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Chesapeake Bay Nutrients, Light and SAV: Relationships Between Water Quality and SAV Growth in Field and Mesocosm Studies

Year 1 - Final Report
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Chesapeake Bay Program

Chesapeake Bay Nutrients, Light and SAV: Relationships Between Water Quality and SAV Growth in Field and Mesocosm Studies

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EXECUTIVE SUMMARY

Short term variability in water quality constituents was measured over 10-day, seasonal studies at two sites in the Chesapeake Bay (June, August, October, 1993; and April, 1994 at the lower bay site only). The first site, Goodwin Island, located near the mouth of the bay in the highest salinity region (12-24 psu), was vegetated primarily with the strap-leaved species *Zostera marina* (eelgrass), with lesser amounts of *Ruppia maritima* (widgeon grass). The second site was located at Havre de Grace in the Susquehanna Flats, a low salinity (<1 psu; practical salinity units) region at the head of the bay. It was characterized by a canopy-dominated meadow vegetated with mixed species of primarily *Vallisneria americana* (wild celery), *Myriophyllum spicatum* (eurasian watermilfoil), and *Hydrilla verticillata* and minor amounts of *Heteranthera dubia* (water stargrass) and *Ceratophyllum demersum* (coontail) . The Goodwin Island site was dominated by the adjacent lower bay waters while the Havre de Grace site was dominated by the riverine influence of the Susquehanna River. Both sites were sampled at intervals of 15 minutes to 3 hours, at 3 or 4 stations, using fixed arrays of remote water quality sampling equipment. Other samples for plant biomass were obtained monthly, and additional water quality samples obtained at biweekly intervals. Our objectives were to investigate the spatial and temporal variability in water quality relative to these SAV communities and to compare these results to biweekly monitoring data currently used to evaluate water quality trends in the Chesapeake Bay system. In addition, a mesocosm study using *Potamogeton perfoliatus* (redhead grass) as a test species investigated SAV community response to variable water quality regimes using pulsed versus continuous dosing of SAV by nitrogen and phosphorus. The objective was to determine which was more deleterious to SAV, equal inputs of inorganic nutrients in lower level continuous doses, and higher level pulsed doses? And, how do these compare to equal loadings of nitrogen and phosphorus in particulate organic form?

The SAV beds at both field sites attained comparable maximum biomass (160-250 gdm m^{-2}), and vegetated the littoral zone to similar depths (0.8-1.0 m MLW), suggesting comparable limits to growth in spite of differences in growth forms. The upper bay bed attained maximum biomass in late summer, while in the lower bay maximum growth and biomass occurred in the spring, followed by dieback in mid-summer, and partial regrowth in the fall.

The two SAV beds demonstrated different capacities to attenuate inorganic nutrients and suspended particles from adjacent channel waters. At Goodwin Island the meadow canopy effectively trapped suspended particles including phytoplankton during April and June when bed development was high, thereby reducing concentrations in the water column within the bed compared to the channel. At Havre de Grace, fine particles carried in by the Susquehanna River were deposited throughout the shallow vegetated flats where they were continually resuspended by wind and currents. This resulted in higher suspended loads and light attenuation within in the bed compared to the channel area. In

the lower bay site this same phenomenon was observed in August when an abundance of fine organic and inorganic material was present within the bed.

Inorganic nitrogen was much higher at Havre de Grace than Goodwin Island and consisted of principally nitrate compared to ammonium in the lower bay study area. Orthophosphate concentrations were, in contrast, much lower at Havre de Grace and may be considered limiting to algal growth there compared to Goodwin where nitrogen was limiting. We did not observe nutrient levels within the bed at Havre de Grace to be significantly lower than the adjacent channel site. In contrast, nitrogen levels were greatly reduced during April and June at Goodwin Island within the bed compared to the adjacent channel. This may have been simply an artifact of lower current velocities and therefore longer residence time of water at the lower bay site rather than faster uptake at Goodwin, although further research would be needed to confirm this. During August, increased standing stocks of remineralized ammonium and orthophosphate were observed at night at Goodwin Island. This was observed to a lesser extent at Havre de Grace in August.

Diurnal patterns of dissolved oxygen (D.O.) demonstrated greater range within the beds compared to outside, illustrating higher metabolic activity per volume of water in the shallows than in the channel. Daily mean and maximum D.O. levels were higher in the beds than in adjacent channel areas during periods of maximum SAV growth and biomass (spring in lower bay and summer in upper bay), and lower during periods of SAV decline (summer in lower bay and fall in upper bay). D.O. minima were generally less in the lower bay site than the upper bay study area. In August, D.O. minima each night were accompanied by increased water column levels of orthophosphate, presumably due to release of orthophosphate from the sediment. These increases were reduced to background levels during the day.

Results of the fall mesocosms experiments demonstrated that when equal loadings of inorganic nitrogen and phosphorus were applied to SAV in pulsed dissolved, continuous dissolved and pulsed particulate forms, continuous loadings elicited the greatest biomass increase by algal components of the systems. Concurrently, decreases in macrophyte growth were greatest in these treatments. In spite of the high loading rates in the pulsed inorganic treatments, water column nutrient concentrations remained, or returned quickly to near background levels. Much of the uptake occurred in the algal components of the system which increased in dominance throughout the experiment. Thus concentrations of nutrients in the water column over a SAV bed are the net of the uptake and release of the system and at times may not necessarily reflect the degree of total nutrient stress, especially in pulsed inputs. On a per unit mass basis, continuous inputs appear more deleterious to SAV than pulsed inputs.

In spite of the fact that daily variability may exceed seasonal ranges in most parameters measured, biweekly monitoring measurements provided a good seasonal measure of median water quality in these two sites. Both sites, which contained persistent SAV, met the habitat requirements set for their respective areas as determined from the biweekly data.

Further research is needed on the effect of pulsed inputs of nutrients to SAV beds. This is especially important in areas where long-term levels of water quality are near the Habitat Requirements levels. Areas which just meet long-term, median water quality levels but have no SAV may be limited by irregularly high levels of TSS, nutrients, or chlorophyll which are not effectively measured by biweekly sampling. For example, a month-long decrease in turbidity may be measured by only one or two biweekly samplings.

In addition, we understand little of the processes which are affecting the large daily changes which we observed in levels of the water quality constituents within the SAV beds, especially in the lower Bay. The seasonal linking of these processes, i.e. uptake and deposition during the spring and re-release during the summer, needs further investigation. The impacts of these processes are important not only for the SAV beds, but the bay system as a whole.

INTRODUCTION

The decline of submersed aquatic vegetation (SAV) in the Chesapeake Bay has been associated with light limitation resulting from changes in water quality (Kemp et al. 1984, Orth and Moore 1983). Eutrophication severely limits the potential for the growth of submersed aquatic macrophytes, not only by promoting planktonic algal blooms (Swingle 1947), but also by promoting excessive epiphytic algal overgrowth (Phillips et al. 1978). Evidence for the negative impacts of eutrophication on submersed macrophytes spans northern and southern hemispheres in marine as well as freshwater environments (Stevenson 1988). For example, nutrient loading of coastal salt ponds in New England has been shown to enhance marine macroalgae at the expense of seagrass species (Lee and Olsen 1985, Valiela and Costa 1988), and appears to be associated with a significant decline of seagrasses in Cockburn Sound, Australia (Shepherd et al. 1989).

Because of these and other relationships observed between water quality and declines in living resources in the Bay, the 1987 Chesapeake Bay Agreement called for the development and adoption of guidelines for the protection of habitat conditions necessary to support Bay living resources (Chesapeake Executive Council 1987). In response to this request, habitat requirements for Chesapeake Bay SAV were developed using empirical models of seasonal medians in water quality, and corresponding growth and survival of natural and transplanted SAV at various regions throughout the bay (Orth and Moore 1988, Funderburk et al. 1992, Batiuk et al. 1992, Dennison et al. 1993, Stevenson et al. 1993).

The major sources of nutrient inputs to Chesapeake Bay, in general, are from agricultural drainage, atmospheric loading, point source outfalls, and oceanic sources; however specific sites can also receive nutrient inputs from adjacent deeper waters via tidal exchange, or wind-forced bottom water intrusion (Sanford and Boicourt 1990). Although the original sources of these nutrient inputs to SAV beds are the same as those to the Bay in general (agriculture, point source, atmosphere), there can be considerable time delays and modulating processes between original input to the estuary and eventual input to the SAV bed. Whereas, nutrient inputs from ground water and point source outfalls are relatively continuous, inputs from rainfall/runoff and tidal exchange are intermittent at various frequencies. The timing, frequency and form (dissolved vs. particulate; organic vs. inorganic) of these nutrient inputs are likely to substantially alter the responses and competitive interactions of SAV, phytoplankton, and epiphytes. However, the response of any one type of SAV system to these different loading scenarios is only now beginning to be determined.

Although general relationships between water quality and SAV response have been defined, a number of questions still remain. Of particular importance in Bay management is the need for a better understanding of the temporal variability of water quality relative to SAV habitat requirements. SAV habitat requirements have been defined based upon seasonal medians using biweekly or monthly sampling of the water column. Only a few studies have investigated short-term variability of certain water quality parameters in shallow SAV sites (Ward et al. 1984). The critical question is whether short-term variability in measured parameters at shallow water vegetated, or potentially vegetated, sites are important considerations for both monitoring programs and/or ecosystem model simulations. Currently, the water quality monitoring program stations that are monitored are sampled at biweekly to monthly intervals, and most sampling is conducted in mid-channel areas. Although this may provide a relative measure of comparison among areas sampled at similar time scales, the variable exposure levels which are likely influencing plant response in the littoral zone may not be adequately measured. Episodic events such as storms of moderate, regular nature are important forcing functions of the system, however their influence on shallow water conditions have not been well documented. Effects of other regular, physical forcing factors such as tidal influences are not easily interpreted by such data (Hutchinson and Sklar 1993). High frequency field sampling is necessary not only to define these conditions, but to validate current ecosystem processes models that simulate certain parameters using stochastic or other functions.

Spatial variability in water quality relative to SAV habitats is another factor that is an important consideration in the continued refinement of SAV habitat requirements and restoration targets. Small scale differences in certain parameters have been documented, such as decreases in the concentration of suspended solids (Ward et al. 1984), that are associated with the baffling effect of the SAV community (Kemp et al. 1984). However, variability of many other factors such as nutrients or light availability are not as well known. SAV beds have the ability to modify their environment, and this may provide one key to their survival.

Because of this capacity it is possible that conditions which permit the continued existence of SAV beds may not be suitable for recovery of denuded sites; or, that conditions which originally caused the declines of SAV beds in the Bay are not the same as those inhibiting recovery. What effects do the SAV beds have on modifying the levels of the individual factors used to define water quality suitable for SAV? How do levels obtained from within a vegetated area compare to those obtained in adjacent, deeper areas? Can any differences be related to some measure of SAV abundance? Are there differences in these relationships that are associated with different community types? How do these relationships change in the short-term (days) and long-term (seasonal)?

Various regional differences in the relationships between SAV communities and habitat conditions throughout the Bay have been identified (Batiuk et al. 1992). In the upper Bay in the Havre de Grace area, for example, dissolved inorganic phosphorus (DIP) may be limiting to algal growth as nitrate levels remain relatively high (>0.70 mg l^{-1}; >50µM) in the vicinity of SAV beds during summer months (Staver 1986, Posey et al. 1993). In the lower bay regions (Choptank and York Rivers) dissolved inorganic nitrogen (DIN) of greater than 0.14 mg l^{-1} (10 µM) is correlated with no SAV growth and N is likely the limiting nutrient to algae. The differences in nitrogen habitat requirements of the SAV beds in different salinity regimes have yet to be satisfactorily explained.

Experimental studies using both micro- and mesocosms have also been used to determine cause-effect responses between nutrient loadings, light availability and SAV growth and survival. Twilley et al. (1985) demonstrated that low levels of nutrient additions (0.42 g N m^{-2} d^{-1} and 0.09 g P m^{-2} d^{-1}) to ponds receiving ambient water from the lower Choptank River caused a 50 percent reduction in SAV biomass, due primarily to epiphyte growth on leaf surfaces, while higher levels resulted in loss of one species (*Ruppia maritima*). Other studies have similarly demonstrated negative response to nutrient enrichment as well as light reductions for bay SAV species (Staver 1986, Goldsborough and Kemp 1988, Neckles 1990, Burkholder et al. 1992, Neundorfer and Kemp 1993). Some of these studies simulated nutrient loadings as pulsed additions, while others have elevated nutrient concentrations through continuous dosing to simulate system eutrophication. In the pulsed nutrient loading studies, in particular, the relationships between loading rates and resultant concentrations in the experimental systems were not well defined. In addition, the question of whether macrophyte community response is different under one or the other loading regime has not been investigated. Therefore, given similar loading rates, are there differences in the resultant autotrophic community (SAV, phytoplankton, algae) response that can be related to the pattern of nutrient availability?

In this project we investigated the patterns of variability in water quality, and resultant effects on SAV using both field and laboratory mesocosm approaches. Our goals are two-fold: to study the spatial and temporal variability in water quality relative to the SAV community, and, investigate SAV response to variable water quality regimes.

Two sites, which represent endpoints in the distribution of SAV in the Chesapeake Bay, have been chosen for intensive study of temporal and spatial variability associated with habitat requirements. The first site, Goodwin Island, is located near the mouth of the York River in the high salinity region of the bay (37°12' N 76°23' W). It is vegetated with higher salinity SAV species (e.g., *Z. marina* and *R. maritima)*, that declined to low levels in the 1970's (Orth and Moore 1983), but have been increasing in abundance in recent years (Orth et al. 1992). It is an National Estuarine Research Reserve System (NERRS) site and the location of other ongoing field studies (Seufzer 1994; Buzzelli et al., unpublished data). The second site, Havre de Grace, is located at the head of the Bay in the Susquehanna Flats Region (39° 32' N 76° 05' W), and is the site of previous investigations (Serafy et al. 1988, Posey et al. 1993). The area is vegetated with intermittent beds of freshwater and low salinity SAV species (e.g., *V. americana*, *M. spicatum*, and *H. verticillata*) and their abundance is significantly reduced compared to historic levels (Bayley et al. 1978).

The seasonal timing of perturbations may have differing effects on ecosystems. Nutrient inputs to SAV communities in the upper bay during their initial growth phase in the spring, may have a greater detrimental effect on survival than inputs in the fall when plants are senescent. SAV mesocosm experiments were therefore conducted during the summer-fall of 1993 and spring-summer of 1994 to encompass the entire growing season of *P. perfoliatus*, a dominant upper bay species. In addition, the form of nutrient input (dissolved vs. particulate), as well as the mode of delivery (pulsed vs. continuous) was tested. Nutrients entering a system on a pulsed basis may result in a short-lived algal bloom, however a continual input may sustain an ongoing bloom condition that may result in greater impacts to the macrophyte community. The results of the summer-fall 1993 mesocosm experiment are included in this annual report.

I. FIELD STUDY GOODWIN ISLAND

Methods

At the Goodwin Island site (37o 12'N 76o 23'W), four stations were established along a transect running approximately NW/SE, beginning in the shallow subtidal flat adjacent to the east shoreline of Goodwin Island, and extending 1.25 km channelward (Figure 1). Stations 1 and 2 were located in the SAV bed and were 130 m and 400 m respectively from the island shoreline. Station 1 (0.4 m MLW) had a mixture of *Ruppia maritima* (widgeon grass) and *Zostera marina* (eelgrass). *Z. marina* was the predominant species at Station 2 (0.6 m MLW). Station 3 (0.8 m) was located at the outer edge of the grass bed, 925 m from the island shoreline, in an area sparsely vegetated with *Z. marina.* Station 4 (1.5 m MLW) was located outside the bed in an area of bare sand bottom, 1250 m from the island with a depth of 1.5 m MLW. At each station a permanent pole, which supported a box that housed the remote sampling equipment, was placed in the bottom (Figure 2).

Water Quality

Water quality at the site was sampled using both intensive (every three hours) and periodic (biweekly) sampling schedules. Intensive sampling was undertaken during four, 10-day periods in June, August, October, 1993, and April, 1994. During each intensive sampling period, water samples were obtained at 3 hr. intervals at each station using automated samplers (ISCO, Inc.) (Table 1). Biweekly sampling was conducted as part of the regularly scheduled Virginia Nearshore Submerged Aquatic Vegetation Habitat Monitoring Program (Heasly et al. 1989).

Water samples from the intensive sampling were obtained at fixed depths of 0.3 m above the bottom, stored on ice for no more than 24 hours, filtered through .45 μ filters, then analyzed in duplicate for dissolved inorganic nutrients and suspended particles. Ammonium was determined spectrophotometrically after Parsons et al. (1984). Nitrite, nitrate and orthophosphate were measured using an Alpkem autoanalyzer, equipped with a model 510 spectrophotometer. Total suspended solids (TSS) were determined by filtration, rinsed with freshwater, and dried at 60°C. Filterable inorganic matter (FIM) and filterable organic matter (FOM) were obtained by ashing the material at 550°C. Chlorophyll *a* was extracted using DMSO/acetone (after Shoaf and Lium 1976) and analyzed by fluorometry. Dissolved oxygen (D.O.), pH, salinity, temperature and water depth were measured at 15-minute intervals using Hydrolab Datasonde instrument systems placed adjacent to the ISCO sampler intakes, and individually calibrated before each field deployment. In situ photosynthetically active radiation (PAR) light attenuation was measured continuously and integrated over 15 minute periods using fixed arrays of underwater, scalar (4π), quantum sensors (LI-193SA, LI-COR, Inc.). The sensors were calibrated by the manufacturer prior to use, and when deployed in the field were cleaned daily to remove any accumulated epiphytes. Atmospheric, downwelling irradiance (2π

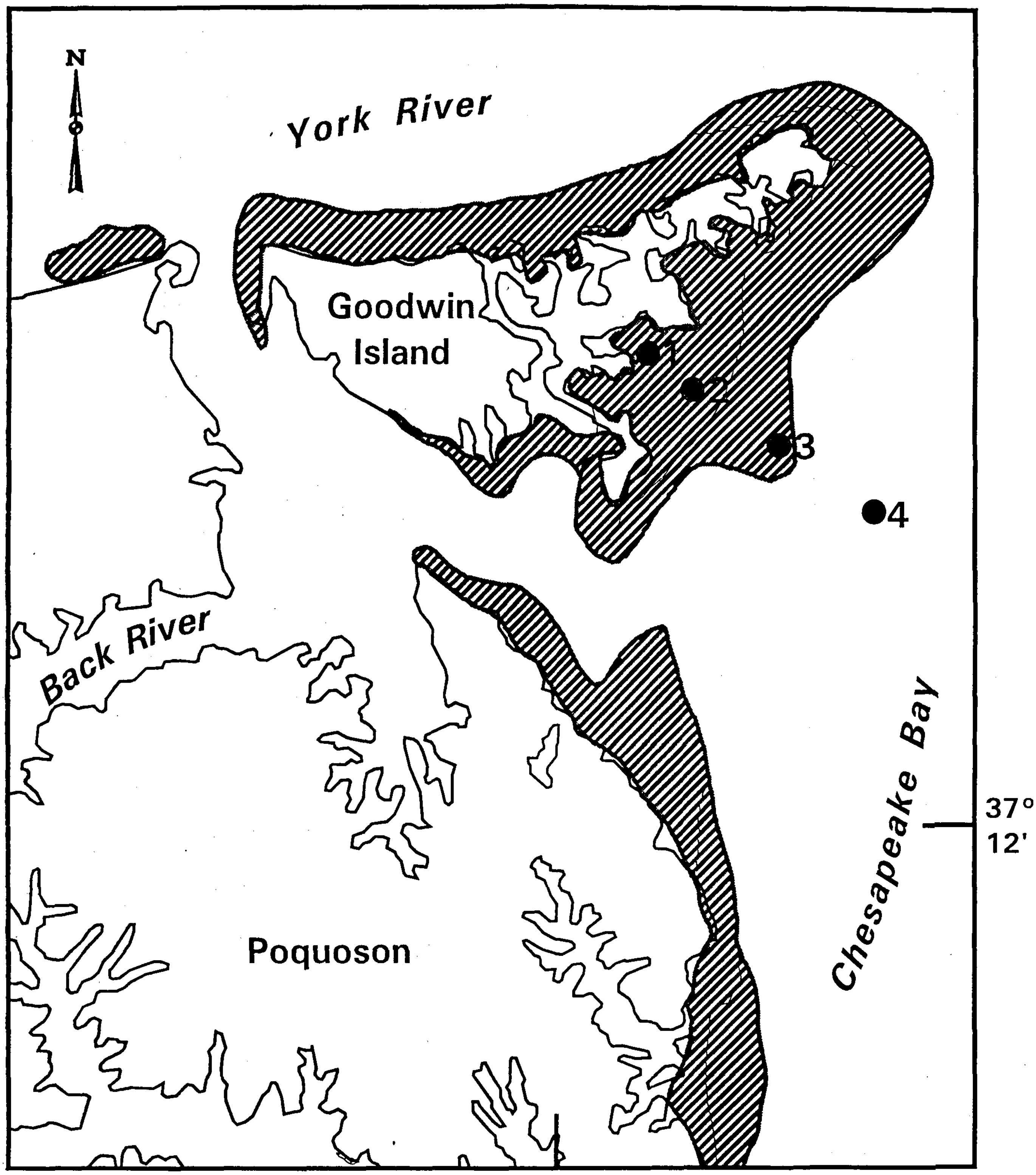

Figure 1: Goodwin Island Site

Fig. 2: Diagram depicting individual station instrument arrays.

