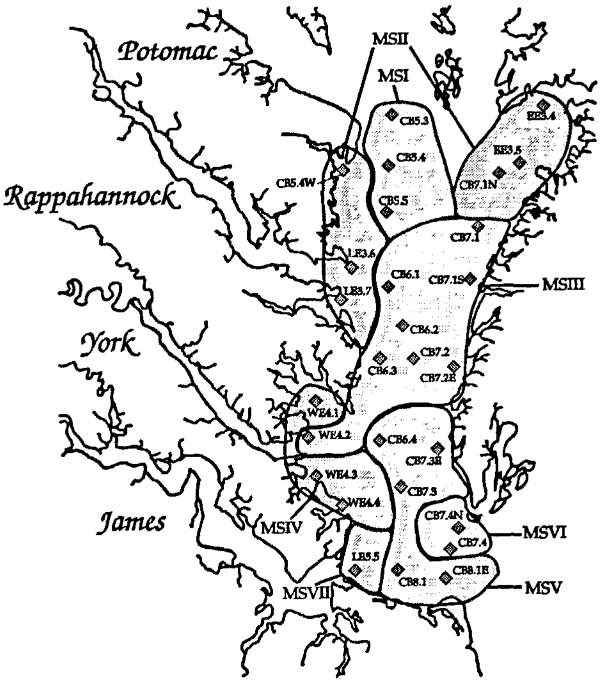

Figure 3

Map of the Virginian waters of the Chesapeake Bay mainstem showing water quality site groups. The roman numerals designate site groups defined by the dendrogram in Figure 2.

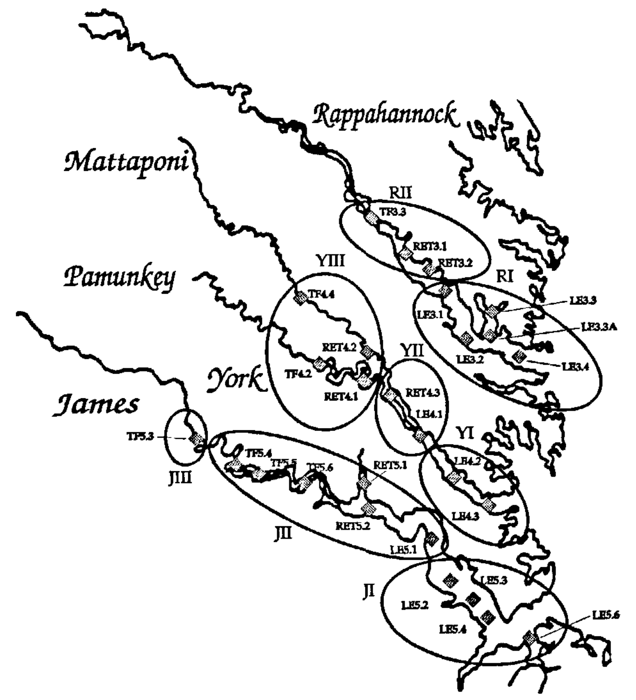

Figure 4

Map of the James, York and Rappahannock Rivers showing water quality site groups.

ammonium near the bottom. Two variable, DIN and DIP loaded on both DF1 and DF2, indicating that they are important in discriminating groups occurring in specific quadrants of the discriminant function plot: MSI (which displays the highest DF1 and DF2 scores) has highest levels of nitrogen-based nutrients moving down the deep trench of the Bay; while MSVII (which displays low DF1 scores, but high DF2 scores) has high levels of dissolved phosphates, indicating that the James River is an important source of phosphorus-based nutrients to the lower Bay, a speculation that has been previously explored (Alden *et al.*, 1991).

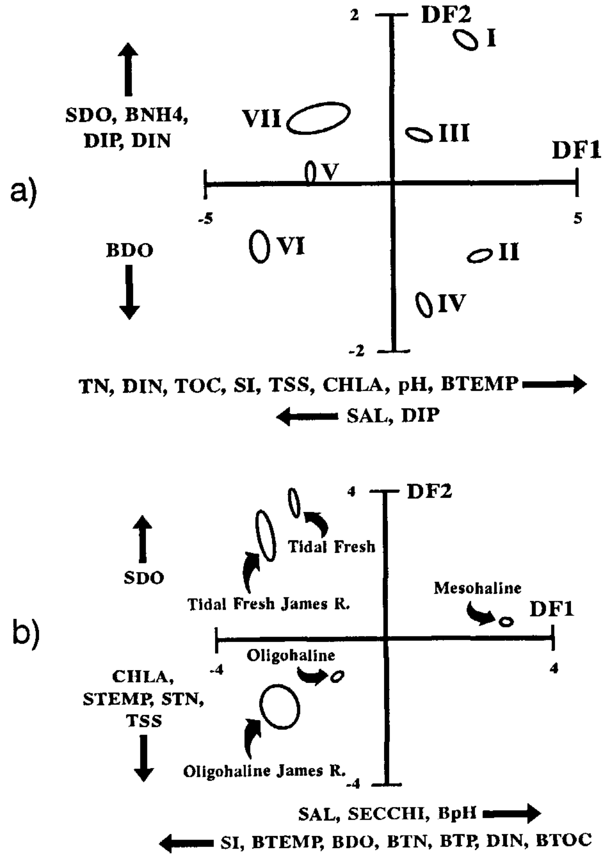

Figure 5

Confidence ellipses ($\alpha = 0.05$) *for canonical discriminant function scores describing spatial differences in water quality conditions: a) for mainstem Bay (see* Fig. *3 for location of site groups); b) for the three major tributaries.*

To avoid a detailed presentation of the results of discriminant/MANOVA analyses for each tributary, the water quality data from all tributaries were combined and analyzed together. Figure 5*b* presents the results of the discriminant/MANOVA analyses of site groups defined by the cluster analysis of the combined data sets. In general, the sites from the various regions of the tributaries tended to group together. The principal exceptions were that the James River sites tended to display more extreme water quality conditions in the oligohaline and tidal fresh zones than did sites in similar regions of the other two rivers. All mesohaline sites grouped together and displayed higher salinities, greater water clarity (*i.e.* greater Secchi depths) and higher pH values in bottom waters; all variables that were positively correlated with DF1. On the other hand, the oligohaline and tidal fresh zones tended to display higher concentrations of nutrients (e.g. SI, BTN, BTP, DIN), BTOC, BDO, as well as higher bottom temperature;

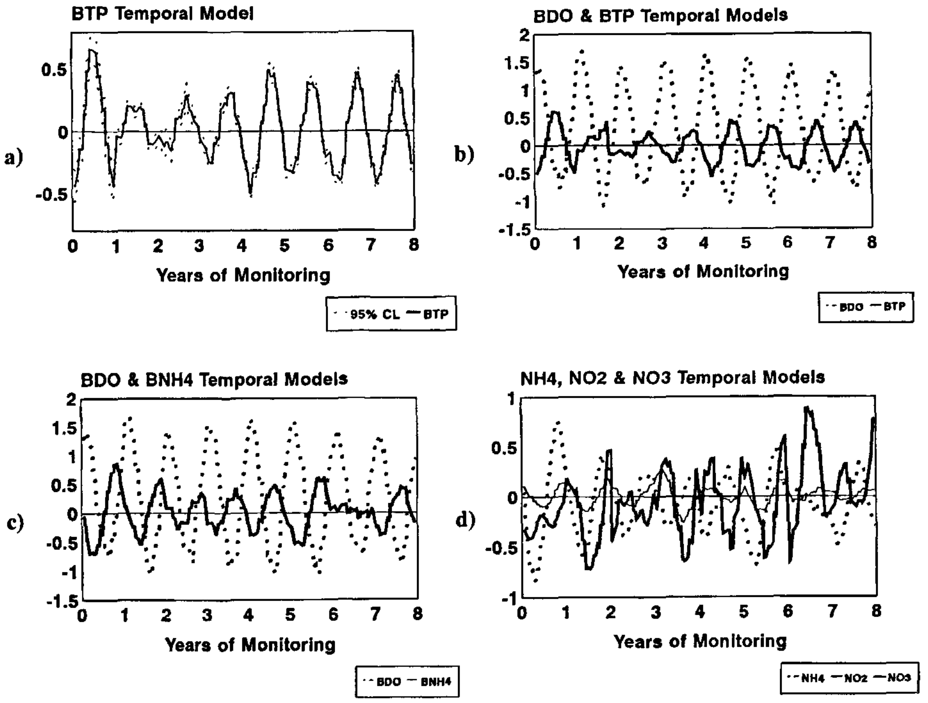

Figure 6

Temporal patterns detected by nonlinear regression analysis of mainstem Bay water quality data (residuals) from which spatial effects have been removed: a) model of BTP with 95% confidence limits; b) BTP and BDO temporal models; c) BDO and BNH4 models; and d) BNH_4, BNO_2, and BNO_3 models.

variables that were negatively correlated with DF2. The James River sites from both the oligohaline and tidal fresh regions tended to display the highest levels of the variables that were negatively loaded on DF2. The DF2 separated the oligohaline from the tidal fresh site groups: the oligohaline regions tended to have higher chlorophyll concentrations, STN concentrations, TSS loads, and surface temperatures. The oligohaline region of the James River displayed the highest levels of these variables. Tidal fresh regions tended to have highest SDO levels, but lower chlorophyll and TSS concentrations than the oligohaline zones.

Once major spatial effects have been taken into account, temporal patterns can be examined. Figures 6 and 7 present examples of results of nonlinear regression analyses conducted on residuals from MANOVAs designed to remove spatial effects. Figure 6*a* presents the predicted values and confidence limits for a nonlinear regression model of BTP from the mainstem Bay. Figure 6*b* presents the same predicted BTP values plotted on the same graph as predicted BDO values. Obviously, these two variables inverse seasonal patterns, with BDO displaying the greater seasonal amplitude. In the summer months, when BDO values are at their lowest levels, BTP concentrations tend to peak; and in the winter, the BDO concentrations are the highest, but BTP levels are lowest.

Ammonium and dissolved oxygen concentrations in bottom waters of the mainstem display a similar inverse relationship, with the maximum increase in ammonium concentrations occurring during mid-summer when BDO values are lowest (Fig. 6*c*). Figure 6*d* displays the cycles of nitrogen-based nutrients: ammonium tends to reach maximum concentrations in late summer/early fall; nitrate levels peak throughout the winter/early spring months; and nitrites display only a small seasonal amplitude, but tend to peak just prior to nitrates. It is interesting to note that during the summer of the sixth year of monitoring (1991), BDO did not tend to fall to as low levels as normal and the ammonium peak did not occur (Fig. 6*c*); however, nitrates did display an unusual mid- summer peak during this time period (Fig. 6*d*).

The approach to examining temporal patterns can also provide insight into relationships between water quality and biological communities. For example, Figure 6 displays relationships between the seasonal cycles of nutrients and that of chlorophyll. Dissolved inorganic phosphorus tended to peak during the summer months until year 4 of the monitoring program (1988), when a regional phosphate ban caused the seasonal amplitude to greatly diminish (Fig. 7*a*; also see discussion of long-term trends). However, the chlorophyll cycle appears to be quite unrelated to DIP, since phytoplankton blooms in the lower Bay tend to occur in late winter/early spring and the chlorophyll concentrations do not respond to the diminishing DIP signal. On the other hand, the DIN cycle tends to match that of the chlorophyll cycle quite closely, with peak concentrations of dissolved nitrogen occurring within a few weeks to a month of (usually prior to) the maximum chlorophyll concentrations (Fig. 7*b*).