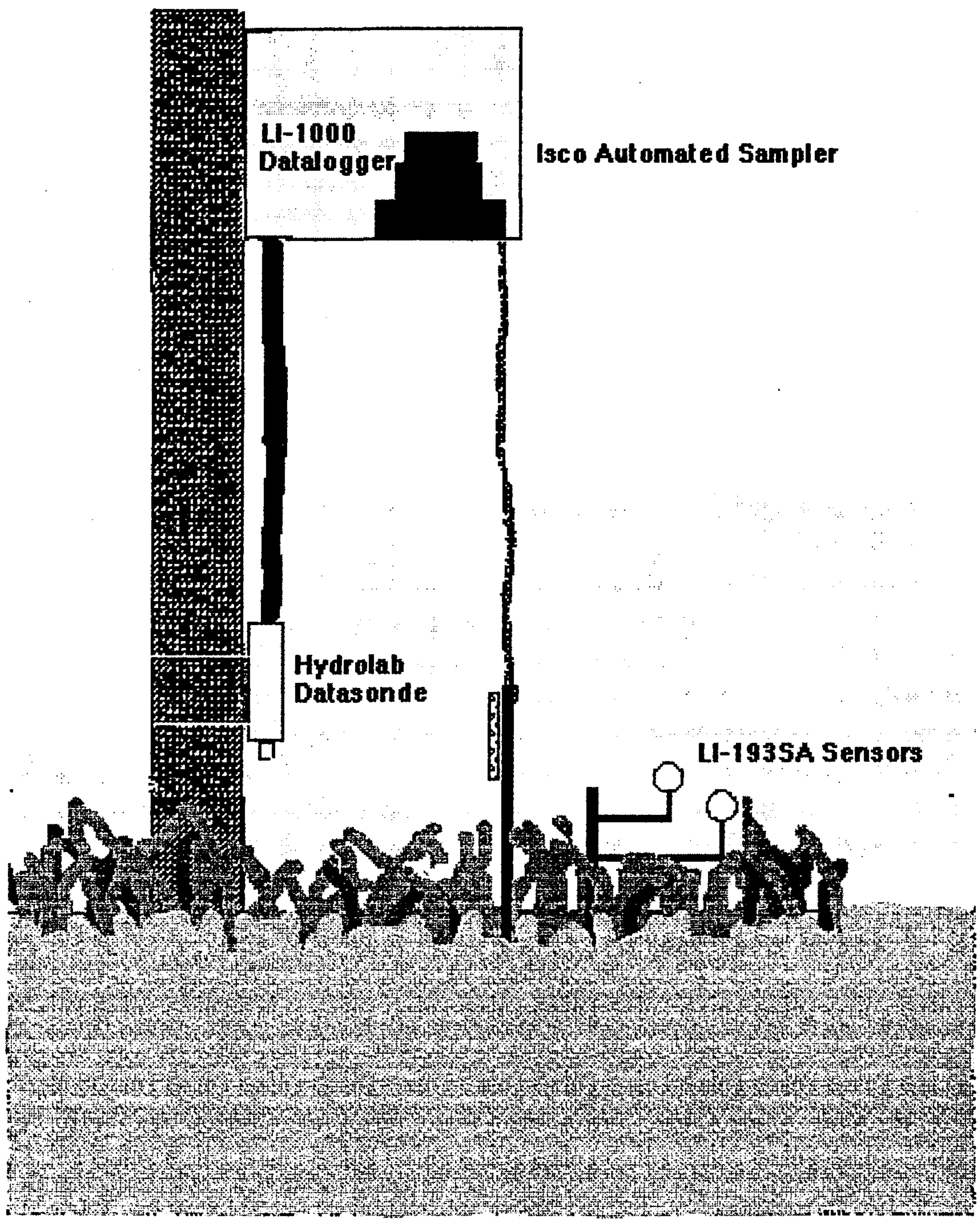

Table 1: Summary of parameters and sampling intervals for SAV and water quality measurements at Goodwin Island, VA study area.

Parameter	Interval
SAV	
Community Transect (% Cover)	**Periodic** (June, August, October, April)
Biomass Above/Belowground, Density, Canopy Height, Attached Epiphytes	**Monthly**
Water Quality	
Routine Sampling (TSS, K_d, Chl*a*, Nitrite, Nitrate, Ammonium, Dissolved Inorganic Nitrogen, Orthophosphate, Temperature, Salinity)	**Biweekly**
Intensive Sampling	**Periodic**
TSS (FIM, FOM)	Every 3 hours for 10 days
Chl*a*	"
Nitrite (NO_2)	"
Nitrate (NO_3)	"
Ammonium (NH_4)	"
Dissolved Inorganic Nitrogen (DIN)	"
Orthophosphate (PO_4)	"
K_d	Every 15 min for 10 days
Temperature	"
Salinity	"
Dissolved Oxygen (D.O.)	"
pH	"
Tidal Depth	"
Wind Direction/Speed	"

quantum, LI-190SA, LI-COR, Inc), and six minute, vector-averaged wind speed and direction were recorded continuously at Gloucester Point, Va., meteorological station (height +45 m Mean Sea Level).

Bi-weekly water samples were obtained in triplicate, at a depth of 0.25 m at Station 2, and placed on ice until returned to the laboratory for analysis of dissolved nitrite, nitrate, ammonium, orthophosphate, Chl a, TSS, FIM, and FOM. Triplicate analyses were made in situ for D.O., pH, water temperature, salinity, and integrated water column Kd (2π quantum, LI- 192SA, LI-COR, Inc.).

Macrophyte Sampling

Monthly, from May, 1993, through April, 1994, measurements of macrophyte biomass were determined at each of the vegetated stations. Five, replicate 0.1 m^2 rings were irregularly placed on the bottom at Stations 1 and 2. All vegetation, including roots and rhizomes to a depth of approximately 0.2 m was removed, gently shaken to remove sediments, placed in plastic bags on ice, and returned to the lab for morphometric and mass determinations. Each sample was separated by species, the shoots were rinsed, counted, measured for length, cleaned of epiphytes and separated into shoots and roots/rhizomes (standardized to the first 5 internodes). Shoot leaf area (LAI; m^2/m^2) was determined using a meter (Li-Cor, Inc., Model 3100 area meter). Dry mass of the shoot and root/rhizome samples were determined by drying at 60 °C.

Separate samples were obtained for epiphyte mass determinations in June, August, October, 1993, and April, 1994. Individual shoots were carefully placed in plastic bags in the field, returned immediately to the lab where they were gently scraped to remove attached epiphytes. The epiphytic material was collected on glass fiber filters, rinsed with freshwater, dried and ashed. Leaf areas of shoots used to obtain each subsample of epiphytes were determined.

Macrophyte Relative Abundance

A transect, adjacent and parallel to the four stations, was sampled for macrophyte abundance during each of the seasonal, 10-day sampling periods in June, August, October, 1993, and April, 1994. At 10-meter intervals, beginning at the shoreward marsh edge and continuing past the channelward edge of the bed, macrophyte standing crop was estimated by point intercept method (Orth and Moore 1988). At each 10-meter point, percent cover of macrophytes, by species, was estimated by a diver who randomly placed a 0.1 m^2 ring on the bottom. At each measurement, water depth, distance along the transect, and time were recorded. A fixed, tidal reference staff was used to measure water height change. These relative depth data were then normalized to mean low water (MLW) using referenced tidal measurements at the National Ocean Survey Gloucester Point tidal gauging station located approximately 10 km west in the York River.

Statistical Analyses

Friedman's ANOVA (Zar 1984), a non-parametric procedure for testing repeated measures, was used to compare dissolved nutrients, TSS, Chl*a*, and physical parameters for significance differences among stations within each sampling period. Analyses were accomplished using Statistica/Mac, StatSoft Inc., Tulsa, OK. If differences among stations were determined significant ($P \leq .05$), multiple, pairwise comparison analysis (Zar 1984) was used to test individual means.

Results

SAV Community Structure and Biomass

SAV Relative Abundance and Biomass

A integrated view of seasonal changes in the Goodwin Island SAV bed are illustrated in Appendices A1-A4. The four stations were located approximately 130 m, 400 m, 925 m, and 1250 m from the island shoreline. Only two species were reported within the bed, *Z. marina* and *R. maritima*. At the location of the transect the bed was approximately 550 m wide and the vegetation extended to a depth of 0.8 m MLW. This depth limit is similar to that reported for other beds in the region (Orth and Moore 1988). Greatest bed structure occurred in June 1993 when nearly the entire bed exceeded 60 percent in cover by vegetation. *Z. marina* dominated at all seasons, while *R. maritima* was found in the shallowest areas near shore. The topography of the meadow area was quite flat with only up to 0.1 m relief over the first 350m of width. After this point the bottom gradually deepened in the offshore direction. Bed width varied with season. During June, 1993, the bed extended nearly 550 m from shore. Dieback throughout the summer resulted in retreat of the apparent, channelward edge to about 350 m by October 1993. This appears to be a seasonal phenomenon, however, as regrowth of this deeper, outer bed area was evident in April, 1994.

Z. marina was most abundant in June throughout the bed with *R. maritima* occurring largely as an understory in inshore areas during this period (Appendix A1). By August, a large die-back in *Z. marina*, particularly in the shallow inshore areas, was evident (Appendix A2). *R. maritima*, however, reached its greatest abundance during this period. Large masses of decaying macrophyte shoot material was present throughout the bed at this time. By October the *R. maritima* standing crop had decreased and although the *Z. marina* standing crop was still low, new growth was evident (Appendix A3). It is during this period that germination of *Z. marina* seeds released in May and June is most pronounced (Moore et al. 1993). Large, unvegetated areas, however, were still observed throughout the bed. By April, 1994, significant regrowth of the bed had occurred, with *Z. marina* predominating (Appendix A4).

The monthly, biomass measurements confirmed the seasonal trends observed in the transect measurements. Both aboveground (Appendix A5) and belowground (Appendix A6) biomass were greatest in May with a rapid decline observed throughout the summer, to a minimum during the winter. *Z. marina* demonstrated a maximum during the spring, a decrease in the summer, and a small regrowth during September and October. *R. maritima* achieved maximum biomass during July and August. Shoot density (Appendix A7) paralleled biomass. *R. maritima* exceeded 500 shoots m^{-2} from July to September, while *Z. marina* reached greatest densities (>150 m^{-2}) in April. Average bed canopy height (Appendix A8) followed a bimodal seasonal pattern, as *Z. marina* dominated the bed structure, with maximum height (>0.3 m) observed in June, minimum in late summer (≈0.1 m) and some regrowth in the fall (≈0.15 m).

Epiphytes

Epiphytes (reported as grams dry mass) were measured during each intensive sampling only. Specific abundances were consistently greater on *R. maritima* than *Z. marina* throughout the year (Appendix A9). Epiphyte loads were lowest in April and June, and greatest in August and November.

<u>Physical Factors</u>

Wind

Wind velocities recorded at the Gloucester Point meteorological station for each of the sampling periods are reported in Appendix A10. Daily, vector averaged wind speeds and directions over the ten-day study periods are presented in Appendices A11-A14. Distinct differences in the seasonal patterns of winds are evident for each of the study periods. During June 1993, winds were light (<1m sec^{-1}) from the west during the morning, before switching to the east and steadily increasing in intensity during the afternoon and evening, gradually changing to the south, and eventually back to the west. During August the change from west (land breeze) to east (sea breeze) was more abrupt, with peak intensities (4 m sec^{-1}) occurring at 1400 to 1700 EST followed by gradual diminution during the evenings. During the October study period northerly winds dominated. Velocities increased rapidly each morning (0200-0600 EST), maintaining nearly constant levels throughout the day. Wind velocities during the April 1994 study period were higher, on average, than the June, August, or October 1993 study periods with peak velocities exceeding 10 m sec^{-1}. During this period winds from the southwest gradually diminished overnight, before changing to the south during the morning (0800-1000 EST) and increasing in intensity throughout the afternoon.

The Goodwin site was predominantly exposed to wind fetch from the northeast to southeast, therefore afternoon winds increased swells and waves in the bed, especially during June and August. High sea states precluded removal of samples from the ISCO samplers during several occasions.

Tides

Tidal heights normalized to mean tidal depth over each ten-day, seasonal study period are presented in Appendix A15. Spring and neap periods were sampled during each of the studies. Tides ranged from approximately 0.5m to nearly one meter with the greatest difference in range occurring during the August study period. During October 1993 the water depth increased nearly 0.5 m over the latter half of the study, while during June 1993 an increase in mean tidal level was observed during mid-study. Tidal levels varied less during the April 1994 study than during the other study periods. Spring to neap ranges were similar and generally low compared to the other seasonal studies.

Water Temperature

Water temperatures demonstrated periodicity on hourly, daily, and seasonal time scales (Appendices A16-A19) with distinct differences among stations. During June, water temperatures exhibited greater range both within a day (6° C), and between days (10° C) at Station 1 compared to channelward Stations 3 and 4. Conversely, the daily temperature ranges at Stations 3 and 4 were just 1°-2° C. Station 2 Hydrolab failed to record during this period. Mean temperatures were also higher at Station 1 (25.3 °C) compared to Stations 3 and 4 (23.8 and 24.0 °C respectively; Table 2a). Daily temperatures exhibited a 5 °C sinusoidal fluctuation throughout the study period with a periodicity of approximately a week. This pattern dampened with distance offshore.

During August 1993, the inshore vegetated stations (1 and 2) again exhibited greater daily temperature variances when compared to Stations 3 and 4 (Appendix A17). Mean temperatures at the stations over the 10-day field study were within 0.4 °C (26.9-27.3 °C; Table 2a), although they were greater in the shallower sites. Daily and weekly fluctuations in temperature were reduced compared to June.

October temperature patterns demonstrated an irregular pattern throughout the study period with day-to-day variability generally exceeding diel ranges. Water temperatures decreased 3-4 °C beginning on Oct. 11. This coincided with increased water levels and a period of strong easterly winds. In contrast to June and August, water temperatures were lower in the inshore, shallow areas compared to offshore as these sites experienced a more rapid fall cooling.

During April, 1994, water temperatures were quite similar at stations 2, 3, and 4 (Appendix A19; Table 2b). Mean temperature was significantly higher at Station 1. This appears principally due to warming of the shallows at Station 1 during the afternoons of April 13-16.

Table 2a: Medians of physical parameters by station from intensive sampling for June and August, 1993 at Goodwin Island, VA. Identical superscripts denote no significant differences ($P>0.05$) among stations within each study period.

June 1993

	Station 1	Station 2	Station 3	Station 4
pH	8.70[a]	N/A	7.85[c]	8.08[b]
D.O. (mg l^{-1})	9.29[a]	N/A	9.80[b]	10.54[c]
Salinity (psu)	15.84[a]	N/A	14.80[c]	15.00b
Temp (^oC)	25.35[a]	N/A	23.89[b]	23.76c
K_d	0.98[a]	1.13[b]	1.05[a,b]	1.55[c]

August 1993

	Station 1	Station 2	Station 3	Station 4
pH	7.98[a]	8.13[b]	7.66[c]	8.17[b]
D.O. (mg l^{-1})	5.02[a]	6.46[b]	7.82[c]	6.78[b]
Salinity (psu)	17.90[a]	19.70[d]	18.30[b]	18.70[c]
Temp (^oC)	27.20[a]	27.00[b]	26.79[c]	26.83[d]
K_d	1.19[a]	0.80[b]	0.90[b,c]	0.94[c]

Table 2b: Medians of physical parameters by station from intensive sampling for October 1993 and April 1994 at Goodwin Island, VA. Identical superscripts denote no significant differences (P>0.05) among stations within each study period.

October 1993

	Station 1	Station 2	Station 3	Station 4
pH	N/A	8.03^{a}	8.12^{c}	8.10^{b}
D.O. (mg l^{-1})	N/A	7.12^{a}	7.94^{c}	7.77^{b}
Salinity (psu)	N/A	23.90^{a}	24.10^{b}	24.20^{c}
Temp (^{o}C)	N/A	19.06^{a}	19.62^{b}	19.74^{c}
K_d	1.37^{a}	1.47^{a}	1.33^{b}	1.23^{b}

April 1994

	Station 1	Station 2	Station 3	Station 4
pH	8.73^{a}	8.63^{a}	8.32^{b}	8.33^{b}
D.O. (mg l^{-1})	N/A	11.02^{a}	8.25^{c}	9.52^{b}
Salinity (psu)	N/A	12.50^{a}	12.62^{b}	13.10^{c}
Temp (^{o}C)	17.26^{a}	15.92^{b}	15.75^{b}	15.70^{b}
K_d	0.95^{a}	0.92^{a}	N/A	0.79^{b}

Salinity

Salinities varied with season and ranged from 15 psu in June, 18-20 psu in August, 24 psu in October, and 13 psu in April (Appendices A20-A23; Table 2a and 2b). Seasonal increases in salinity in the fall reflect typical regional patterns related to river flows to the bay. There were few differences among the stations, as expected, since there is no freshwater input other than rain to the site. Some differences among the stations did occur, however. During June, salinities were highest at Station 1. While, overall, during all the other study periods salinities were greater at the deeper, channelward stations, especially Station 4. This reflected the higher salinity bottom water present at these deeper areas.

Water Quality Constituents

Chlorophyll a and Total Suspended Solids

Suspended particles in the water column, reflected in measurements of both TSS and Chl *a* , demonstrated differences among stations and study periods (Table 3a and 3b; Appendices A24-A31). In June 1993, when SAV biomass was greatest (Appendices A24 and A28), levels of TSS and Chl *a* were consistently lower in the bed (study period means 4.2-4.6 mg^{-l} and 8.7-14.9 $\mu g\ l^{-1}$, respectively) than out (7.7-8.5 mg^{-l} and 23.8-24.5 $\mu g\ l^{-1}$). Additionally, pulses of markedly higher suspended loads were much more evident in the two channelward stations compared to the vegetated stations. In August 1993 when bed development was greatly reduced, levels of suspended particles in and out of the bed were quite similar over the study period (Table 3a). Periods with increased concentrations of TSS and Chl *a*, lasting from 3 to 15 hours, were more evident at Stations 1 and 2 compared to 3 and 4. Wave action in the shallows may have been resuspending bottom sediments. The pulses of suspended particles reached higher concentrations in mid-bed Station 2. At the shallowest site reduced wave action may have limited resuspension, while greater depths and less fine material available for resuspension, limited resuspension at stations 3 and 4. Due, in part, to these pulsing events in August, mean TSS and Chl *a* levels were highest at Station 2.

By October 1993, fall regrowth of the SAV was occurring, the detrital material was largely gone, and mean concentrations of TSS and Chl *a* were again lower at the two inshore, vegetated stations compared to channelward stations 3 and 4 (Table 3b). A strong northeast wind and storm event precluded sampling during the period of October 11-13. Although suspended particle and nutrient samples were not available for this time period, elevated light attenuation measurements indicate that resuspension was very high within the bed.

Bed canopy structure, i.e.. shoot length, density and biomass, was again high in April, 1994, when Chl *a* and TSS concentrations were consistently lower in station 1 (in bed) compared to station 4 (outside bed). This pattern supports

Table 3a: Medians of inorganic nutrients and suspended particles by station from intensive sampling for June and August, 1993 study periods at Goodwin Island, VA. Identical superscripts denote no significant differences (P>0.05) among stations within each study period.

June 1993

	Station 1	Station 2	Station 3	Station 4
NO_2	0.0006 [a] (0.044)	0.0005 [a] (0.038)	0.0009 [a] (0.069)	0.0003 [a] (0.024)
NO_3	0.0034 [a] (0.242)	0.0024 [a] (0.181)	0.0034 [a] (0.244)	0.0043 [a] (0.310)
NH_4	0.0147 [a] (1.05)	0.0161 [a] (1.15)	0.0167 [a] (1.19)	0.0281 [a] (2.01)
DIN	0.0195 [a] (1.40)	0.0214 [a] (1.53)	0.0216 [a,b] (1.54)	0.0322 [b] (2.30)
PO_4	0.013 [a] (0.41)	0.015 [a] (0.48)	0.015 [a] (0.48)	0.015 [a] (0.48)
TSS	3.58 [a]	3.90 [a]	7.35 [b]	7.50 [b]
Chl*a*	8.48 [a]	14.40 [b]	24.80 [c]	24.80 [c]

August 1993

	Station 1	Station 2	Station 3	Station 4
NO_2	0.0013 [a] (0.100)	0.0004 [b] (0.030)	0.0003 [b] (0.020)	0.0004 [b] (0.030)
NO_3	0.0039 [a] (0.280)	0.0029 [a] (0.210)	0.0042 [a] (0.300)	0.0041 [a] (0.290)
NH_4	0.025 [a] (1.77)	0.016 [b] (1.17)	0.012 [b] (0.87)	0.014 [b] (0.98)
DIN	0.032 [a] (2.30)	0.021 [b] (1.51)	0.017 [b] (1.22)	0.019 [b] (1.33)
PO_4	0.011 [a] (0.335)	0.0096 [a] (0.300)	0.010 [a] (0.325)	0.010 [a] (0.290)
TSS	4.05 [a]	6.11 [b]	3.91 [a]	4.58 [a]
Chl*a*	9.12 [a]	10.96 [b]	9.44 [a]	10.48 [b]

*** All parameters in mg l^{-1}, ( ) in μM; Chl*a* in $\mu g\ l^{-1}$**

Table 3b: Medians of inorganic nutrients and suspended particles by station from intensive sampling for October 1993 and April 1994 study periods at Goodwin Island, VA. Identical superscripts denote no significant differences (P>0.05) among stations within each study period.

October 1993

	Station 1	Station 2	Station 3	Station 4
NO_2	0.0012 [a] (0.085)	0.0015 [a] (0.109)	0.0003 [b] (0.019)	0.0002 [b] (0.015)
NO_3	0.0049 [a] (0.348)	0.0056 [a] (0.403)	0.0080 [b] (0.570)	0.0074 [b] (0.530)
NH_4	0.025 [a] (1.78)	0.025 [a] (1.77)	0.025 [a] (1.80)	0.024 [a] (1.70)
DIN	0.034 [a] (2.40)	0.033 [a] (2.35)	0.037 [a] (2.67)	0.046 [a] (3.29)
PO_4	0.008 [a] (0.265)	0.010 [a] (0.325)	0.010 [a] (0.325)	0.009 [a] (0.290)
TSS	3.95 [a]	4.84 [a,b]	5.73 [a,b]	6.51 [b]
Chl*a*	5.96 [a]	8.32 [b]	14.24 [c]	13.92 [c]

April 1994

	Station 1	Station 2	Station 3	Station 4
NO_2	0.003 [a] (0.193)	0.006 [b] (0.430)	0.007 [c] (0.525)	0.007 [b] (0.510)
NO_3	0.009 [a] (0.64)	0.077[b] (5.50)	0.133 [b] (9.53)	0.136 [b] (9.74)
NH_4	0.019 [a] (1.36)	0.012 [a] (0.85)	0.016 [a] (1.11)	0.015 [a] (1.08)
DIN	0.043 [a] (3.07)	0.096 [b] (6.84)	0.160 [c] (11.41)	0.158 [c] (11.27)
PO_4	0.0099 [a] (0.310)	0.0106 [a] (0.330)	0.0104 [a] (0.325)	0.0091 [a] (0.285)
TSS	2.40 [a]	2.46 [a]	2.68 [a]	4.92 [b]
Chl*a*	15.65 [a]	23.20 [b]	25.20 [b]	24.24 [b]

*** All parameters in mg l^{-1}, ( ) in μM; Chl*a* in $\mu g\ l^{-1}$**

similar observations in June and October.

Light Attenuation

Light attenuation (reported as K_d) demonstrated considerable variation throughout each day with greatest apparent attenuation during the morning and afternoon, and least at mid-day. This pattern has been observed elsewhere (Moore and Goodman 1993) when continuous measurements of shallow water light attenuation have been recorded. It is possibly a function of the longer path length of light in shallow water during low sun angles and not related to increased turbidity of the water. To compensate for this apparent diel variability only mid-day (1000-1400) attenuation values were used here (Appendices A32-A35).

Except for the June, 1993, field study, all other study periods (August 1993, October 1993, April 1994) demonstrated higher mean attenuation values at stations 1 or 2 or both, compared to stations 3 and 4 (Table 2a and 2b). This does not agree with the patterns evident for suspended particle concentrations (Chl *a* and TSS), which demonstrated consistently lower levels for stations in the bed compared to out, during all study periods except August. There may have been differential fouling between the sensors at each site with greater fouling on the bottom sensor compared to the top. This appears unlikely since the sensors were cleaned each morning, however, resuspension of bottom sediments with relatively greater deposition on the bottom sensor remains a possibility. Conversely, attenuation by dissolved substances, which were not measured here, may be important.

Dissolved Oxygen and pH

Dissolved oxygen levels demonstrated markedly greater diurnal range in concentrations inside the SAV bed compared to outside during all study periods (Appendices A36-A39). In June 1993, for example, diurnal D.O. levels varied up to 10 ppm within the bed at station 1, compared to approximately 3 ppm at station 4. Overall, mean levels were higher at station 1 than stations 3 and 4 during this period. Maximum daily levels occurred in the afternoon at 1700 hrs. EST, while minimum levels were observed at 0600-0700 hrs. In August D.O. was lower, on average, at station 1 than stations 2, 3, and 4. This higher relative respiration is evidenced by the very low nighttime oxygen concentrations at this time. During October a coastal storm with sustained strong winds occurred during the 10th to 12th. During this period, diel variability in D.O. was dampened considerably. Overall mean D.O. levels among all stations in each study period were lowest at stations 1 and 2 compared to stations 3 and 4 during June, August, and October (Table 2a and 2b). In April, D.O. was higher inside the bed than outside, however, malfunctioning of the Hydrolab at station 1 limited the data available for this comparison. Rapid *Z. marina* growth, characteristic during this spring period, supports these observations. Seasonally, D.O. concentrations reached highest levels in June and April during periods of greatest SAV biomass and productivity, and lowest levels in August when decaying organic material was observed throughout the bed.

As pH levels in marine waters generally reflect the inverse of total carbon dioxide (bicarbonate) concentrations, pH varied in a pattern similar to D.O (Appendices A40-A43). High levels of photosynthesis within the SAV bed resulted in lower total carbon dioxide and therefore higher pH levels in the late afternoon. Nighttime respiration increased carbon dioxide in the water and therefore pH was lower. As with D.O., pH levels had greater daily range within the SAV bed compared to without. Overall, mean levels were lower in the bed that out during each season except April. Seasonally, pH levels were highest in April and June and lowest in August (Table 2a and 2b).

Dissolved Inorganic Nitrogen

Ammonium comprised the overwhelmingly largest fraction of the dissolved inorganic nitrogen (DIN) species measured at Goodwin Island during the June, August, and October 1993 study periods (Table 3a and 3b). Only during April, 1994, was nitrate the most abundant nitrogen species.

During June, DIN consisted of approximately 80% ammonium. Levels were highest at station 4 and decreased within the bed. Intermittent periods of elevated ammonium lasting from 3 to 12 hours were apparent at station 4, especially during June, 12-14 (Appendix A48). These increases were not evident at the shallower stations. Both salinity and water temperatures decreased during this period, possibly due to a change in water mass enriched with ammonium in the offshore area. Lower ammonium levels within the bed suggest that uptake was occurring in the vegetated area. Chl *a* levels (Appendix A28) were lower in the bed compared to out. Epiphytes were also low, while macrophyte biomass was at seasonal maximum. Thus, most uptake was likely accomplished by the SAV. Nitrite and nitrate demonstrated little difference among the stations over this June study period (Table 3a). Small pulses of nitrite and nitrate lasting 12 to 18 hours were evident, especially at the channel stations 3 and 4 (Appendices A52 and A56). These pulses were dampened or were absent at stations 1 and 2.

In August DIN was, on average, higher at station 1 than at the other three stations in contrast to June (Table 3a). The increase was due principally to diurnal pulses of ammonium that were observed within the bed each night. This diurnal increase was not observed during the other seasonal study periods. When ammonium concentrations are aggregated over a diel cycle the nightly increase in water column levels is evident. Potentially, these increased concentrations could be due to release of remineralized ammonium from the sediments. When dissolved oxygen concentrations are similarly aggregated a relationship between D.O. and ammonium is evident. At stations 3 and 4 average diurnal variability in water column D.O. was approximately 3 mg l^{-1} (Appendix

A64) and, on average, D.O. minima are 6 mg l^{-1} at the sensor height of 20 cm. Mean ammonium concentrations are relatively consistent at 0.014 mg l^{-1} (1 μM). At station 2, however, increased biological activity decreases average D.O. levels during the evening to 5 mg l^{-1} and ammonium concentrations increase to 0.025 mg l^{-1} (1.75 μM) (Appendix 64). Finally, at station 1 mean D.O. concentrations at the 20 cm sensor height fall to below 3 mg l^{-1} with a corresponding increase in ammonium to 0.042 mg l^{-1} (3 μM) (Appendix 64). Nitrate and nitrite concentrations were low with little difference among the stations in August (Table 3a). Nitrite was near undetectable levels throughout the study period except for several periods when levels reached 0.007 mg l^{-1} (0.5 μM) (Appendix A53). There was both spatial and temporal discontinuity in these small pulsing events. Nitrate demonstrated more regular increases (Appendix A57).

In October DIN consisted principally of ammonium with no differences detected among station means (Table 3b). Levels were higher overall compared to June and August. Concentrations were elevated at all stations beginning October 9th, immediately preceding a period of increasing wind velocities (Appendix A46). Nitrate demonstrated higher levels offshore, especially after the wind event (Appendix A58). Nitrite concentrations were consistently low, but increased markedly during the period October 12th to 14th after the storm (Appendix A54).

Higher DIN levels were recorded in April compared to the other three sampling periods. During this spring study period nitrate was the most abundant inorganic nitrogen species. Nitrate levels were highest overall in the channel station and decreased to very low levels inshore at station 1 (Table 3b). Ammonium demonstrated few consistent differences among the stations (Table 3b; Appendix A51). Nitrite concentrations were consistent and highest overall at the channel stations 3 and 4 (Table 3b; Appendix A55). At stations 1 and 2, levels were lower and demonstrated periodicity in the standing stocks. Nitrate concentrations also demonstrated considerable periodicity that appeared to be tidally influenced. When time-series plots of nitrate and tidal height are compared (Appendices A65-A68) the correspondence of increased nitrate concentrations and tide height are evident. Thus the shallows were receiving flooding water high in nitrate, and these concentrations decreased markedly during ebb. Salinity changes during the tidal cycles were minimal (less than 5 to 10% change from high to low tide) while nitrate varied from 2 to 5 times or more. It would appear that rapid uptake of nitrate was occurring both within the water column and the macrophyte community. Overall deceased levels within the SAV bed suggest that uptake from the water column was occurring. Chl *a* levels were observed to be lower in the bed compared to out (Table 3b) while epiphytes were lowest of all seasons sampled (Appendix A9). This suggests that the macrophyte may be largely responsible for this decrease.

Dissolved Inorganic Phosphorus

Orthophosphate concentrations maintained consistent levels of 0.0064 to 0.016 mg l^{-1} (0.2 to 0.5 μM) among all four stations and all four sampling periods (Table 3a and 3b; Appendices A60-A63). This suggests rapid buffering of orthophosphate, most likely through sorption-desorption processes involving suspended clay and organic detrital particles. During August, however, there was evidence of significant increase in orthophosphate concentrations in the SAV bed during the early morning when water column D.O. concentrations were at daily minima. This was not observed during other study periods. Appendix A69 present mean D.O. and orthophosphate concentrations aggregated over a diel cycle for stations 1 through 4 respectively. At stations 3 and 4 mean orthophosphate concentrations consistently average 0.0096 mg l^{-1} (0.3 μM) throughout the day while diurnal D.O. variability is moderate. At station 2, however, a sharp rise in orthophosphate concentrations was observed at about 0400 hrs. EST which corresponded to average water column D.O. minima of approximately 5.0 mg l^{-1} (Appendix A69). At the most inshore, vegetated station as D.O. decreased to average minima of 2.5 mg l^{-1}, water column orthophosphate correspondingly increased to over 0.019 mg l^{-1} (0.6 μM) before returning to average levels of 0.0096 mg l^{-1} (0.3 μM) by mid-day (Appendix A69). This relationship between D.O. and orthophosphate is consistent with the hypothesis that dissolution of insoluble phosphorus precipitates from the sediments or water column particles is occurring under conditions of low redox.

Water Quality Comparisons

Table 4 presents a summary comparison of median levels of five key water quality parameters that have been used to define habitat requirements for SAV growing in polyhaline regions of the Chesapeake Bay (Batiuk et al. 1992). Polyhaline SAV habitat requirements have been defined as median levels of these particular water quality constituents measured at regular intervals during the growing season, that correspond to areas where SAV beds have remained persistent in the highest salinity regions of the bay (Moore 1992). Results of biweekly monitoring of water quality at station 2 in Goodwin Island in 1993 demonstrate that this SAV bed would have met all criteria except that for Chl *a* during this year. These results support the habitat requirement concept, where similar comparisons have demonstrated that all or all but one of the habitat requirements will be met in areas where SAV are persistent.

Medians of each intensive monitoring study at station 2 are presented for comparative purposes. For the five parameters, the habitat requirement criteria were exceeded only twice: during October, 1993, for K_d, and during April, 1994, for Chl *a*. K_d medians in October are influenced by high K_d values during the morning and afternoon. During the April study period high levels of DIN (mostly nitrate) are supportive of the highest levels of phytoplankton observed. Quantitative comparison with the biweekly sampling results is difficult, since both sets of medians reflect different intensities and duration of sampling. Obviously, the biweekly sampled growing season medians do not reflect the short term or seasonal variability associated with this site. In areas of marginal water quality

Table 4: Summary comparison of Polyhaline SAV Habitat Requirements* for five key water quality parameters with median levels calculated using: 1) 1993 growing season biweekly monitoring at Station 2; 2) Station 2 seasonal, intensive study data; 3) 1993 growing season, biweekly monitoring data at two nearest bay mainstem monitoring stations (WE4.2/4.3); 4) Station 4 seasonal, intensive study data. Underlined values exceed habitat requirements.

Key Water Quality Parameters	**Polyhaline SAV *Habitat Requirements**	**1) Goodwin Station 2 Biweekly Monitoring**	**2) Goodwin Intensive Monitoring Station 2 (inside SAV)**				**3) Mainstem WE4.2/4.3 Biweekly Monitoring**	**4) Goodwin Intensive Monitoring Station 4 (outside SAV)**			
			June	**Aug**	**Oct**	**Apr**		**June**	**Aug**	**Oct**	**Apr**
K_d (m^{-1})	1.5	**1.3**	1.2	1.0	1.7	1.1	**1.3**	1.7	0.9	1.2	0.88
TSS ($mg\ l^{-1}$)	15	**7.8**	3.7	6.0	4.9	2.5	**13.0**	6.9	4.6	6.5	4.9
Chl*a* ($\mu g\ l^{-1}$)	15	**16.8**	13.6	10.8	8.8	23.2	**9.7**	23.8	10.4	13.9	24.2
DIN ($mg\ l^{-1}$)	0.15	**0.02**	0.02	0.02	0.03	0.10	**0.04**	0.02	0.02	0.05	0.16
(μM)	(10)	**(1.5)**	(1.3)	(1.5)	(2.4)	(6.8)	**(2.8)**	(1.5)	(1.3)	(3.3)	(11.3)
DIP ($mg\ l^{-1}$)	0.02	**0.02**	0.02	0.01	0.01	0.01	**0.004**	0.02	0.02	0.01	0.01
(μM)	(0.67)	**(0.50)**	(0.44)	(0.30)	(0.40)	(0.33)	**(0.10)**	(0.47)	(0.60)	(0.30)	(0.29)

*From Batiuk et al. 1992

this variability could be important in determining long term success of the SAV The biweekly growing season medians do, however, appear to accurately characterize the water quality classification of this area in regard to SAV requirements. They provide an overall measure of water quality that is similar to that presented by the short term, hourly sampling.

Growing season medians were also determined using surface data from adjacent, mainstem monitoring stations. These medians when compared to similar, biweekly data for station 2, inside the bed, are: identical for K_d, higher for TSS and DIN, and lower for Chl *a* and DIP (Table 4). Habitat requirement levels were not exceeded for any of the parameters. Of the five parameters investigated, only TSS and DIP seem to be somewhat out of line with values from the shallow water site. These differences may also reflect differences in methodologies. At a deeper water, mid-channel station, TSS might be expected to consist in large part of Chl *a*. However, Chl *a* levels are lower here than at station 2. DIP, which were generally consistent across the Goodwin Island transect stations, were much lower at the mid-channel station 2. When the mainstem data are compared to seasonal medians from station 4, the site of intensive monitoring closet to the mid-channel, similar results are obtained. Although there are some differences with data from the intensive studies, overall, the mid-channel monitoring data do support the conclusion that water quality in this area meets the SAV habitat requirements, and therefore SAV should survive and grow in this region.