Long-term trends

Relationships to flow

The results of the flow correction process are summarized in Figure 8. Nearly 80% of all variable-salinity regime

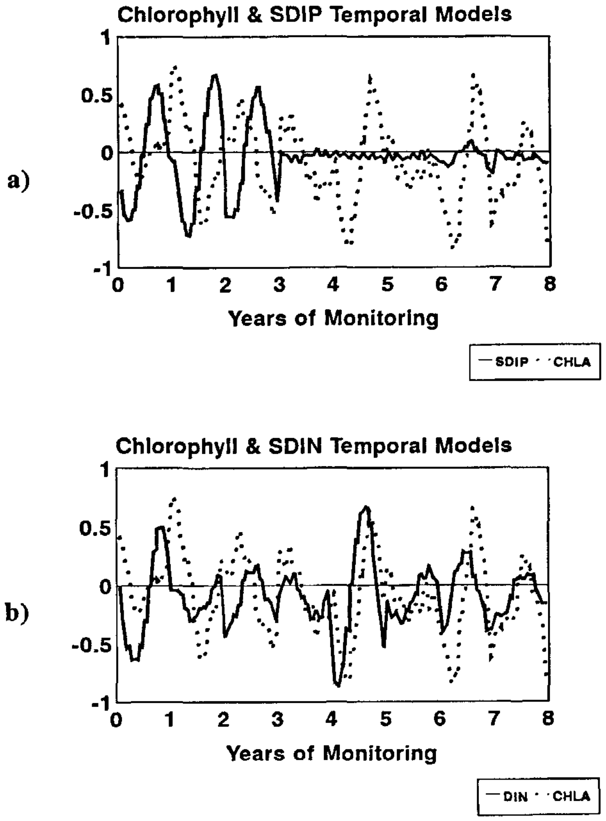

Figure 7

Temporal patterns detected by nonlinear regression analysis of mainstem Bay water quality data (residuals) from which spatial effects have been removed: a) SDIP and CHLA models; b) SDIN and CHLA models.

combinations in the tributaries displayed significant ($p<0.01$) relationships to flow (Figs. 8*a*, *b*). The amount of the total variance "explained" by flow effects (as measured by the R^2 expressed as a percentage) ranged from less than 2 % (for many of the variables in the James River oligohaline region) to nearly 55 % (SSAL in the mesohaline region of the Rappahannock River). The percentages of variables displaying significant relationships to flow for specific tributary salinity regimes were as follows: 96 %, 91 % and 87 % in the tidal fresh, oligohaline and mesohaline regions of the James River; 48 %, 78 % and 100 % in the tidal fresh, oligohaline and mesohaline segments of the York River; and 74 % and 65 % of all variables tested were significantly correlated to flow in the oligohaline and mesohaline regions of the Rappahannock Rivers, respectively. The James River data displayed the greatest number of relationships to flow, although many of the regression models for the oligohaline data set explained less than 2 % of the total variance.

Some variables tended to increase with long residence times and decrease with high flow events, while others displayed the opposite pattern. The following variables were generally observed to have a negative relationship with flow: salinity, temperature and chlorophyll (except mesohaline regions). Variables generally observed to have a positive relationship with flow included dissolved oxygen, silicic acid, ammonium and total phosphorus (and, to a lesser extent, dissolved inorganic phosphorus, which had many values below detection limits). Total nitrogen and dissolved inorganic nitrogen concentrations also generally displayed a positive relationship to flow except in the mesohaline Rappahannock River and in the tidal fresh region of the James River. Total suspended solids and Secchi had inverse relationships to each other, both suggesting that suspended solids loads/turbidity increased with flow, except in the mesohaline region of the Rappahannock River and tidal fresh segment of the James River. Regardless of the direction of the relationships, the flow correction process produced "corrected" data sets which were centered around the grand mean of the raw data, but which displayed no relationship to flow (*see*, for example Fig. 9*a*, *b*).

Flow corrections were also made for data from the lower Bay Main Stem using flow data from the USGS for segments described by Bue (1968). The USGS Segment C generally corresponded to stations in segments MSI-V and Segment D generally corresponded to MSVI- VII. Figures 8*c* and 8*d* present the results of the flow correction regression models for the lower Bay mainstem. In general, fewer of the regression models for the variable-segment combinations were significant (70 % for Segment C and 35 % for Segment D) than were observed for the tributary segments and the R^2 values were lower (ranging from < 1 % to 14 %; with most explaining <2 % of the total variance).

The directions of the relationships between the water quality variables and flow for the Bay mainstem were often similar to those observed for the same variables in the tributaries: surface and bottom temperature displayed a negative relationship to flow; while dissolved oxygen displayed a positive relationship to flow. Many of the other variables displayed the opposite relationships to flow in the Bay Main Stem compared to those observed in the tributaries, although the low R^2 values for most variables suggest that this inverse pattern may have negligible ecological significance.

Trends in water quality

Tables 2 and 3 summarize the trends for the tributary and mainstem data sets, respectively. There were very few season- specific trends detected (<5 % of the variable-segment combinations analyzed in the mainstem and none in the tributaries) and no trends were observed to be site-specific or associated with a significant site-season interaction. Therefore, only the overall trends are presented in the tables.

Figure 10 presents examples of three possible relationships observed for the uncorrected and corrected data when analyzed for trends: 1) some trends persisted following adjustment for flow (Fig. 10*a*); 2) some trends disappeared when the data sets were corrected for flow effects (Fig. 10*b*); and 3) some new trends appeared in the corrected data sets (Fig. 10*c*).

Among the upward trends in the tributaries, phosphorus (TP and, to a lesser extent, DIP) was observed to increase in the lower James River (JI), in the riverine-estuarine transitional (YII) and tidal fresh (YIII) regions of the York River and in the transitional region (RII) of the