Study period medians from both inside the SAV bed, at station 2 and outside SAV bed at station 4 are very similar (Table 4). During June, 1993, median levels of Chl *a* exceeded the habitat requirement limits at station 4 and not at station 2, while during April, 1994, DIN was also exceeded at station 4 and not at station 2. These differences, potentially, reflect the ability of SAV beds to baffle out suspended particles and take up nutrients; especially during periods when SAV growth and bed development is high. These results suggest that during certain seasons, established SAV can improve water quality sufficiently within the bed to achieve the habitat requirements when the adjacent water mass is above these habitat requirements. These results suggest that during seasonal pulses in reduced water quality, the existence of beds provides a positive feedback which may enhance their continued growth and survival.

II. FIELD STUDY HAVRE DE GRACE

Methods

Havre de Grace is located at the head of Chesapeake Bay, near the mouth of the Susquehanna River, 20 km downriver of the Conowingo Dam (Figure 3). The submersed aquatic vegetation (SAV) in this area has been studied previously (Staver 1986, Serafy et al. 1988, Posey et al. 1993, Wigand and Stevenson 1994). The site is strongly influenced by two physical factors: unprotected exposure to southerly winds across a large fetch (approx. 10 km), and river flow from the Susquehanna. The shallows adjacent to the shore line were vegetated with mixed beds composed primarily of *Vallisneria americana*, *Myriophyllum spicata*, and *Hydrilla verticillata* and minor amounts of *Heteranthera dubia* and *Ceratophyllum demersum* during the 1993 study period.

Three stations, approximately 100 m from each other (Figure 3), were chosen for intensive sampling. Two stations were located within an SAV bed in an area that had been sampled over the last eight years (Staver 1986, Serafy et al. 1988, Posey et al. 1993, Wigand and Stevenson 1994). The shallowest, Station 1 (39° 32.20' N x 76° 05.11' W; 0.5 m mean water depth), was consistently dominated by *H.verticillata*, and the other, Station 2 (39° 32.17' N x 76° 05.13' W; 0.75 m mean water depth), was consistently dominated by *V. americana*. An unvegetated station, Station 3 (39° 32.17' N x 76° 05.06'W; 0.5m mean water depth), was located outside of the grassbed on a slope of rapidly deepening water 20 m from a channel with MLW=2.1 m. The channel led into an active marina that accommodates primarily recreational boaters. The mean water depths at Stations 1, 2, and 3 were 0.5, 0.75, and 1.5 m, respectively. In order to facilitate sampling, 4"x 6" posts (12' to 16' long) with plywood boxes housing ISCO water samplers, LI-COR data loggers and Hydrolab Sonde Units were jetted into the sediments at each station (Figure 4).

Water Quality

In order to compare water quality sampling strategies, two separate regimes (Table 5) were used for this study. Twice monthly sampling of physical parameters and nutrient conditions was undertaken at one vegetated station (Station 2) from May through October 1993. Temperature, D.O., pH and conductivity were measured with a Hydrolab Surveyor II, light attenuation was determined with LI-COR spherical sensors and a data logger (see below), and water samples for nutrient, chlorophyll *a* and total suspended solids were collected in an acid washed nalgene bottle and kept on ice or in a refrigerator until processing (see below).

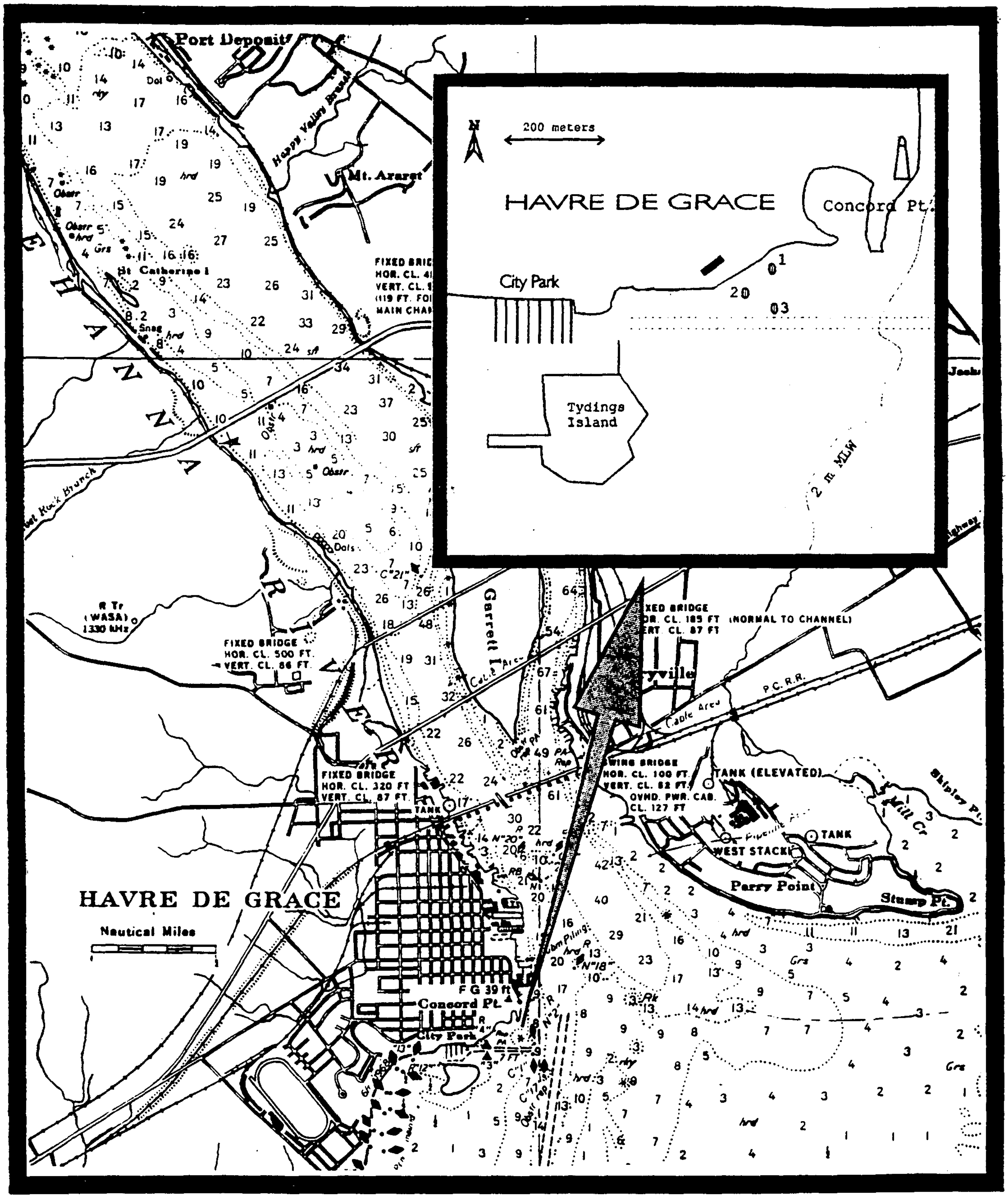

Figure 3. Study site at Susquehanna Flats.

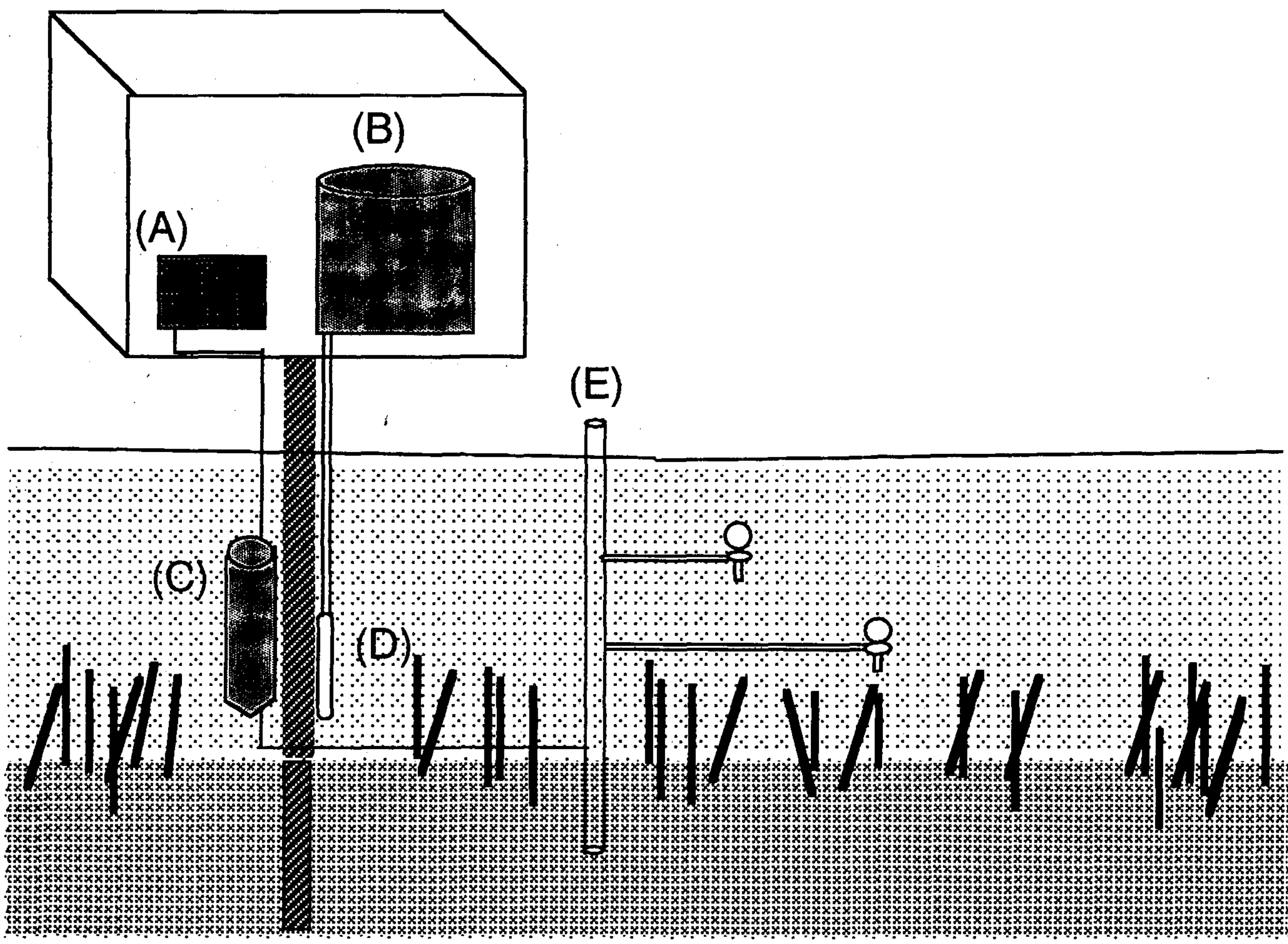

Figure 4. Schematic drawing of equipment deployed at Havre de Grace. (A) LI-COR data logger (B) ISCO water sampler (C) Hydrolab (D) water sampler intake (E) light attenuation array .

Table 5. Summary of parameters and sampling intervals for SAV and water quality measurements at Havre de Grace, MD study area.

Parameter	Interval
SAV (Above and Belowground biomass)	Periodic (June, August, October)
WATER QUALITY ROUTINE SAMPLING (TSS, Kd, Chl, NO2, NO3, NH4, DIN, PO4, Temperature, Conductivity)	Monthly (May-October)
INTENSIVE SAMPLING (TSS, Chl, NO2, NO3, NH4, DIN, PO4) (Kd, Temp, Conductivity, pH, D.O., Depth)	Periodic (June, August, October) (every 3 hours for 10 days) (every 30 min for 10 days)

Intensive water quality monitoring was conducted at all three stations during three ten day periods (June 15-25, 1993; August 1- 12, 1993; and October 3-13, 1993). Water samples for nutrient analysis were collected at approximately 30 cm from the bottom at 3-hour intervals using automated ISCO samplers. The raw water samples were kept on ice in the ISCO canister, retrieved from the field once daily, and brought to the CEES Northern Bay Facility at Havre de Grace for immediate processing. Hydrolab Sonde II units were deployed such that the sensors were 30 cm above the bottom; conductivity, pH, D.O., temperature and water depth were measured and recorded at 30-minute intervals. Light extinction coefficients (K_d) were determined at two stations during each sampling period by measuring photosynthetically active radiation (PAR) at 30-minute intervals at two depths (35 cm (Station 1) or 50 cm (Stations 2 and 3) apart with a LI-COR (model 1000) datalogger equipped with underwater spherical (4 pi) quantum sensors which were cleaned daily of fouling organisms throughout the study period. An average daily K_d for the hours from 1000h to 1400h EST was determined. This effectively eliminated high K_d values obtained in the hours around dawn and dusk (see Section I for discussion).

All water samples collected for dissolved nutrient (nitrate, nitrite, ammonium and phosphate) determinations were filtered through Whatman GFF filters. The filtrates were frozen for later analysis on a Technicon AutoAnalyzer II system at Analytical Services at Horn Point Laboratory. Detection limits were as follows: nitrate 0.007 mg l^{-1}; nitrite 0.007 mg l^{-1}; ammonium 0.063 mg l^{-1}; phosphate 0.001 mg l^{-1}. The filters were frozen for later fluorimetric determination of chlorophyll *a* concentrations (Parsons et al. 1984). Total suspended solids were measured gravimetrically after filtering onto an ashed, pre-weighed Whatman GFF filter.

Above and belowground biomass were collected during each study period at each of the three stations using 0.25 m^2 quadrats. Three replicate quadrats were placed randomly on the bottom at each station. All aboveground vegetation was clipped and the belowground sediment was excavated with a shovel. After bringing it to the surface, the vegetation was rinsed gently, separated from sediments, and placed in plastic bags for transport to the lab. Plant matter from each quadrat was sorted by species, dried at 60 oC and weighed.

Statistical Analyses

Friedman's method for randomized blocks (Zar 1984), a non- parametric test in which the variates are ranked within each block, was used to compare nutrient, seston, chl*a* concentrations, and physical parameters among stations in June, August and October 1993. Sampling times with data missing from any one station were not included in this analysis. Station means presented in the text were calculated using only the data used for statistical analyses. If differences among stations were determined to be significant, multiple, pairwise comparison analysis was used to test individual means (Zar 1984). Analyses were accomplished using Statistica/Mac, StatSoft Inc., Tulsa, OK.

Results

Plant Community

The three most abundant species of SAV at Havre de Grace during 1993 were *V. americana*, *M. spicata*, and *H. verticillata*. *V.americana* is indigenous to Chesapeake Bay (Stevenson and Confer 1978) whereas the latter two species are introduced. *V americana* is a meadow forming grass that emerges from tubers in early spring. *M.spicata* is a canopy forming macrophyte that often overwinters along the bottom and sprouts from the previous year's roots and quickly reaches the water's surface to form a dense canopy (Staver 1986). *H.verticillata* is also a canopy forming macrophyte, but differs from the other species at Havre de Grace because it has a very small amount of root biomass (Stevenson 1988). It requires warmer water temperatures than the other two species to germinate, and grows more slowly than *M. spicata* does in spring (Carter et al. 1994). Therefore, the *H. verticillata* canopy typically forms later in the growing season (Staver and Stevenson 1994) which accounts for the lack of this species in the shallows on our first sampling in June.

Biomass

In June, aboveground biomass at Station 2 was estimated to be 25 g m^{-2}. The bed consisted of *V. americana*, with a small amount of *M. spicata* and no *H. verticillata* present. Vegetation was absent at Station 1 during the June study period..

By August, the two introduced species dominated the SAV bed. Total aboveground biomass was much greater at Station 2 (183 g m^{-2}) than at Station 1 (60 g m^{-2}) (Appendix B1). At Station 1, the greatest percentage of biomass consisted of *H. verticillata*, whereas at Station 2, *H. verticillata* and *M. spicata* each comprised about half of the biomass.

Production in the SAV bed increased dramatically after June and continued throughout August and September with peak biomass in October. Aboveground biomass at Station 2 (161 g m^{-2}) was slightly less than at Station 1 (182 g m^{-2}) (Appendix B1). During the October study period, *M. spicata* and *H. verticillata* each contributed to roughly half of the biomass at both stations, with *V. americana* making up 9 percent of the biomass at Station 1, and 4 percent at Station 2.

No vegetation was present at Station 3 during the June, August or October study periods.

Physical Factors

Depth, Temperature and Conductivity

Hydrolabs were deployed at all three stations for each time period, but because of malfunctions data was only logged at Stations 1 and 2 in June and at Stations 2 and 3 in August. A complete record of all three stations was obtained in October.

The tidal range at all three stations during each sampling period was about 1 m (Appendix B2). Mean depth varied between the three stations from 0.5 m at Station 1 to 0.75 m at Station 2 to 1.5 m at Station 3. Water depth at the Havre de Grace site is strongly influenced by wind and discharge of the Susquehanna River as well as by gravitational forces. The tidal cycle was most consistent in August, when the river discharge was low, and most erratic in October.

Generally water temperatures showed strong diel patterns at all three stations (Appendices B3-B9). The range of temperatures within a day were consistently greater at the shallower vegetated stations, and the range between days was greater in October than in June. In August the water temperature ranges were notably smaller than during the other two sampling periods. Water temperatures were highest in August and lowest in October (Table 6).

In June, water temperatures at Stations 1 and 2 were similar (Table 6). Hydrolabs at both stations were collecting data simultaneously from June 18-22. During this time, water temperatures at Station 1 exhibited a greater daily range of values (Appendix B3) than at Station 2 which was deeper (Appendix B4). The dampening of the daily water temperature cycle seen at both stations beginning June 21 corresponds to a rain event (Appendix B10).

In August, the mean water temperatures at Stations 2 and 3 were similar (Table 6), but the two stations displayed distinct differences. The shallower station showed more variability, 23.5-30.0 ^{o}C at Station 2 compared to 24.2-29.4 ^{o}C at Station 3, and was more strongly influence by the rain of August 6 (Appendices B5, B6 and B11).

In October, the water temperatures at all three stations had cooled almost 10 degrees and Stations 2 and 3 were similar, while Station 1 was about 0.5 ^{o}C cooler (Table 6). Maximum temperatures ranged from 19.5 ^{o}C (Station 3) to 20.6 ^{o}C (Station 2), while minimum temperatures ranged from 11.4 ^{o}C at Station 2 to 13.9 ^{o}C at Station 3 (Appendices B7-B9). Once again, the deeper station showed less variability and was less dramatically influenced by meteorological events such as the rapid decrease in air temperatures from October 9-11 and the rain of October 12.

Salinity at the Havre de Grace site is <1 psu; therefore conductivity was recorded as a more reliable measure of total dissolved solids. Although sinusoidal curves of conductivity suggested tidal influences, there were several records where conductivity is comparatively flat over several days, indicating the importance of both riverine and atmospheric inputs (Appendices B3-B9). The differences between stations were in the range of 25 μS cm^{-1} in June with the shallower Station 1 being lowest, varying from 280 to 300 μS cm^{-1}. There was a slight increase in conductivity throughout the June sampling period at both stations, with no major precipitation events. In August conductivity at both

Table 6. Physical parameter medians by station for each sampling period at Havre de Grace, MD.

June 1993

	Station 1	Station 2	Station 3	
pH	7.53	7.80		**
DO (mg/L)	6.08	10.86		**
Conductivity (µS/cm)	293	334		**
Temperature (°C)	26.23	26.31		**
Kd		1.59	1.56	ns

August 1993

	Station 1	Station 2	Station 3	
pH		8.20	8.49	**
DO (mg/L)		8.58	5.82	**
Conductivity (µS/cm)		322	356	**
Temperature (°C)		27.22	27.07	*
Kd	1.15	1.98		**

October 1993

	Station 1	Station 2	Station 3	
pH	8.35	8.38	7.82	**
DO (mg/L)		10.00	9.69	nc
Conductivity (µS/cm)		342	320	nc
Temperature (°C)	17.07	17.59	17.56	**
Kd	1.73		1.29	**

*-- statistically significant at $p<0.05$

**- statistically significant at $p<0.01$

ns-- not statistically significant

nc-- no statistical analyses performed

Stations 2 and 3 increased after the August 6 rain, and then oscillated with the deeper station (Station 3) having a higher range of 345-385 µS cm^{-1} compared with Station 2 (305-345 µS cm^{-1}). In October Station 2 conductivity is much more erratic (320-350 µS cm^{-1}) than Station 3 (320-325 µS cm^{-1}) despite two precipitation events.

Dissolved Oxygen and pH

During all months at all stations, dissolved oxygen concentrations exhibited diel patterns (Appendices B3-B9) which were correlated with macrophyte and phytoplankton production of oxygen by day and respiration at night. Greater daily D.O. variances occurred at the vegetated stations. For example, in August the daily change in D.O. at Station 2 was approximately 10 mg l^{-1}, while at Station 3 it was only 5 mg l^{-1}, and in October the daily change in D.O. at Station 2 was approximately 7 mg l^{-1}, while it was only 2 mg l^{-1} at Station 3. D.O. concentrations were lowest during the August sampling period (Table 6). Oxygen production by macrophytes contributed to higher D.O. levels at the vegetated stations during all three sampling periods.

All stations exhibited diel pH patterns similar to the D.O. patterns with greater daily variability again observed at the vegetated stations (Appendices B3-B9). In addition to enhancing daily pH ranges, macrophyte consumption of CO_2 for photosynthesis increased pH values (Table 6) throughout the growing season in the vegetated stations (Station 1 pH was 7.53 in June and 8.35 in October, Station 2 mean pH was 7.80 in June, 8.20 in August, and 8.38 in October). In comparison, pH decreased from August (8.49) to October (7.82) at Station 3 (Table 6). This decrease is associated with markedly lower temperatures in October as compared with August.

Response to precipitation and higher runoff is especially evident in the August data. The pH maximum was dampened at both Stations 2 and 3 on August 6, after a substantial rain (Appendices B5 and B6), but are much more evident at Station 2 where macrophyte photosynthesis controls pH fluctuations. In October there was a pH peak and dampening of the daily range at Station 3 towards the end of the sampling period. This corresponded to a chl *a* pulse which was observed at all three stations (see below). The increase in pH at Station 3 is most likely due to phytoplankton photosynthesis. The effects of additional algal production in the grassbed was insignificant when compared to macrophyte production.

Weather

Weather conditions in June remained relatively stable, with light rain showers on June 19, 20 and 21 (Appendix B10). A front moved through the area on August 6 (Appendix B11). It was accompanied by decreasing barometric pressure and air temperatures, and a light to moderate rain event from 0700h to

2000h. This coincided with an immediate drop and subsequent increase in conductivity, a depression in the D.O. and pH peaks, and a steady decrease in water temperature (Appendices B5 and B6). Weather conditions were least stable in October. Barometric pressure exhibited more fluctuations than during the June and August sampling periods. Air temperatures dropped from a high of 26.7 ^{o}C for October 9 to a high of only 13.3 ^{o}C for October 10 (Appendix B12). Similarly, the low air temperatures for October 9, 10, and 11 were 12.2, 6.7, and 2.8 ^{o}C, respectively. A corresponding decline in water temperature was observed at all three stations (Appendices B7-B9).

Water Quality Constituents

Light Attenuation

Light attenuation was successfully recorded at Stations 2 and 3 in June, Stations 1 and 2 in August, and Stations 1 and 3 in October. In June, light attenuation was fairly consistent from day to day (Appendix B13), and there were no significant differences (Table 6) between the two stations (K_d was 1.59 m^{-1} at Station 2 and 1.56 m^{-1} at Station 3).

In August, however, light attenuation showed greater variability (Appendix B13). In general, daily K_d values were higher for August 6-10 than for August 2-5. This can be explained by increases in chl*a* and suspended solids (see below) which can be attributed to the rain event on August 6. There were also significant differences (Table 6) in light attenuation between the two stations. Station 2, which had a greater SAV biomass, also had a higher K_d (1.98 m^{-1}) than Station 1 (1.15 m^{-1}). Although biomass had been cleared out in a 1 m diameter circle where the light sensors were deployed, the angle of the sun was such that there was interference when the *H. verticillata* canopy was especially dense.

In October, light attenuation was consistent at Station 3, but highly variable at Station 1 (Appendix B13). Light attenuation was significantly greater at Station 1, which had a greater suspended solids concentration (see below) than Station 3 (Table 6).

Total Suspended Solids

In order to understand the total suspended solid (TSS) data obtained in June, August and October, a temporal and spatial perspective of the study site is necessary. In March and April, abnormally high flows from the Susquehanna brought large quantities of sediment into the Bay. The "chocolate milk" which pervaded the upper Bay in April settled out by June, resulting in a several centimeter thick flocculent layer of sediment on the shallows at Havre de Grace. Although this at first seemed like a disastrous year for SAV growth, the improvement in water clarity in June favored late germinating species such as *H. verticillata* , rather than *V. americana*. However, *H. verticillata* roots make up less than 1 % of total plant biomass and do not hold the fine grained sediments which can become easily resuspended.

This easily resuspended flocculent layer is the most likely scenario for why the shallow water TSS concentrations were so variable at Stations 1 and 2, compared with the deeper sandier Station 3 during all sampling periods (Appendices B14-B16). In general, TSS concentrations consistently increased from June, which had no frontal passages, to August and into October when weather conditions were much harsher (Table 7).

In order to portray temporal variability over the ten–day study periods, it is important to consider average (± standard error) concentrations in addition to median values. In June, TSS concentrations were 12.26 (±1.64) and 9.68 (±1.62) mg l^{-1} at Stations 1 and 2, respectively, and only 4.86 (±0.31) mg l^{-1} at Station 3. Concentration peaks of 30 to 60 mg l^{-1} were observed at the vegetated stations, whereas the maximum TSS concentration at Station 3 was only 11.43 mg l^{-1} (Appendix B14). The vegetated sites were shallower and the sediments siltier, both of which facilitate resuspension. This explains the higher TSS variability inside the grassbed.

In August, TSS concentrations at the three stations were all significantly different from each other (Table 7). Seston concentrations at Stations 1 and 2 were 35.42 (±7.02) and 21.68 (±3.88) mg l^{-1}, respectively (Table 7). At Station 3, TSS concentrations were lower than both vegetated stations, with a mean of 10.26 (±0.54) mg l^{-1}. In addition to variability, the range at the unvegetated station (Station 3) was also much smaller (3.29-23.46 mg l^{-1}) than the range for the shallower vegetated stations (3.52-261.13 mg l^{-1}) (Appendix B15). The peaks in TSS seen at all three stations on August 6 occurred after a substantial rain. The peaks seen at all three stations on August 9, 10, 11 and 12 correspond to increasing wind speed and alternating high tides (Appendices B11 and B2), and are dampened with increasing depth.

TSS concentrations were less variable at all stations in October (Appendix B16), although the trend of significantly higher TSS concentrations (Table 7) and greater variability at the vegetated stations continued. The October TSS means at Stations 1, 2 and 3 were 36.75 (±0.83), 26.76 (±3.94) and 10.44 (±0.50) mg l–1, respectively. All three stations showed sharp increases in TSS concentrations on October 12. This corresponded to a light rain event locally (Appendix B12), but is more likely due to increased runoff and riverine flow down the Susquehanna (see discussion of chl *a* below).

TSS comparisons within and outside of the SAV bed show that TSS was always significantly higher inside the bed throughout the growing season (Table 7). This does not support the hypothesis that TSS concentrations are lower inside than outside of a grassbed (e.g. Kemp et al. 1984). Generally, dense vegetation increases fine particle deposition and decreases resuspension by baffling water movement (Ward et al. 1984). However, the Havre de Grace grassbed is dominated by *H. verticillata* and *M. spicata*, two canopy forming species with whorled leaves (that are highly branched in *M. spicata*) and a high surface area. The increased surface area enhances fine particle deposition on the leaves

Table 7. Nutrient medians by station for each sampling period at Havre de Grace, MD.

June 1993

	Station 1	Station 2	Station 3
NO2 (mg/L)	0.029 a	0.035 b	x
(µM)	2.06	2.49	2.45
NO3 (mg/L)	1.045 a	1.255 a	1.312 a
(µM)	74.66	89.65	93.68
NH4 (mg/L)	0.045 a	0.045 a	0.052 a
(µM)	3.25	3.24	3.71
DIN (mg/L)	1.144 a	1.358 a	1.427 a
(µM)	81.71	97.02	101.90
PO4 (mg/L)	0.0006 a	0.0006 a	0.0006 a
(µM)	0.02	0.02	0.02
TSS (mg/L)	8.81 a	7.06b	8.63 b
CHL A (µg/L)	5.07 ab	4.80 a	5.19 b

August 1993

	Station 1	Station 2	Station 3
NO2 (mg/L)	0.031 ab	0.026 a	0.041 b
(µM)	2.22	1.88	2.95
NO3 (mg/L)	0.568 ab	0.490 a	0.700 b
(µM)	40.58	34.97	49.97
NH4 (mg/L)	0.034 a	0.027 a	0.019 b
(µM)	2.40	1.91	1.37
DIN (mg/L)	0.634 ab	0.538 a	0.767 b
(µM)	45.30	38.42	54.78
PO4 (mg/L)	0.0001 a	0.0003 b	0.0006 c
(µM)	0.03	0.01	0.02
TSS (mg/L)	13.33 a	11.45 b	8.55 c
CHL A (µg/L)	5.63 nc	6.65 nc	7.44 nc

October 1993

	Station1	Station 2	Station 3
NO2 (mg/L)	0.009 a	0.008 a	0.016 b
(µM)	0.62	0.555	1.12
NO3 (mg/L)	941a	0.773 a	0.915 a
(µM)	67.21	55.24	65.33
NH4 (mg/L)	0.011 a	0.010 a	0.010 a
(µM)	0.80	0.68	0.72
DIN (mg/L)	0.964 a	0.788 a	0.940 a
(µM)	68.83	56.30	67.14
PO4 (mg/L)	0.0019 A	0.0016 B	1622 AB
(µM)	0.06	0.05	0.05
TSS (mg/L)	16.34 a	12.67 a	9.43 b
CHL A (µg/L)	5.27 nc	5.69 nc	5.53 nc

values followed by identical letters (A,B or a,b) are not significantly different from each other at $p<0.05$ or $p<0.01$, respectively

nc=no statistical analysis performed

themselves. Also carbonate forms on the leaves as a product of the high pH in the bed. When the vegetation is disturbed, the particulates on the leaves can be easily resuspended and thus the bed is particularly susceptible to waves and currents resulting from frontal passages and even wind events from the exposed southeast.

All the evidence suggests that this Havre de Grace site is very physically influenced by river flow from the Susquehanna. The Susquehanna River is the largest source of freshwater to Chesapeake Bay. Current speeds outside the SAV bed near Concord Point at Havre de Grace have been measured as high as 60 cm s^{-1} (Wigand, pers. comm.). During high flow we would expect currents to exceed 1 m s^{-1} when Conowingo Dam has all the sluice gates open, as happened in March and April of 1993. Stations 1 and 2 are more protected from strong currents by Concord Point which allows the deposition of silty substrate. Station 3 is less protected from the flow, as evidenced by a sandier substrate.

The Havre de Grace site is also physically influenced by unprotected exposure to southeasterly winds across a fairly large fetch (approx. 10 km). August data illustrates the effects of strong winds on suspended solid concentrations. The effects are more obvious at the shallower vegetated stations than at Station 3 where the deeper waters and sandier sediments minimize the effects of wind driven resuspension. Similarly, rain showers and thunderstorms during all three sampling periods illustrate the effects of rain driven resuspension of sediments.

It has been suggested that disturbances during sampling may have caused the elevated TSS levels in the grassbed. Although this seems to be the case at Stations 1 and 2 in August when TSS peaked at over 100 mg l^{-1} three times, the exclusion of samples taken during these potential disturbances revealed no change in the overall means. This analysis suggests that although there may be problems during actual visits, our long term data collection was unaffected. Thus, in these environments, automatic sampling is very important in reducing artifacts.

It appears that physical factors such as water depth, substrate type, wind and rain have the most long lasting impacts on suspended solids at the Havre de Grace site. The impact of general boating activities, aside from our sampling, on TSS is still an open question.

Chlorophyll a

Due to observations in a previous Chesapeake Bay study (Kemp et al. 1984), we expected significantly less chl *a* in the SAV bed compared to Station 3. However, few consistent differences were observed. All stations exhibited considerable variability, and although variability at Station 3 was always lower than at the vegetated stations, the discrepancy was not as great as that seen in the TSS data. During June, mean chl *a* concentrations at Stations 1 and 2 were 5.64 ($\pm$0.42) and 5.04 ($\pm$0.30) $\mu g\ l^{-1}$, respectively. At Station 3, however, chl *a* concentrations were noticeably lower, at 3.96 ($\pm$0.22) $\mu g\ l^{-1}$ (Appendix B17).

In August, mean chl *a* concentrations at Stations 2 and 3 were similar (8.30 (±0.65) µg l^{-1} and 7.99 (±0.41) µg l^{-1}), while chl *a* concentrations at Station 1 were lower (6.40 (±0.39) µg l^{-1}, Appendix B18). Chl *a* concentrations increased slightly towards the end of the August sampling period at the two vegetated sites after a substantial rain (Appendix B18).

Chl *a* concentrations were similar at all stations in October. The means at Stations 1, 2 and 3 were 6.68 (±0.55), 7.31 (±0.63), and 6.37 (±0.46) µg l^{-1}, respectively. Chl *a* concentrations at all stations ranged from 0.80 to 28.90 µg l^{-1}, and variability was lowest outside of the SAV bed (Appendix B19). Chlorophyll *a* increased on October 11 and 12 after a three day weekend, when flow from Conowingo Dam increased again (Appendix B32). Most likely this chlorophyll rich water came from the lake. Regulation of flow from the dam in combination with high flow rates allows for parcels of water, in this case a chlorophyll rich parcel, to pass through the Havre de Grace study site quickly.

Both inside and outside the grassbed chl *a* concentrations increased from June to August, then decreased from August to October (Table 7). In June, chl *a* concentrations were significantly lower at Station 2. In August and October there was no difference between the vegetated and unvegetated areas. Station 2 was the only station with vegetation in June (Appendix B1) that was capable of shading the water column.

An important consideration for the August data is the peak chl *a* concentrations (>15 µg l^{-1}) at all three sites (Appendix B18). If one considers the median values, which are more applicable in determining habitat requirements (see discussion below), chl *a* concentrations are highest at Station 3 (7.44 µg l^{-1}), and lowest at Station 1 (5.63 µg l^{-1}). This suggests that the Kemp et al. (1984) hypothesis may be viable. Although their data is limited to one day, it was at the same time of the year. Inside the grassbed, phytoplankton may be filtered somewhat and production may be limited by low light from high TSS and by the macrophyte canopy and relatively low water column phosphorus (see below).

At the beginning of our sampling in October, when water temperatures were lower, phytoplankton biomass had decreased considerably outside of the grassbed. Inside the grassbed, macrophyte uptake of nutrients was past the peak growth period and senescence had begun, presumably rendering nutrients more available to phytoplankton. However, other factors, such as decreased temperature, lower ambient light with shorter days as well as generally increased turbulence due to storm events, may all have limited in situ planktonic productivity in the shallows. Our hypothesis that the sudden rise in chl *a* (to 25 µg l^{-1}) at 1800 hours on Oct. 11 at Station 3 is due to runoff from Lake Conowingo, needs to be checked further. However, the fact that the peak at Station 1 is three hours later than at Station 3 strongly suggests that the origin of the chl *a* is from outside the bed.

Dissolved Inorganic Nitrogen: Nitrite, Nitrate, Ammonium

Dissolved inorganic nitrogen (DIN) concentrations were very high (0.538 to 1.427 mg l^{-1} (38.42 to 101.90 μM)) and extremely variable at all three stations throughout the growing season (Appendices B20-B22, DIN; Appendices B23-B25, ammonium; Appendices B26-B28, nitrate; Appendices B29-B31, nitrite), with ≥90% of DIN being attributed to nitrate. The variability cannot be easily attributed to tides, storms, or boating activities. There was a decrease in DIN concentrations at all stations from June to August, and an increase from August to October, although DIN concentrations were not restored to the June levels (Table 7). The nitrate fraction at all three stations followed the same seasonal pattern that DIN did (Table 7). This may be related to discharge at Conowingo Dam, which was about 13,500 cfs during the June and October sampling periods, but less than half that during August (Appendix B32) and to uptake by macrophytes and phytoplankton. Ammonium, on the other hand, showed a steady decline from June to August to October (Table 7). This can probably be attributed to nitrification as well as uptake by macrophytes and phytoplankton.

In June there were no significant differences in DIN or the component DIN species (ammonium, nitrate, nitrite) between sites (Table 7). Macrophyte growth, and therefore nutrient uptake, had not yet peaked. Ammonium levels exhibited a slightly diel pattern, with concentrations increasing during the night as D.O. decreased. This diel pattern was more evident at Stations 1 and 2 than at Station 3 (Appendix B23).

In August, DIN and nitrate concentrations were lower inside the grassbed than at Station 3, due to macrophytic uptake, while ammonium concentrations were higher inside the grassbed than at Station 3 (Table 7). Ammonium concentrations again exhibited a diel pattern which was dampened at Station 3 (Appendix B24). Higher ammonium concentrations and the enhanced diel curve inside the grassbed may be attributed to regeneration of nutrients in the surficial sediment layer.

In October, as in June, there were no differences between DIN concentrations between the three sites (Table 7). Even though macrophyte biomass was at its peak in October, growth of both macrophytes and phytoplankton was past peak, and there were no differences in nutrient uptake between the vegetated and unvegetated stations. Ammonium concentrations (Appendix B25) exhibited the same diurnal pattern, dampened at the deeper station, as was noted previously. At all three stations, nitrite concentrations were highly variable during the first half of the sampling period, then decreased in both concentration and variability from October 7 to 12, then increased again, perhaps a result of incomplete nitrification (Appendix B31).

Dissolved Inorganic Phosphorus

Phosphate concentrations were very low at all three stations throughout the growing season, although the data reveal several pulses (Appendices B33-35). These pulses may be parcels of water originating from Conowingo Lake that had very brief residence times at the study site. Phosphate concentrations decreased from June to August at Stations 1 and 2, while at Station 3, they remained the same (Table 7). The decrease inside of the SAV bed can be attributed to nutrient uptake by macrophytes.

From August to October, phosphate concentrations increased at both stations inside of the grassbed. Macrophyte and phytoplankton growth, and therefore nutrient uptake, was past its peak, explaining the increasing water column concentrations. Plants were also beginning to senesce and may have been leaking phosphate from the leaves. There was a trend in October of decreasing phosphate concentrations outside the grassbed during the ten day sampling period (Appendices B35 and B31). Concentrations of these nutrients were generally higher October 3- 8 than October 8-14. This could be related to increases in chl *a* concentrations during this time (Appendix B19).