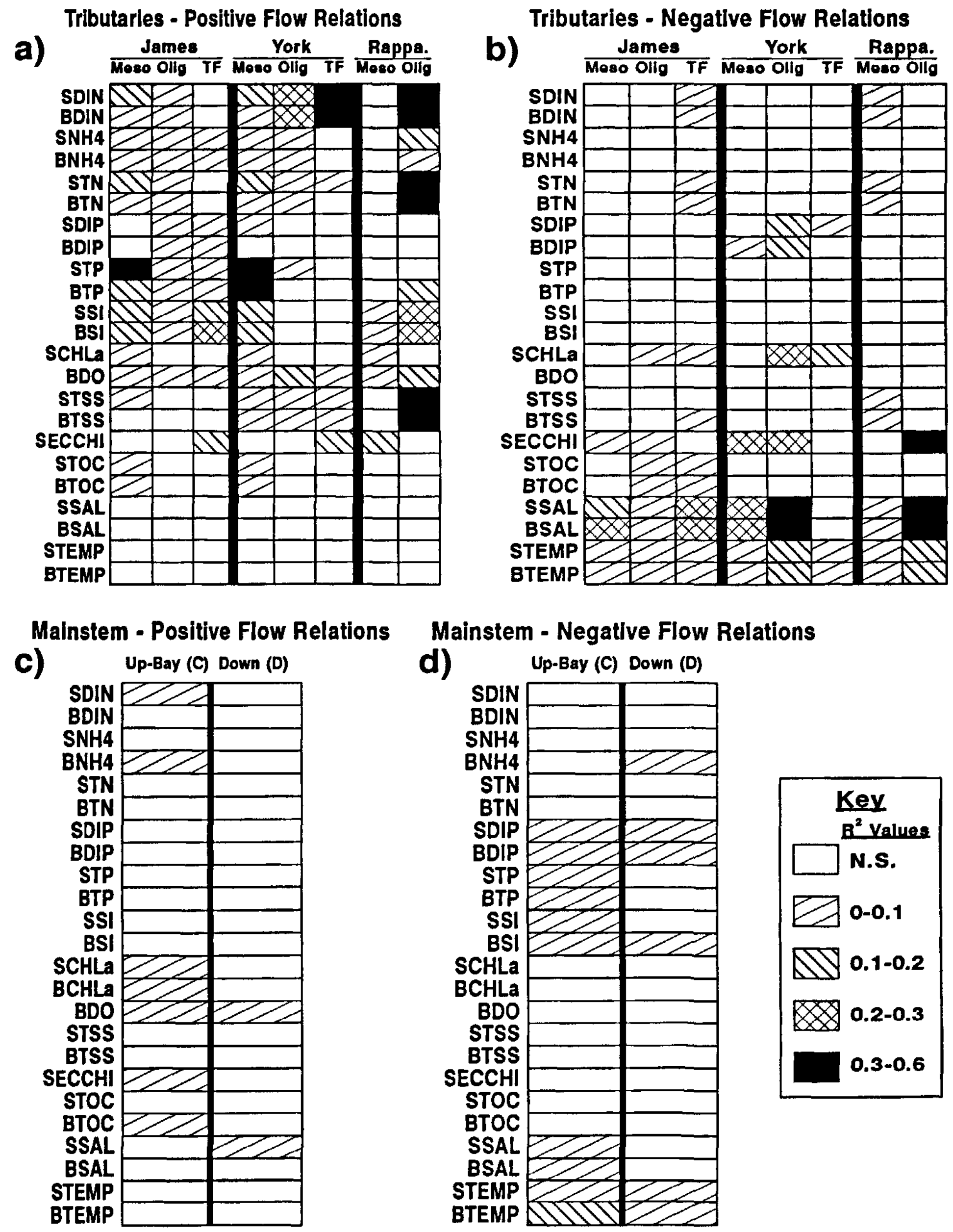

Figure 8

Summary of relationships between water quality variables and flow which were detected by nonlinear regression analysis. The patterns represent ranges of R^2 values associated with significant relations between water quality variables and flow: a) positive relations in tributary site groups; b) negative relations in tributary site groups; c) positive relations in mainstem site groups; and d) negative relations in mainstem site groups.

Rappahannock River (Table 2). Most of these trends could be attributed to flow patterns, since the TP trends for JI, YII, YIII and RII (surface) disappeared in the corrected data set (Table 2). An upward trend for BTN in JI also disappeared in the corrected data set. Surface and bottom concentrations of silicic acid appeared to be increasing in both the corrected and uncorrected data except in RI where the trend for BSI disappeared after flow corrections. Surface chlorophyll concentrations were observed to increase in both the uncorrected and corrected data from nearly all regions of the three tributaries, except in JIII where the trend disappeared after flow corrections were made. Increasing trends for BDO concentrations from JIII appeared for both uncorrected and corrected data sets. Upward trends in TSS concentrations of bottom waters of the tributaries were observed to disappear in the corrected data set. Increasing water temperatures for the James (JI-JII) and Rappahannock (RI-II) Rivers appeared only in the corrected data set.

The most evident downward trends in the tributaries were observed for all nitrogen and phosphorus nutrients in the tidal fresh James River (JIII). All of these trends persisted in both the uncorrected and corrected data sets, indicating that these long-term trends are not caused by flow effects. The transitional region of the James (JII) also displayed downward trends in some of the nitrogen nutrients (NH4 and STN), but the results indicated that

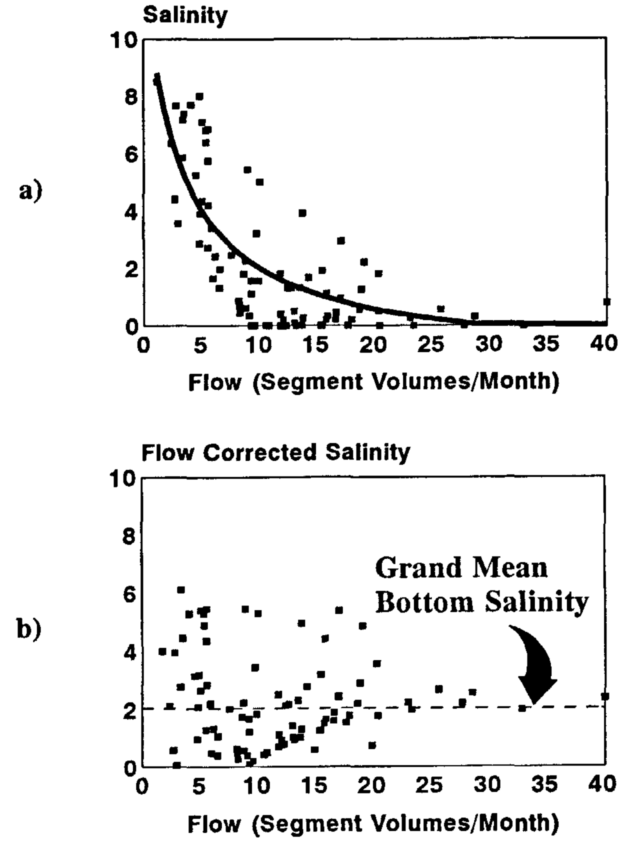

Figure 9

Example of the results of the flow correction process: a) negative relation between salinity in the oligohaline region of the Rappahannock River and flow; b) flow-corrected data displaying no relation to flow, but retaining the same grand mean.

flow effects may have obscured potential decreases in DIN and SDIP. Likewise, downward trends in certain nutrients in the Rappahannock were only observed in the flow corrected data set: NH4 in RI; and SDIN and NH4 in RII. Total organic carbon concentrations decreased in the James and Rappahannock Rivers, persisting in both the uncorrected and corrected data sets for both STOC and BTOC. Decreasing salinities appeared to be related to flow in the JI and YI regions, since these trends disappeared in the corrected data set. However, the declining trends in salinities for YII and RI persisted in the corrected data set. Decreasing trends for BDO from RI were only observed in the corrected data set, suggesting that a potential long term pattern of decline had been obscured by flow effects.

The predominant upward trends in the Bay mainstem (Table 3) were observed for TSS and, particularly TOC, although some of these trends disappeared in the corrected data set. Potential upward trends in TSS were observed for MSI only in the corrected data set. Likewise, a potential upward trend for bottom salinity from this segment was observed only in the corrected data set. Upward trends in water temperatures in region MSIII persisted in the flow corrected data, but disappeared in the flow corrected data from MSII.

The most obvious of all trends for the Bay mainstem were the long-term decreases in nutrients (Table 3): DIN and NH_4 decreased throughout most of the segments (MSI-V); and phosphorus (TP and DIP) decreased in many of the "down-Bay" segments (MSV-VII and, to a lesser extent, MSIII-IV). Most of these trends persisted for the corrected data. However, some potential decreasing trends may have been obscured by flow effects: declining trends for Secchi depth for MSIV and decreasing SNH4 concentrations for MSVII were only observed in the corrected data set. Likewise, potential decreasing trends for chlorophyll concentrations from MSI were only observed in the corrected data set. A potential downward trend in BDO was apparently obscured by flow effects in the segments near the Bay mouth (MSV-MSVII). Downward trends in salinities observed in segments MSII, and MSIII were apparently associated with flow patterns, since they disappeared following flow correction. The declining salinities observed for MSIV persisted in the corrected data.

DISCUSSION

Spatio-temporal patterns

The multivariate approach that has been developed to examine spatio-temporal patterns proved to be effective in summarizing water quality patterns that are observed in descriptive univariate statistics, as well as in providing "big picture" insights into patterns in the data base. The spatial and temporal groups defined by the protocol can be plotted on discriminant function axes to provide an effective visual presentation of water quality conditions that vary from one region to another, or from season to season. Furthermore, by taking spatial patterns into account before examining temporal effects and vice versa, new patterns may be discerned that otherwise would have been overlooked in the complex, often confounding, variability that is typical of environmental data sets.

Spatial and temporal effects are of nearly equal importance in defining water quality conditions in the mainstem Bay. On the other hand, spatial patterns of water quality are clearly much more important than seasonal changes in the tributaries. This contrast in the relative importance of spatial and temporal patterns makes sense when one considers the striking spatial differences in water quality that occurs as one moves from the tidal fresh to oligohaline to mesohaline regions of tributaries. The large regions of the mainstem Bay have water quality conditions that are much more likely to be mixed together and influenced by seasonal climatic events (e.g. storms and prevailing wind patterns; seasonal runoff in various parts of the watershed; seasonal stratification; etc.).

Spatial patterns in the mainstem Bay appear to be influenced by the estuarine-coastal water gradient encountered moving from the deep trench region of the Bay towards the Bay mouth. Nutrients, organic carbon and suspended solids loads and chlorophyll concentrations are greater in the up-Bay regions, while the regions near the Bay mouth tend to display less eutrophic conditions and greater salinities. Deeper regions tend to have lower dissolved oxygen and higher ammonium values in bottom waters, probably due to the decomposition of organic materials that settle in these areas, as well as

Table 2

Summary of the results of the trend analyses of uncorrected (U) and flow-corrected (C) water quality data for the Virginia tributary site groups (see Fig. *3 for locations). A blank cell or a "ns" indicates that no trends were detected at $p < 0.01$.*

	James						York						Rappahannock			
	JI		JII		JIII		YI		YII		YIII		RI		RII	
	U	C	U	C	U	C	U	C	U	C	U	C	U	C	U	C
SDIN			ns	-0.004	-0.064	-0.066									ns	-0.004
BDIN			ns	-0.007	-0.054	-0.053										
SNH4			-0.023	-0.020	-0.067	-0.068							ns	-0.002	ns	-0.014
BNH4			-0.021	-0.024	-0.061	-0.060							ns	-0.002		
STN			-0.035	-0.027	-0.075	-0.074										
BTN	0.015	ns			-0.080	-0.080										
SDIP	0.001	0.001	ns	-0.001	-0.025	-0.025			0.002	0.002						
BDIP	0.001	ns			-0.023	-0.023			ns	0.002						
STP	0.001	ns			-0.020	-0.020			0.001	ns	0.001	ns			0.001	ns
BTP	0.001	ns	0.005	0.003	-0.021	-0.021			0.001	ns	0.001	ns			0.003	0.004
SSI	0.1635	0.1461	0.2882	0.2201	0.4208	0.4136	0.1020	0.1064	0.3307	0.3382	0.5140	0.5061	0.1455	0.1314	0.3271	0.1903
BSI	0.1168	0.1058	0.2930	0.2237	0.4523	0.4598	0.0597	0.0605	0.3271	0.3350	0.5178	0.5140	0.0935	ns	0.3875	0.2709
SCHLA	1.7	1.7	2.5	4.1	1.4	ns	1.5	1.8	3.2	3.3	0.3	0.7	1.0	0.8	1.6	3.7
BDO	ns	-0.08			0.18	0.18							ns	-0.10		
STSS			1.0	ns												
BTSS	0.2	ns	0.3	ns							0.5	ns	0.1	ns		
SECCHI																
STOC	-0.210	-0.268	-0.265	-0.256	-0.277	-0.240					-0.170	-0.170	-0.267	-0.298	-0.193	-0.206
BTOC	-0.270	-0.319	-0.242	-0.227	-0.303	-0.262							-0.290	ns	-0.215	ns
SSAL	-0.49	ns							ns	-0.46			-0.35	-0.25	<0.01	ns
BSAL	-0.35	ns					-0.33	ns	-0.55	-0.63			-0.31	-0.23	<0.01	ns
STEMP			ns	0.29									ns	0.19	ns	0.27
BTEMP	ns	0.12	ns	0.29											ns	0.27