Water Quality Comparisons

A summary of median values of five water quality parameters we have used previously to define the health of SAV in Chesapeake is presented in Table 8. Results of biweekly monitoring and intensive monitoring inside and outside of the grassbed are compared to each other and to the tidal freshwater SAV habitat requirements (Batiuk et al. 1992). Both inside and outside of the grassbed, the biweekly sampling regime produced median levels comparable to those determined during the intensive sampling periods. However, the biweekly median does not adequately represent either the seasonal variations or the daily variations that the intensive monitoring characterizes.

Light availability is the single most important single factor influencing SAV distribution and growth (Kemp et al. 1983, Wetzel and Neckles 1986, Dennison et al. 1993). Light availability for SAV is dependent on at least four additional factors in estuaries such as Chesapeake Bay: TSS, chl *a*, DIN, and DIP (Batiuk et al. 1992). Table 8 compares the tidal freshwater SAV habitat requirements to median levels of these environmental factors determined in the grassbed at Havre de Grace in 1993. There are no habitat requirements for DIN in areas with less than 5 psu salinity because phosphorus limitation usually acts to inhibit algal growth which competes with SAV.

Table 8. Comparison of median water quality parameters during the 1993 growing season at Havre de Grace, MD with tidal freshwater SAV habitat requirements.

Parameter	Tidal Freshwater SAV Habitat Requirements*	Havre de Grace Grassbed Biweekly Monitoring	Havre de Grace Grassbed Intensive Monitoring			MDE monitoring station CB1.1	Havre de Grace Channel Site Intensive Monitoring		
		May-October	Jun 15-25	Aug 1-12	Oct 3-13	May-October	Jun 15-25	Aug 1-12	Oct 3-13
Kd (/m)	<2	1.42	1.59	1.15	1.73	1.55	1.56	---	1.29
TSS (mg/L)	<15	8.00	8.81	13.33	16.34**	4.95	8.63	8.55	9.43
CHLa (µg/L)	<15	5.76	5.07	5.63	5.27	7.2	5.19	7.44	5.53
DIP (mg/L)	<0.02	0.00093	0.0006	0.0001	0.0019	0.0025	0.0006	0.0006	0.0016
DIN (mg/L)	---	0.90	1.144	0.634	0.964	1.13	1.427	0.767	0.940

* from Batiuk et al. 1992

** exceeds habitat requirements

The Havre de Grace SAV bed met all of the habitat criteria during the 1993 growing season as determined by biweekly monitoring. In fact, the habitat requirements were only exceeded in October when median TSS concentrations were 16.34 mg l^{-1}. These data support the habitat criteria established by Batiuk et al. (1992). As the intensive monitoring medians were within the range of the bimonthly medians, it appears that the latter sampling strategy is an appropriate measure for water quality, even in an area where temporal variability is high.

One of the problems that Batiuk et al. (1992) encountered was the lack of sufficient nitrogen data to establish a water quality parameter for DIN in the tidal freshwater regions of the Bay. Although our research was not specifically designed to obtain a DIN threshold, it is clear that SAV survives at a median DIN concentration of 0.9 mg l^{-1} at Havre de Grace, which is six times higher than the habitat requirements in higher salinity zones (Batiuk et al. 1992). Interestingly, this concentration is more than double the maximum that Burkholder et al. (1992) found to deregulate growth of *Z. marina* in mesocosms in North Carolina. Although their work is somewhat controversial due to other possible factors, i.e. high temperatures which interfere with *Z. marina* growth, the possibility that nitrate inhibits SAV directly needs to be better understood. Previous studies in Chesapeake Bay have only explored the indirect problems of high DIN in the water column, for example epiphytic overgrowth and planktonic competition for light. It is not clear to what extent similar physiological processes might exist in freshwater and low salinity species such as *V. americana*. Nitrogen inhibition might be one of the reasons that *V. americana* growth was so low during 1993 at Havre de Grace, after the large freshet brought in high nitrogen. Although it is perhaps still premature to offer a DIN habitat requirement for SAV, it might be in the range of 1.4 mg l^{-1} (100 μM). This may not apply for species such as *H. verticillata* and *M. spicata* and may therefore account for species shifts in the Upper Bay towards introduced species.

III. FALL 1993 MESOCOSMS STUDY

Methods

The first phase of the SAV mesocosm experiments was conducted in the fall of 1993 to test the temporal scaling on nutrient inputs to SAV ecosystems. A series of small mesocosms, under natural light with continuous flushing were established to examine the seasonal (fall) response of a native Chesapeake Bay SAV species (*Potamogeton perfoliatus* L.) and its associated phytoplankton and epiphytic algal assemblages to nutrient enrichment in varying forms and frequencies. In these experiments, the same moderate level of nutrient loading (38 μmol l^{-1} d^{-1}) was delivered to replicate mesocosms in three ways: 1) as continuous dissolved inorganic N and P; 2) as weekly pulses of dissolved inorganic N and P; and 3) as weekly pulses of particulate organic N and P (Table 9). These three treatments are compared to continuous inputs of low nutrient waters. Dissolved inorganic nutrient concentrations in the mesocosm water columns were measured routinely and community responses were measured as SAV growth, biomass, morphology and tissue nutrients, biomass of algal and other epiphytic materials and biomass of phytoplankton. Similar experiments were conducted in the spring and summer of 1994 to complete the temporal cycle, with the results to be reported separately.

Experimental Design

Experiments were conducted in the greenhouse located at Horn Point Environmental Laboratory; Cambridge, Md. Plants were collected from experimental ponds located on the property, planted in a PVC pot containing 1.5 L of sediments collected from the Choptank River. The pots were then placed in clear acrylic microcosms (15.2 cm x 15.2 cm base x 61 cm height) containing a volume of 10L. The microcosms were placed in large cooling tanks to maintain ambient river water temperature. Each pot contained ten *P. perfoliatus* plants, which were allowed to acclimate for a period of two weeks with Choptank River water cycling through the chambers at a turnover rate of once per week. Each microcosm was bubbled with air to facilitate mixing and to minimize oxygen inhibition and carbon dioxide limitation.

Nutrients in the pulse treatments were added by hand to each of four replicate chambers on a weekly basis, while continuous inputs were administered with a peristaltic pump. All nutrient additions were made at a loading rate of 38μM N $\cdot l^{-1} \cdot d^{-1}$, with phosphorus added to result in a 10:1 atomic NP ratio. Dissolved nutrient additions were made using ammonium nitrate and sodium phosphate. Particulate nutrient additions were made using heat killed algal slurries (Kana , pers. comm.).

Table 9. Nutrient loading rate, input concentrations and input rate for experimental chambers.

TREATMENT	N-LOADING (μ mol $\cdot L^{-1} \cdot D^{-1}$)	INPUT CONC (μ M)	INPUT RATE
CONTROL	0.2	1.3	$1 cm^3 \cdot min^{-1}$
DISSOLVED CONTINUOUS	38.2	364 input	$1 cm^3 \cdot min^{-1}$
DISSOLVED PULSE	38.2	532×10^3	$5 cm^3 \cdot wk^{-1}$
PARTICULATE PULSE	38.2	984×10^3	$2.7 cm^3 \cdot wk^{-1}$

Results

Physical Parameters

As expected with season temperatures in the chambers declined over the experimental period from a high in August of 28.6 °C to a low of 22.1 °C in late October. Salinities ranged from 14.3 to 15.4 psu. Generally, light conditions also declined throughout the period. However, in the two dissolved (pulse and continuous) nutrient treatments, light conditions were considerably lower than the control and particulate treatments.

Nutrient Concentrations

Nutrient concentrations exhibited different patterns with each mode of delivery. Continuous input concentrations were relatively constant throughout the experimental period (Appendices C1a-c), while dissolved pulse concentrations exhibited peaks immediately following nutrient additions, but returned to low levels fairly rapidly (Appendices C2a-c).

Despite relatively high levels of nutrient inputs, concentrations in the continuous treatments were comparable to concentrations in the control chambers (Appendices C1a-c). Ammonia levels were very similar in both treatments throughout the experiment, but were somewhat elevated in the continuous addition toward the end of the experiment, suggesting nutrient regeneration (Appendix C1a). Nitrite-nitrate concentrations were only slightly higher in the nutrient addition chamber, but concentrations remained low (around 1 μM) throughout the experiment (Appendix C1b). Phosphate concentrations, although relatively high (0.2-1.0 μM), were very similar in both chambers for the first 3-4 weeks of the experiment, then became slightly elevated in the nutrient enriched chambers (Appendix C1c), suggesting phosphate saturation and possible nitrogen limitation.

Time series of the nutrient concentrations in the dissolved pulse treatments indicate that ammonia and phosphate are greatly reduced after three hours and are comparable to control levels by twelve hours (Appendices C2a and C2c). Nitrate and nitrite levels remain elevated for approximately 48 hours following addition (Appendix C2b). There were no differences in these patterns throughout the experimental period. Nutrient concentrations in the particulate treatments were not different from controls.

Plant Response

Plant growth rate generally exhibited a similar growth pattern in all treatments for the duration of the experiment (Appendix C3). During the first 4 weeks plant growth rates increased slightly, but declined steadily for the remainder of the experiment. However, during the last five weeks of the experiment, plant growth rate in the dissolved treatments declined more rapidly than in the particulate and the control treatments, with negative values beginning after week eight (Appendix C3).

Other indicators of plant response further suggest stress in the plants within the dissolved treatments. Above and below ground plant biomass and root to shoot ratio were reduced in both dissolved treatments (Table 10), but slightly enhanced in the particulate treatment. Plants in all nutrient treatments were longer, but had less leaves per stem, perhaps indicating etiolation and light stress (Table 10).

Algal Concentrations

As expected, algal concentrations increased with nutrient additions. Chlorophyll levels in all treatments, except the dissolved continuous, remained relatively low and ranged from 0.5 to 14.3 $\mu g \cdot l^{-1}$ (Appendix C4). For the first 4 weeks, levels in the continuous chambers also were relatively low, but then showed a steady weekly increase to very high concentrations of 150 $\mu g . l^{-1}$. Macroalgae increased, in comparison to controls, in all chambers with nutrient additions, but exhibited variability within treatments (Appendix C4). Epiphyte biomass was higher in all nutrient enriched treatments at the end of the experiment (October), but followed different patterns with mode of nutrient addition. Epiphytic mass actually decreased in the particulate pulse treatment, but increased in both dissolved treatments. Epiphytic mass in the control changed little during the experimental period. Estimates of benthic deposition and algal concentrations can be derived from the percent organic matter in the top five centimeters of sediment. This value was higher in all treatments, but highest concentrations were found in the continuous treatment (Appendix C4).

Discussion

The water column nutrient concentrations remained low (around 1.0 μmol, Appendix C1) in spite of the relatively high loading rates (38 $\mu mol \cdot l^{-1} \cdot d^{-1}$), suggesting a lack of correspondence between loading rates and water column concentrations. Obviously, the nutrients were utilized rather rapidly upon addition to the chambers (Appendices C2a, b, c) and resulted in an increase in algal components (phytoplankton, macroalgae, epiphytic algae and benthic algae) (Appendix C4). A nitrogen budget (Appendix C5) was calculated from direct measurements (plant CHN analysis, sediment CHN analysis) and from literature values for nitrogen concentrations in phytoplankton, epiphyte and macroalgae (Twilley et al 1986). This budget supports the redirection of nutrients from plant biomass (control) to algal biomass (dissolved nutrient treatments).

Nutrients added continuously in the dissolved form elicited the greatest response by the algal communities, while those added on a pulse bases in both

Table 10: Morphological parameters. Summary of mean ($^+$SE) values for *Potamogeton perfoliatus* biomass, root to shoot ratio, shot length, and leaf number in control and nutrient enriched treatments (n=4).

Treatment	Biomass (gdw) Above	Below	Root:Shoot Ratio	Shoot Length (cm)	# Leaves per Shoot Length
Control	.32322	.91856	2.8377	52.9	1.05
	($^+$.106)	($^+$.304)	($^+$.176)	($^+$20.4)	($^+$.03)
Particulate Pulse	.51477	1.23791	2.9574	152.4	1.07
	($^+$.106)	($^+$.142)	($^+$.422)	($^+$57.4)	($^+$.14)
Dissolved Pulse	.32250	.52267	1.6531	134.4*	.79*
	($^+$.082)	($^+$.129)	($^+$.641)	($^+$32.4)	($^+$.06)
Dissolved Continuous	.10327	.19965	1.8552	123.6	.84*
	($^+$.176)	($^+$.414)	($^+$1.720)	($^+$10.4)	($^+$.06)

* Indicates significance at $p < 0.05$ from Control, student's t-test.

the dissolved and particulate form had less of an effect. These findings suggest that nutrients entering aquatic systems from any continuous input (i.e. waste water treatment plants) may result in higher algal concentrations than those entering on a pulse basis (i.e. storm runoff).

Plant response, to these nutrient additions were not as evident as in past experiments (Twilley et al. 1985; Neundorfer and Kemp 1993). This may be, in part, because of the seasonal timing of the experiment. All plants exhibited a general senescence (die back) due to the natural growth cycle of these plants. However, there was evidence of plant stress in the dissolved nutrient treatments in plant growth rates (Appendix C3) and end of experiment plant biomass and morphological features (Table 10). The low root:shoot ratio in the dissolved pulse and dissolved continuous additions suggests that these plants have less storage for spring regrowth. In nature this lack of reserves could lead to the demise of the plants.

These results suggest that dissolved nutrients have a greater immediate effect on SAV communities than particulate nutrient additions. Increased algal growth and declines in plant growth rates and storage capabilities support this hypothesis. Furthermore, seasonal timing of nutrient additions may play an important role in SAV survival.

REPORT SUMMARY

SAV Community Structure and Biomass

The SAV beds studied in the two field sites contained five species, three in the upper bay at Havre de Grace and two in the lower bay at Goodwin Island. Maximum biomass was comparable at each site, 200-250 gdm m^{-2} at Goodwin and 160-180 gdm m^{-2} at Havre de Grace. Depths were also similar, approximately 0.25m and 0.5m at MLW at the vegetated stations in the upper bay study area and 0.4m and 0.6m in the lower bay site. Offshore stations were also similar in depth at approximately 1.3 to 1.5m MLW. These results suggest that during this study period the two SAV communities occupied comparable zones in the subtidal and were similarly successful in vegetating these zones. However, because both SAV communities can attain higher peak standing crops than are reported here, it may be alternatively suggested that they were responding to conditions that limited growth to similar degrees.

There were distinct differences in the seasonality of the development of the macrophyte communities. The upper bay SAV community grew throughout the summer and attained maximum standing crop at the end of the growing season in October. *V. americana* (wild celery) was initially dominant in the early summer, while *H. verticillata* and *M. spicatum* (Eurasian watermilfoil) developed later and eventually became the dominants in the community. At Goodwin Island in the lower bay, vegetation was persistent throughout the entire year. Maximum standing crop in the spring consisted principally of eelgrass (*Z. marina*) with *R. maritima* (widgeon grass) dominating the inshore shallow areas in the mid-summer as *Z. marina* died back. In the fall as temperatures dropped below 25 °C a second growth period of *Z. marina* occurred, with new growth consisting of vegetated shoots and newly germinated seedlings. In the winter the standing crop consisted of *Z. marina* only.

P.perfoliatus (redhead grass), which was used as the test species in the mesocosm study, did not occur at either of the two field study sites. It is, however, common throughout the mid bay region where salinities are intermediate between these study areas, and can co-occur with SAV species found at the Havre de Grace site. It develops a canopy more similar to *H. verticillata* and *M. spicatum* than the filiform plant structure of *V. americana* or *Z. marina*, and is characterized by a unimodal annual growth cycle with maximum biomass in late summer and early fall.

Physical Parameters

Although there were differences in physical regimes at the two sites, in general, wind speeds and tidal ranges were similar. Afternoon sea breezes were more prevalent at the lower bay site, but peak wind velocities were comparable.

There were no extreme wind events at either of the sites, however during October consistently high east and northeast winds were prevalent in the lower bay study area. Tidal ranges were slightly higher at Goodwin Island than Havre de Grace (0.5-0.6 vs 0.7-0.8 m; upper bay and lower bay neap-spring tides respectively). Localized conditions such as wind effects and dam discharge rates seemed to be related to the more dramatic day-to-day variability in tidal heights observed at the upper bay site than the lower bay site, where the spring-neap tidal variability was more evident.

Water velocities in and out of the beds were not measured, however, general observations and other available data suggest that they were quite different. This, in turn, has important implications for the measured standing stocks of many water quality constituents such as inorganic nutrients, where differences inside and outside of the beds are directly related to the residence time of water within and over the canopy. Seufzer (1994) reported water velocities within the Goodwin Island bed as generally not exceeding 10 cm sec^{-1}. Stevenson (unpublished data) observed velocities at the edge of the Havre de Grace bed to reach 60 cm sec^{-1}. Therefore, some observed differences between the sites may not be related so much to differing bed processes, but to our ability to detect the net result of these processes. In many cases, high water velocities combined with high constituent levels can obscure the effect of an SAV bed on water quality. Conversely, this highlights the fact that a SAV bed's ability to modify the local environment can be limited by high water velocities.

Water temperatures varied seasonally between the areas, reflecting, in part, the dominance of the oceanic environment at Goodwin Island and terrestrial environment at Havre de Grace. Temperatures in the upper bay site were warmer by June and cooler by October than the lower bay. August temperatures were comparable. A greater diel temperature range was observed in both beds compared to out, especially during August and October. This was due largely to the shallower depths of the vegetated stations. Both areas demonstrated dramatic day-to-day changes (up to 2 °C) in water temperatures that were driven by changes in regional weather. The mesocosms were cooled with ambient Choptank River. water during the experimental period of August, 1993 to October, 1993. In August water temperatures were comparable to the field sites at about 28°C, while by the end of the experiment in October water temperatures were slightly higher than either field site at 22°C.

Salinities in the field sites reflected the two end points of the bay system. Salinities in the upper bay (measured as conductivity) were less than 1 psu (practical salinity units). In the lower bay they ranged from 12 to 24 psu. Seasonally, salinities were highest in October and lowest in the spring (April-June). There was little tidal variability in salinity in the lower bay, although there were periods when salinities dropped up to 1 psu over the course of one day as the water mass in the region changed due to wind and tides. In the upper bay site tides were observed to have some effect on conductivity, however, absolute changes were slight. In general, salinities inside the beds were very similar to outside. Salinities in the mesocosm experiment were intermediate between the two field sites at 14 to 15 psu.

Water Quality Constituents

Chlorophyll a, Total Suspended Solids, and Light Attenuation

Previous research suggests that suspended particles should be, for the most part, baffled out by the SAV canopy structure as water velocities are reduced. Similarly, with fewer particles in the water column, light attenuation should decrease. However, this was not always the case at both of the study sites, and it suggests that particle concentrations and light attenuation levels result from a complex interaction of dissolved and particulate levels in adjacent waters, and settlement and resuspension of material within the bed. In comparing the two field sites the general conclusions were that suspended particles were higher in the bed than out at Havre de Grace and lower in than out at Goodwin Island. This difference can be explained in large part as a difference in the dynamic balance between source, deposition and resuspension of particles in the vegetated shallows.

In the Susquehanna region large quantities of suspended sediments and other seston are carried into the region by the river flow. This material is deposited in the shallows, including the vegetated areas, where currents are reduced and is therefore available for resuspension throughout much of the growing season. Additionally, much of this fine particle load is deposited on the canopy-forming leaves of *H. verticillata* and *M. spicatum* where, along with carbonates it is easily resuspended. The channel areas are deeper and more sandy, and therefore resuspension is less.

In contrast, at Goodwin Island in the lower bay, suspended particle loads were lower in the bed than out during June, October and April. Sediments here are sandy in comparison to the Susquehanna Flats area, and there is no large source of suspended material. Carbonate formation on strap-like leaves was also low. Therefore resuspension of deposits of fine material was less. During August, however, when the bed contained an abundance of detrital material, apparent resuspension of benthic and epiphytic material resulted in generally higher levels of suspended particles in the bed than out.