Table 3

Summary of the results of the trend analyses of uncorrected (U) and flow-corrected (C) water quality data for the Virginia mainstem site groups (see Fig. *2 for locations). A blank cell or a "ns" indicates that no trends were detected at $p < 0.01$.*

	MSI		MSII		MSIII		MSIV		MSV		MSVI		MSVII	
	U	C	U	C	U	C	U	C	U	C	U	C	U	C
SDIN	-0.005	-0.005	-0.007	-0.008	-0.005	-0.005	-0.004	-0.005	<-0.001	<-0.001				
BDIN	-0.006	-0.005	-0.007	-0.007	-0.006	-0.005	-0.005	-0.006	<-0.001	<-0.001	<0.001	<0.001		
SNH4	-0.002	-0.002	-0.002	-0.003	-0.002	-0.002	-0.002	-0.002	<-0.001	<-0.001			ns	-0.002
BNH4	-0.003	-0.003	-0.002	-0.002	-0.002	-0.002	-0.002	-0.004	<-0.001	ns				
STN														
BTN							ns	0.008	-0.006	-0.007				
SDIP	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	ns	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	-0.001	-0.001
BDIP	<-0.001	ns	<-0.001	<-0.001			<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	<-0.001	-0.001	-0.001
STP	0.169	0.139	<0.001	ns	<0.001	<0.001			-0.002	-0.002	-0.002	-0.002	-0.003	<-0.001
BTP					<-0.001	<-0.001			-0.003	-0.003	-0.002	-0.002	-0.005	<-0.001
SSI														
BSI														
SCHLA	ns	-0.4					ns	0.3						
BDO					ns	-0.07			ns	-0.11	ns	-0.13	ns	-0.13
STSS			0.7	0.6	0.5	ns	0.8	1.0	0.3	0.3	0.3	0.3		
BTSS	ns	0.9	0.5	ns			0.6	ns	0.9	0.9	1.0	0.8		
SECCHI							ns	-0.04	-0.05	-0.05				
STOC			0.216	0.196	0.194	0.177	0.232	0.266	0.114	0.110	0.071	0.072	0.110	ns
BTOC	0.157	0.160	0.223	0.221	0.192	0.183	0.245	0.284	0.102	0.101	0.115	0.113	0.169	ns
SSAL			-0.16	ns	-0.12	ns	-0.22	-0.42						
BSAL	ns	0.12	-0.11	ns			-0.23	-0.42						
STEMP					0.09	0.18								
BTEMP			0.09	ns	ns	0.16	ns	-0.04						

greater potential for stratification (and conversely, lower potential for reaeration processes). The deep trench that transports waters down the Bay is characterized by high concentrations of dissolved inorganic nitrogen, possibly due to these decomposition/remineralization processes. The James River also appears to be a source of nutrients to the Bay, but mainly in the form of dissolved inorganic phosphorus.

The spatial patterns in the tributaries clearly reflect an upstream-downstream gradient. The tidal fresh and

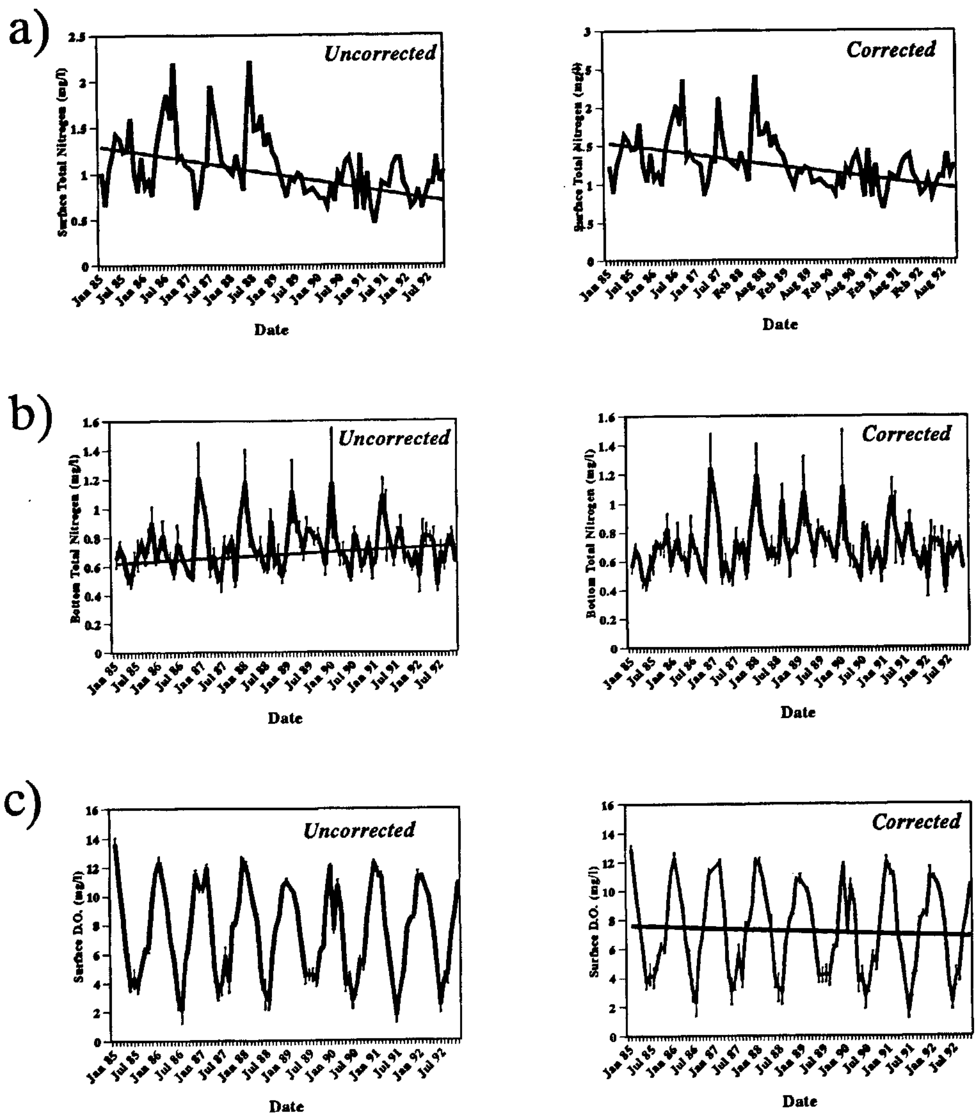

Figure 10

Examples of trend plots for selected variable/site group combinations: a) uncorrected and flow-corrected STN data from site group JIII; b) uncorrected and flow-corrected BTN data from site group JI; and c) uncorrected and flow-corrected BDO data from site group RI. Median slope trend lines are shown for data sets in which a significant trend was detected.

oligohaline regions of the tributaries, especially the James River, appear to be very rich in nutrients compared to the mesohaline regions. The oligohaline regions had greater suspended solids loads than the tidal fresh regions, reflecting the fact that they contained the turbidity maximum zones of all three rivers. Despite the greater turbidity, these regions also displayed the highest concentrations of chlorophyll, suggesting that they may be the most eutrophic of the tributary salinity regimes. The mesohaline regions displayed clearer, less nutrient rich, and more saline waters. The James River, while displaying the same spatial patterns as the other two tributaries, is clearly more nutrient rich, a characteristic that is made more important by the fact that its flow is greater than the other two combined. The tidal fresh portion of the James River has major municipal point sources of nutrients associated with a large population center in the area of Richmond, the state capital. Therefore, a great deal of management attention has been focused upon nutrient control in sewage treatment plants in this region.

The examples used to demonstrate the utility of the approach to the examination of temporal patterns in the mainstem Bay also provide insight into important water quality patterns. The importance of the summer thermal stratification to water quality can be observed in the seasonal cycles of phosphorus and ammonium in the bottom waters. The anaerobic sediments appear to flux first phosphorus and then ammonium into the bottom waters during the summer months. These field observations fit very well with observations from experimental flux studies conducted in the northern Chesapeake Bay (Boynton *et al.*, 1991). The fact that the phosphorus flux appears to occur as soon as the bottom waters become hypoxic/anoxic and the ammonium concentrations peak later in the summer may support speculation that the phosphorus release is due to redox-driven chemical processes dissolving iron phosphates and other compounds in the sediments (Krom and Berner, 1980; Klump and Martens, 1981), while the ammonium release from the sediments is due to slower, biologically mediated decomposition processes (Boynton et al., 1980, 1991). The temporal pattern of the nitrogen-based nutrients in the mainstem Bay appears to reflect a nitrification process hypothesized for the Bay (Boynton *et al.*, 1991): ammonium is released by decomposition processes during the summer months when low oxygen limits nitrification to nitrates; and when dissolved oxygen increases in the bottom waters during cooler months, the ammonium is nitrified to nitrites and then to nitrates. It is interesting to note that the summer with highest BDO concentrations had a peak of nitrate instead of ammonium, suggesting that more oxidizing conditions of this unusual season allowed nitrification to take place earlier in the year. Thus, the empirical data from the Bay appear to support the experimental data and theoretical speculations. The paradigm can be taken one step further to indicate that nitrates that peak in the colder months display a close inferential relationship with the peaks in chlorophyll concentrations that are associated with the late winter/early spring phytoplankton blooms. On the other hand, the phosphorus-based nutrients do not appear to be temporally related to these blooms, supporting the speculations that many scientists proposed early in the Bay program that phytoplankton populations in the saline regions of the Bay are not likely to be phosphorus limited.

Effects of flow on water quality

The significance of flow effects on water quality conditions became obvious during the course of this study. Over 80% of the water quality variables collected in the tributaries and nearly 50% of the variables from the Bay mainstem displayed significant relationships to flow. These relationships explain up to 55% of the total variation in the 8-year data set for some of the variables in the tributaries. On the other hand, the amounts of variation attributed to flow for variables in the Bay mainstem tended to be quite low. This contrast is not too surprising due to the longer flushing times in the wide, deep waters of the lower Bay, a characteristic which may buffer against major flow effects. It is interesting to note that the James River, which has the largest flow, had the greatest percentage of variables displaying significant relationships to flow.

The direction of most of the flow effects in the tributary water quality variables are understandable. Variables displaying a negative relationship to flow include salinity, temperature, and chlorophyll (except in mesohaline regions). Salinity would be expected to display a negative relationship to flow due to the dilution effects of greater freshwater runoff. Temperatures could have a negative relationship due to the increased introduction of colder runoff water during high flow conditions, due to the seasonality of high flow events tending to take place in the colder months (late winter/early spring and, occasionally, fall) or both. The patterns of decreasing chlorophyll concentrations with increased flow could be associated with a hydraulic flushing effect: faster flow produces such short residence times that the resident phytoplankton may not be capable of producing substantial growth before the populations are washed downstream. On the other hand, when residence times are prolonged, the phytoplankton may be capable of producing dense blooms while in a river segment. In the mesohaline reaches, where the pattern reverses itself, the tributaries tend to widen and the relative flushing rates slow, so population growth may be able to keep up with the lessened flushing effect, especially when stimulated by the greater nutrient loads that are often associated with high flow events (see below). In some cases, the downstream displacement of oligohaline phytoplankton blooms during higher flow events may also increase chlorophyll concentrations in the mesohaline region.