From the standpoint of water quality monitoring we can conclude that measures of suspended particles obtained from channel areas do not reflect the actual particle loads, and potentially light attenuation within the SAV community. In some areas or at certain times of the year, particle concentrations may be higher, at other times or in other areas they may be lower. Therefore SAV models which rely on empirical measurements of light attenuation from channel areas need to be modified to account for these potential differences.

In contrast to the field studies, resuspension in the mesocosm experiment was negligible. However the study did demonstrate that under high levels of dissolved nutrient enrichment, phytoplankton blooms can markedly decrease light available to the macrophytes. In natural settings the SAV beds may either decrease these concentrations (Goodwin Island) or trap and resuspend these particles (Havre de Grace).

Dissolved oxygen and pH

Dissolved oxygen and pH measurements demonstrated greater diel ranges in the SAV beds compared to out, reflecting the greater metabolic activity per volume in the shallows compared to the channel. These greater ranges can have potentially important implications for the SAV communities themselves. For example, lower pH in the beds, as observed in the upper bay, can result in greater carbonate deposition on leaves which, in turn, can reduce light availability. Varying D.O. levels can affect sediment geochemistry with resultant effect on nutrients, sulfides and other sediment constituents. Low D.O. levels can affect the macrophytes themselves by increasing sediment oxygen demand, as well as affect benthic and epibenthic organisms which play an integral role in system stability. Seasonally, D.O. levels reached highest levels in the spring when macrophyte photosynthesis:respiration ratios are greatest, and lowest in the late summer when temperatures are high and microbial activity is greatest.

Among the two sites, D.O. levels reached lower concentrations in the lower bay site than in the upper bay study area, suggesting that heterotrophic activity was greater there. Short term changes in pH were more buffered in the lower bay than upper bay and less evident in the bed than out. Rain events markedly decreased pH for short periods of time in the upper bay channel water, however these spikes were rapidly attenuated within the bed.

Nutrients

Inorganic nitrogen demonstrated distinct differences in both concentrations and dominant nitrogen species at the two field sites. Results from the mesocosm study suggest that in the fall, at least, the mode of nitrogen delivery can have important implications on macrophyte community response.

In the lower bay Goodwin Island area, the principal nitrogen species during all study periods, except for April, was ammonium. This is sometimes referred to as "old" or regenerated nitrogen as compared to nitrate or "new" nitrogen whose primary source is the watershed. Considering that this site is near the mouth of the bay, and farthest removed from river inputs the dominance of ammonium observed is not surprising and has been well documented. Only during April when riverine inputs were highest of all the study periods was nitrate the dominant species. At the upper bay site 90% of the nitrogen was in the form of nitrate. Again, located close to the principal freshwater source of the bay one would expect most nitrogen to be as "new" nitrate.

Uptake of dissolved inorganic nitrogen (DIN) was observed at both sites during periods when macrophyte abundance was high. In the upper bay this was in August, while in the lower bay in was in April and June. During periods of highest water temperatures and therefore increased microbial activity, regeneration of ammonium was observed in both SAV beds. Net uptake of nitrate in the spring was replaced by net regeneration of ammonium in the summer at Goodwin, while both uptake of nitrate and regeneration of ammonium were observed at Havre de Grace at this time. Rapid uptake of DIN by the macrophyte community reduces the pool of nutrients available for phytoplankton growth. This may be especially important in the lower bay where nitrogen levels are lower. In areas of transitional water quality, the existence of large established beds of SAV may improve local conditions for their continued survival during years of high runoff. Small isolated patches may be overwhelmed. In the upper bay site DIN is in excess abundance and is apparently not limiting to epiphyte, phytoplankton or macrophyte growth.

The ability of SAV community to reduce nutrient concentrations was very evident in the mesocosm study where pulses of nutrients were rapidly removed, and despite relatively high levels of nutrient inputs, concentrations in the continuous dosing treatments were comparable to the controls. Much of the nitrogen was taken up by the algal components of the system, with a resultant negative effect on the macrophytes. At some point the macrophytes will become overwhelmed and the system will shift to an algal community. Dissolved nitrogen administered in a continuous mode had the most negative effect on the macrophytes. This reinforces the importance of reducing the overall standing stocks of DIN in bay waters for SAV, and especially in controlling long term continuous sources such at waste water treatment plants.

Orthophosphate levels were well buffered and apparently not limiting in the lower bay, but were very low in the upper bay site. Thus the ability of SAV in the Susquehanna Flats region to sustain themselves despite very high DIN is likely due to the low orthophosphate levels. Maintenance of existing SAV and recovery to other areas in this region is related, in part, to controls of anthropogenic sources of orthophosphate. Given the high ambient levels of DIN in this region, the results of the mesocosm experiment suggest that any increase in orthophosphate should have a deleterious effect on SAV.

Water Quality Monitoring

Given the negative effects of continuous dosing of inorganic nutrients on SAV we observed in the mesocosm experiment, the importance of monitoring inorganic nutrient concentrations over the long term as a measure of stress to SAV is underscored. Organic, particulate nitrogen and phosphorus were not directly linked to SAV decline during the fall study period, however the remineralization of this material and its impact on SAV, especially during the summer are likely to be important. SAV beds similar to Goodwin Island are effective traps for phytoplankton and other particulate material during the spring, and secondary effects of microbial decomposition during high water temperatures can contribute to SAV declines, or shorter growing seasons. When combined with other stresses, such as reduced light availability, these annual diebacks may become permanent.

Although biweekly to monthly sampling does not capture the diel, tidal and other pulses or variability in water column constituents which we observed in these studies, they do provide a reasonable characterization of water quality levels in these areas. If elevated short-term pulses are important in reducing long-term SAV survival they will not be effectively measured by this sampling schedule. Daily variability may exceed seasonal variability for most parameters measured, however the median levels of these constituents are near the lower levels observed, and the high pulses are short lived. Thus only infrequently will the pulses be measured in the biweekly sampling. Many times these pulses will occur at night or during storm events and they will not be sampled with infrequent, point sampling. However, the monitoring will likely capture the median conditions. In both areas studied here growing season medians were below the SAV habitat requirement set for each area. Thus, they correctly predicted that these areas should be suitable for SAV growth.

Records of seasonal, short term, site-specific variability such as those investigated here are also important. Not only do they provide a more integrative view of SAV-water quality relationships, and processes relating the two, but they provide a test of the effectiveness of the more spatially distributed, infrequent data.

Except in areas where groundwater or local upland runoff is high, mid-channel nutrient concentrations are useful to characterize the long term inputs or stresses to the macrophyte, or potential macrophyte areas. Where SAV occur, concentrations inside the beds can be quite different than outside. These differences reflect the net effect of the SAV bed community on the particular water quality constituent. As the mesocosm and field studies demonstrate, rapid uptake and release of inorganic nutrients can occur by the SAV, algal, heterotrophic and microbial components of the system. Therefore, nutrient concentrations outside the bed better reflect long term system impacts to SAV areas than concentrations measured within large SAV meadows, especially where water residence time is high. In areas where SAV beds are small and scattered, or where water velocities are high and residence time is short, concentrations of nutrients within the beds will more reflect channel concentrations.

Other important variables including suspended particle load and light attenuation can also be quite different in and out of existing beds. However, since the macrophyte communities are integrating the light available to them, not the light available outside of the bed, measurements should be made over the vegetated areas. In shallow water areas this water column attenuation may be more or less than attenuation in the channel. In sparsely vegetated areas differences between channel and shallows may be less than in areas with extensive vegetation. Estimates of these differences are needed if models relating water quality to SAV are to be accurate. In certain areas, such as regions of marginal water quality in the lower bay, persistence of vegetation is likely related to the capacity of the vegetation to improve water clarity. The timing, duration and intensity of seasonal pulses of higher turbidity water are also important for long term SAV survival. In canopy forming species such as found at Havre de Grace, survival may be linked to spring shoot elongation up to the water surface where water column turbidity is less of a factor. This capacity is not only affected by conditions during the spring, but to reserves stored from the previous year's growth. Thus, there may be a time lag between limiting conditions and SAV survival. In the lower bay limiting conditions earlier in the year may be reducing survival during the summer. Natural year-to-year variability in SAV may also be not only related to annual differences in water quality, but to the normal interrelationships between SAV and bay waters.

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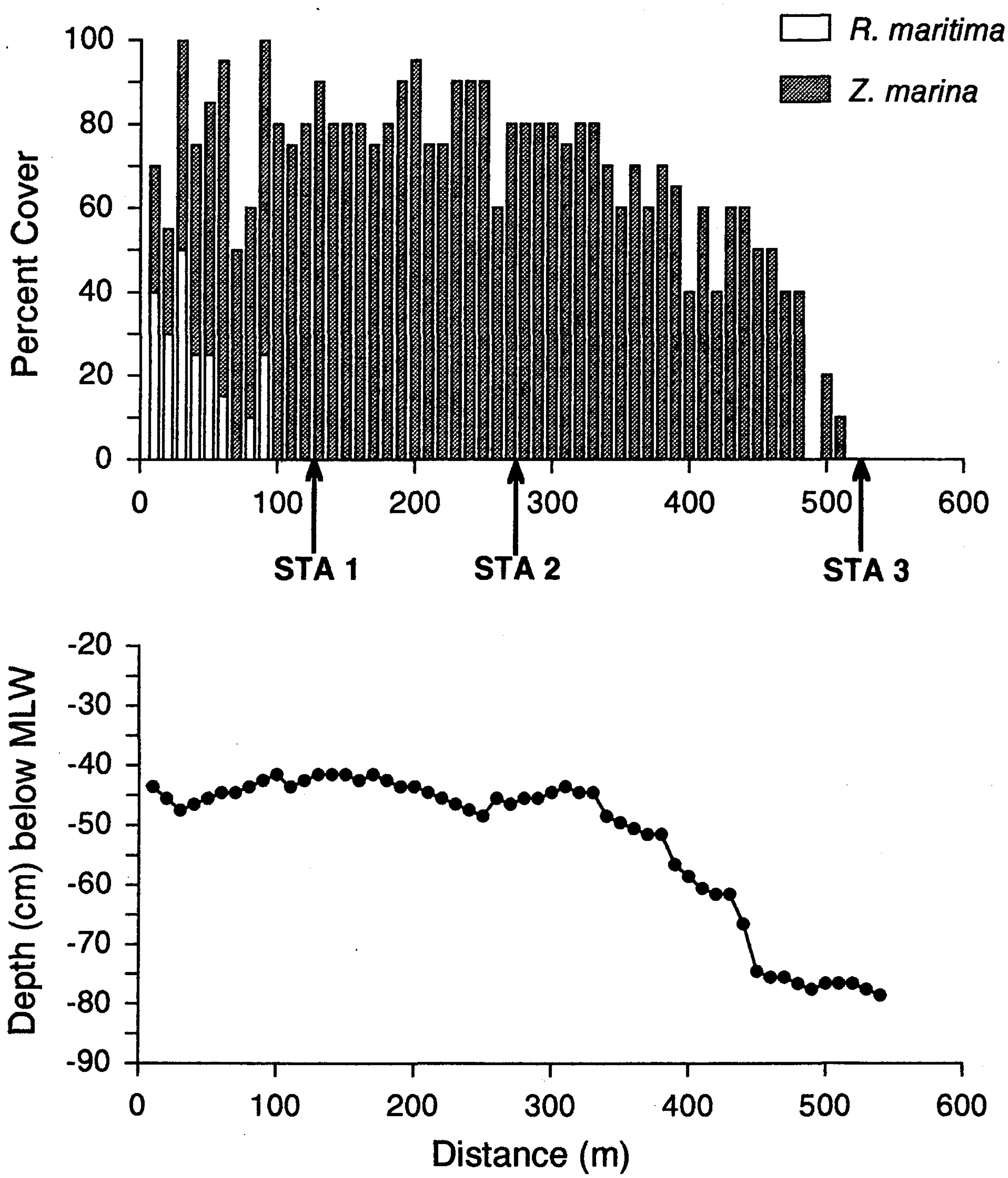
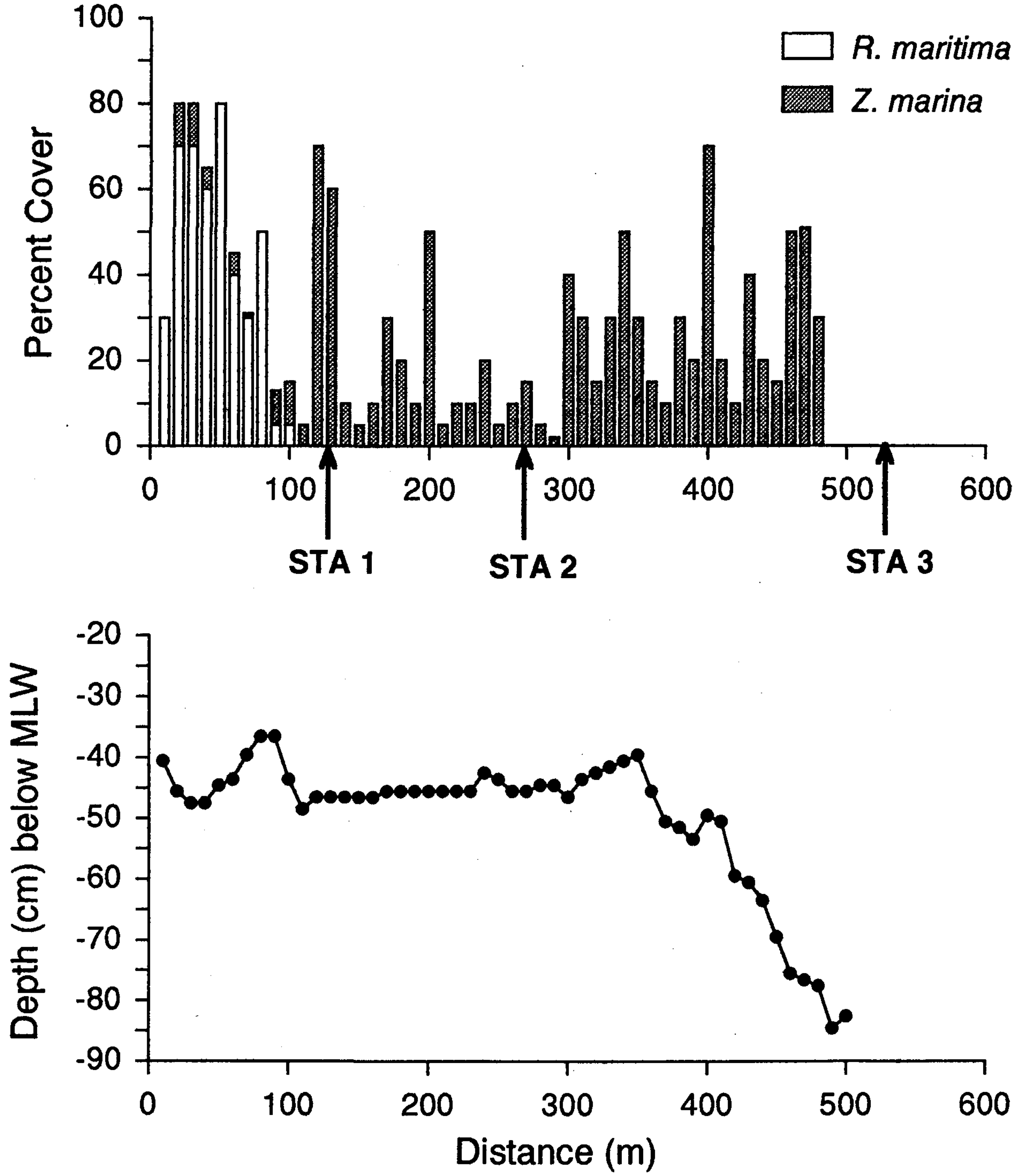
Appendix A

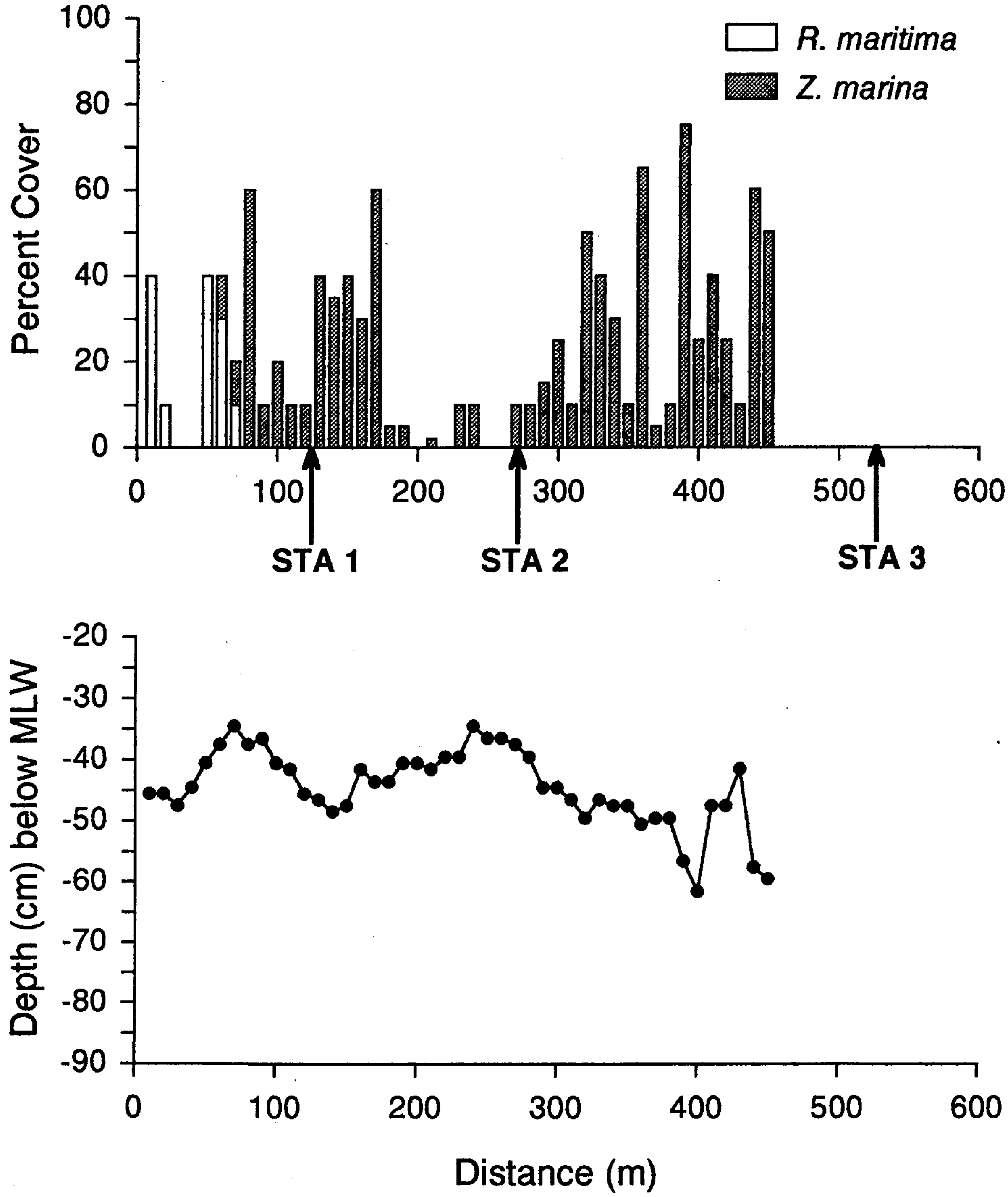
A1: Percent cover by species and depth profile along sampling station transect. June 16, 1993.