The variables tending to display a positive relationship with flow included BDO, SI, NH4, TN, and TP. This relationship for BDO could be due to the reaeration effect of increased surface runoff and the associated turbulence, and/or due to the seasonality of flow events which may be associated with cooler water, which can hold higher concentrations of dissolved oxygen. The increasing loads of most of the nutrients with increasing flow rates could be associated with greater inputs from stormwater runoff. On the other hand, the higher levels of chlorophyll concentrations associated with long residence times may suggest that nutrients may tend to be depleted by dense phytoplankton populations during low flow events. While both of these processes could be responsible for the observed relationships, the latter cannot explain why the chlorophyll-flow relationships reverse themselves in the mesohaline regions, but those for most of the nutrients do not (*i.e.* TN, NH4, DIN, TP and SI continue to display positive relationships with flow in the mesohaline regions of the York and James Rivers).

The effects of flow on water clarity were generally as expected: suspended solids loads tended to increase with flow, while Secchi depth tended to decrease. Increased erosion and runoff input of suspended materials would be expected to be associated with high flow events. The major exception to this pattern was observed for the mesohaline region of the Rappahannock River. The hydrography of this segment is different from those of the corresponding regions of the York and James Rivers, in that there is a shallow sill across the mouth of the Rappahannock. This feature may restrict flow through the mesohaline segment until high flow conditions flushes it out. Most water quality variables collected from this region displayed relationships to flow that were opposite from those observed from the other mesohaline regions, perhaps due to the effects of its unique hydrography.

Long-term trends in water quality

A discussion of the long-term trend results of this study must focus on the integration of two topics: the water quality trends actually observed in the lower Bay and its tributaries; and the effects of flow on the trends. In the tributaries, the upward trends for nutrients and chlorophyll concentrations noted for the five-year data set (Alden *et al.*, 1991) continued for many of the segments of the three rivers, albeit at more moderate rates of increase than observed previously. At least half of the increasing trends for nutrients appear to be associated with flow effects, since they disappeared in the corrected data set. Likewise, most of the river segments displayed increasing trends for suspended solids loads which were attributable to flow effects. It should be noted that two of the three rivers increased substantially in median flow rates during the second half of the study period: based upon monthly averages, median flow in the James River went from 147 m^3/s from 1985 through 1988 to a median flow of 230 m^3/s from 1989 through 1992 (a 57% increase); while the median flow rates for the Rappahannock River increased from 32 m^3/s to 48 m^3/sec for the same two periods (a 55% increase). The York River data did not indicate a similar trend, but a key USGS flow gauging station for this River was not operational for a two year period during the time of greatest change, so the apparent lack of flow pattern may have been due to the incomplete data set. Nonetheless, the directional temporal patterns observed for the other two tributaries would suggest that flow effects could produce significant trends for some of the variable-segment combinations.

The distinct downward trends for nitrogen and phosphorus based nutrients in segment JIII were not associated with flow effects. Rather, these trends, which were observed in both uncorrected and corrected data sets, appear to be associated with local point source controls. In a report for environmental managers in Virginia (Alden *et al.*, 1992), the authors demonstrated statistically that point source controls in this region would have produced decreasing trends in nutrients in the 5-year data set, if it was not for opposing trends in increasing nutrient loads coming from above the fall-line. After eight years of monitoring, the effectiveness of the point source controls are evident, despite the influence of any flow effects. Improvement in water quality conditions is also reflected by the increasing dissolved oxygen in bottom waters in this region.

Flow effects are also apparent in the form of "potential" long-term trends that have been obscured in the raw data. For example, downward trends in various nutrients may have been observed in segments JII, RI and RII, if flow effects had not overwhelmed them. Thus, potentially declining trends in nutrients, which may have otherwise been attributed to management actions, are "hidden" from the monitoring program.

It is not too surprising that the effects of flow on trends are much less apparent in the mainstem data sets. While some trends associated with TSS (upward), salinity (downward), and temperature (downward) can be associated with flow effects, most of the trends persist in both the uncorrected and corrected data sets. Ammonium and DIN tended to decrease in the up-Bay segments of the lower Bay, while DIP and TP tended to decrease in the segments nearer to the mouth of the Bay. Unfortunately, neither TN nor chlorophyll concentrations displayed overall downward trends throughout either region.

Total organic carbon increased throughout all segments. For the most part, the TOC trends could not be attributed to flow effects. These upward trends in TOC could be a genuine widespread phenomenon or could reflect the effects of methodological changes that have occurred in some of the monitoring laboratories. This issue should be explored further, since such an overall trend could have significant ecological implications, as well as potentially affecting water quality modelling efforts in the Bay.

Management implications

The results of the statistical approach taken have management as well as scientific implications. The regions of the Bay and its tributaries that are demonstrated to have similar water quality characteristics could obviously form the basis of management regions. Insight into which areas display high or low environmental quality is an important step toward the development of regional management strategies. Likewise, the ability to track water quality conditions throughout the year can provide an understanding of how the one variable may influence another. Thus, management strategies can be developed that are more holistic, recognizing that the factors that influence water quality conditions are both complex and dynamic. The ability to identify which factors are associated with seasonal nutrient fluxes or phytoplankton blooms can serve to optimize management approaches. In the case of the Chesapeake Bay Program, point source controls aimed at preventing phosphorus input into the mainstem may be less effective than nonpoint source controls aimed at nitrogen-based nutrients.

The effects of river flow on long-term trends in water quality that have been observed during this study can have important management implications. Trends of degrading water quality conditions in some of the regions of the tributaries can be attributed to flow alone. Obviously, such trends would tend to frustrate managers examining monitoring data for indications of the success of management actions. The protocol for conducting trend analysis on uncorrected and corrected data would allow such situations to be identified. Likewise, the protocol would allow managers to observe "potential" trends that may have been realized, if flow had not been a confounding factor. On the other hand, the process also would allow managers to "validate" trends that persist in the corrected data in order to demonstrate that the trends in water quality are really due to factors such as management actions (or, alternatively, due to anthropogenic damage) and not due to flow patterns alone. Since flow is a factor beyond the direct control of most management actions (at least in the tributaries of the lower Bay), it is important to be able to account for and "filter out" these effects in order to focus on trends that are associated with either management actions, or with anthropogenic degradation of the Bay.

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