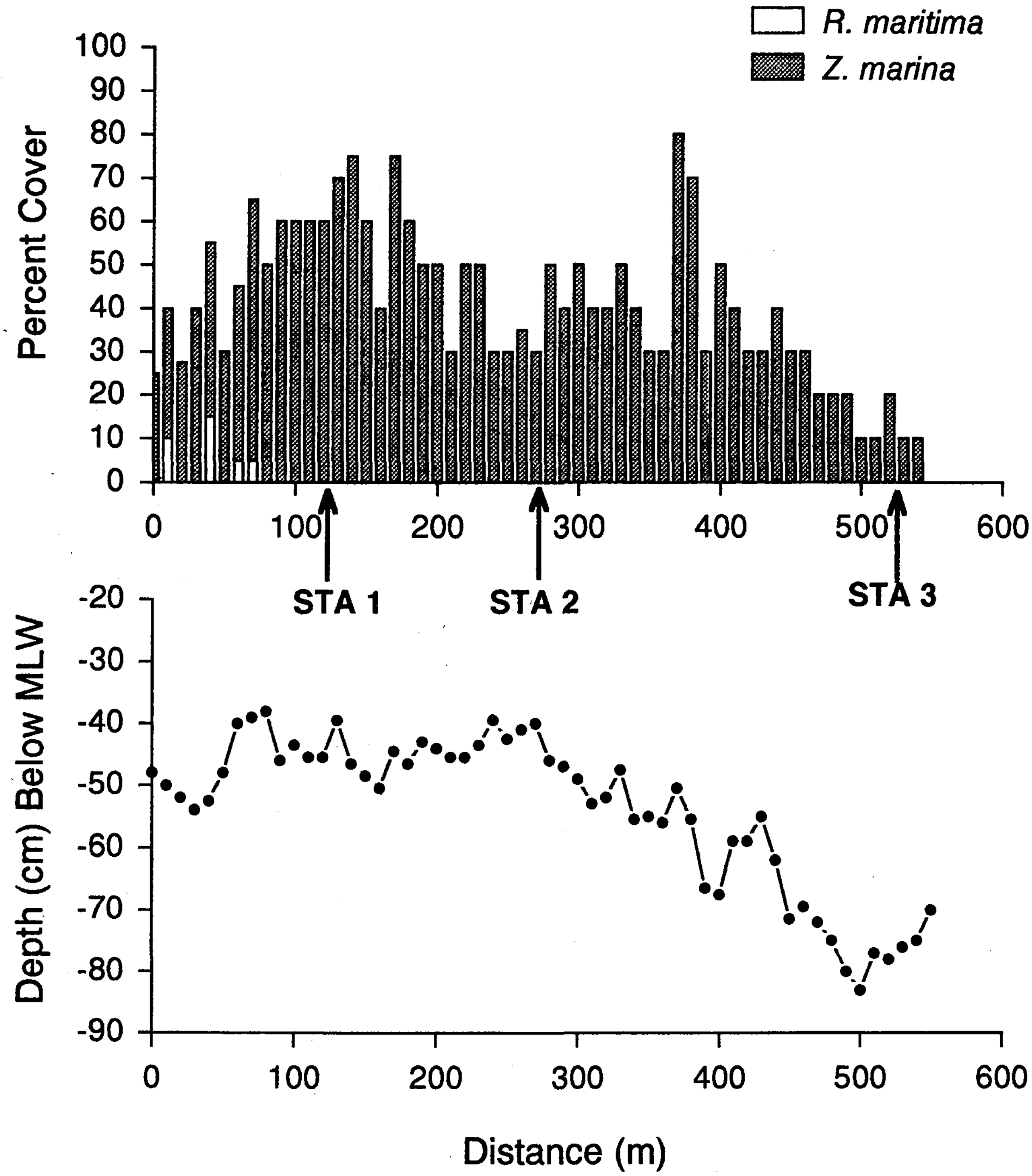
A2: Percent cover by species and depth profile along sampling station transect. August 10, 1993.



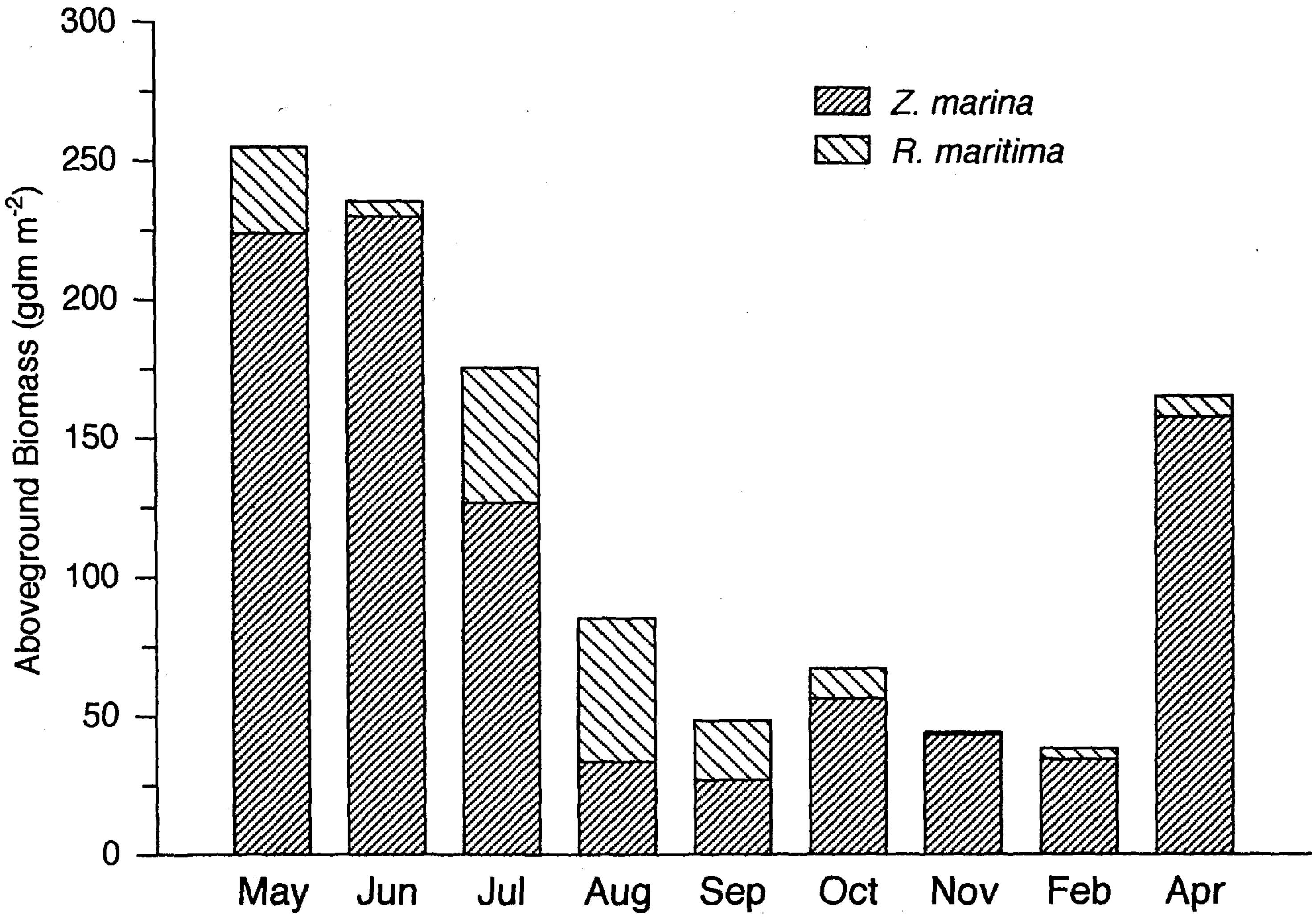
A3: Percent cover by species and depth proflie along sampling station transect.
October 5, 1993.



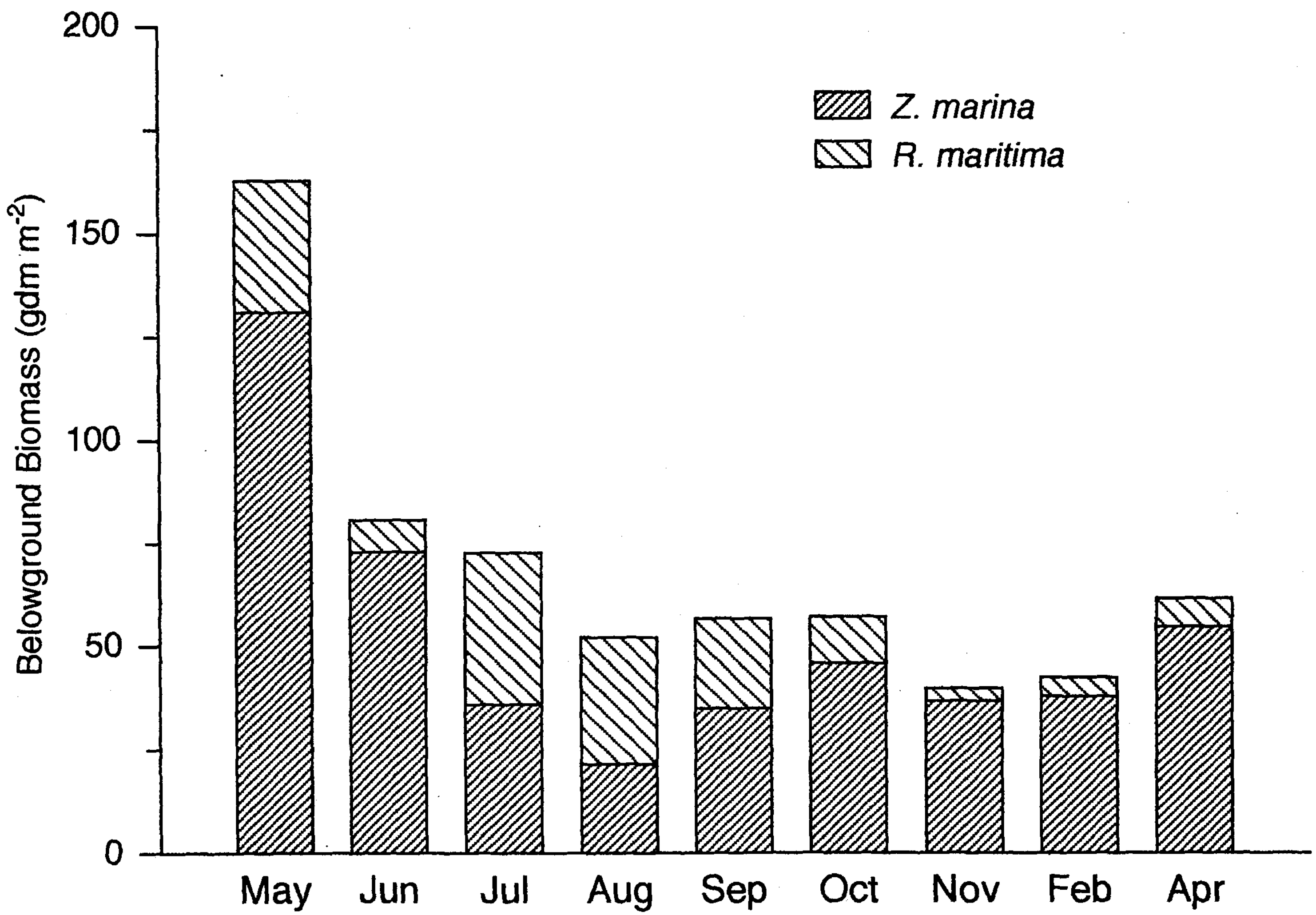
A4: Percent cover by species and depth profile along sampling station transect. April 18, 1994.



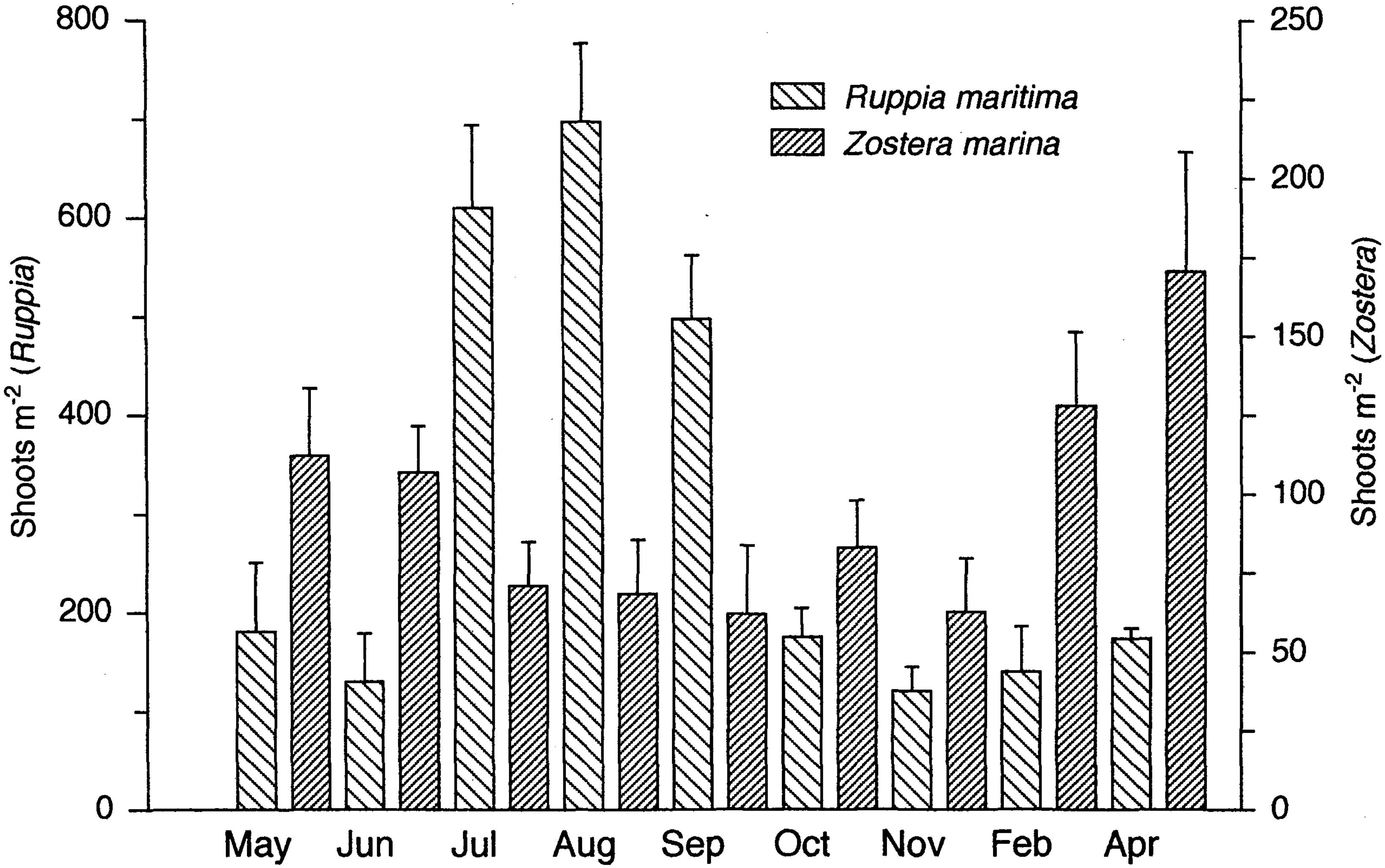
A5: Aboveground SAV biomass by species at Goodwin Island, VA study site. Values are means of 10 replicates sampled in vicinity of stations 1 and 2.



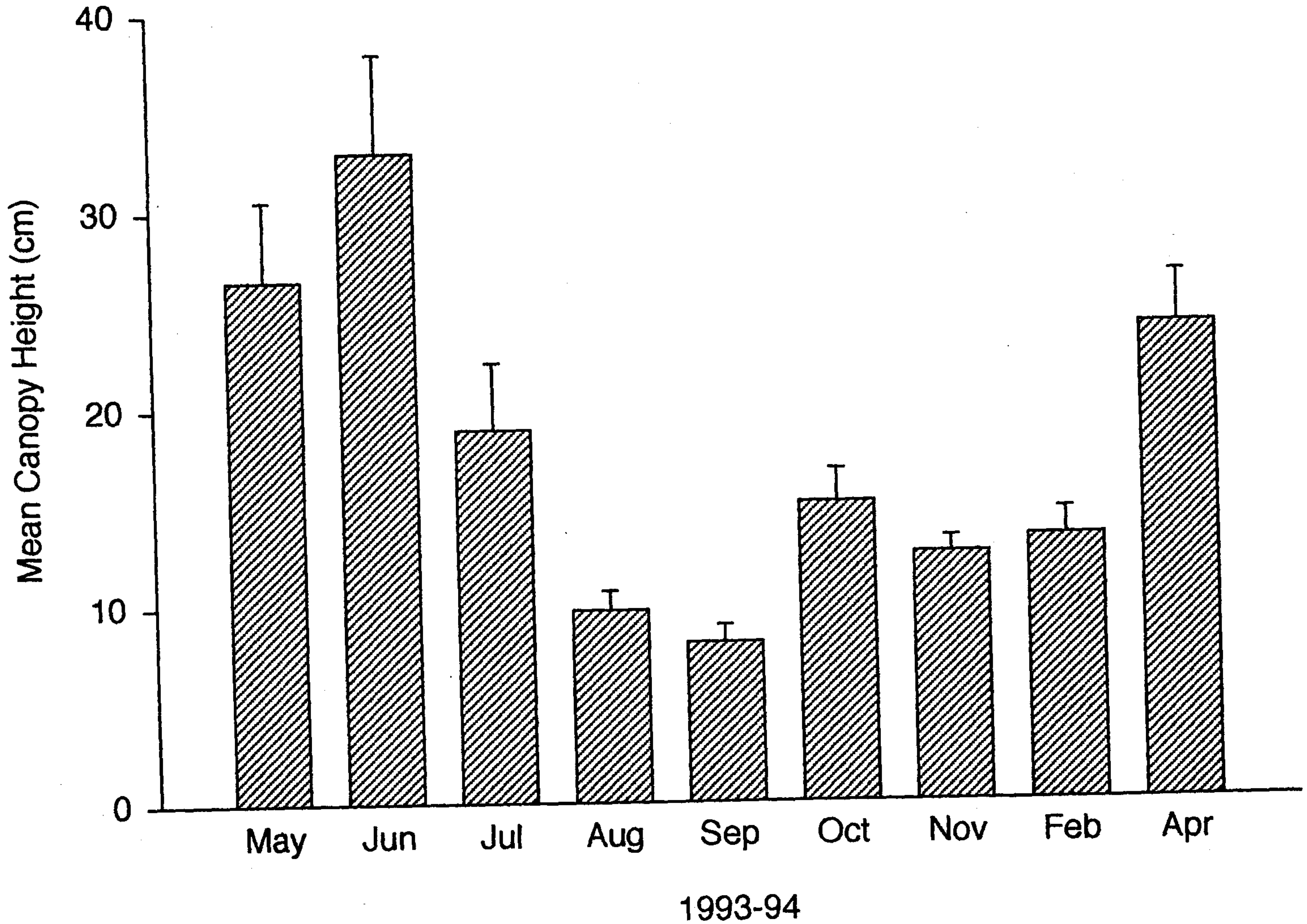
A6: Belowground SAV biomass by species at Goodwin Island, VA study site. Values are means of 10 replicates sampled in vicinity of stations 1 and 2.



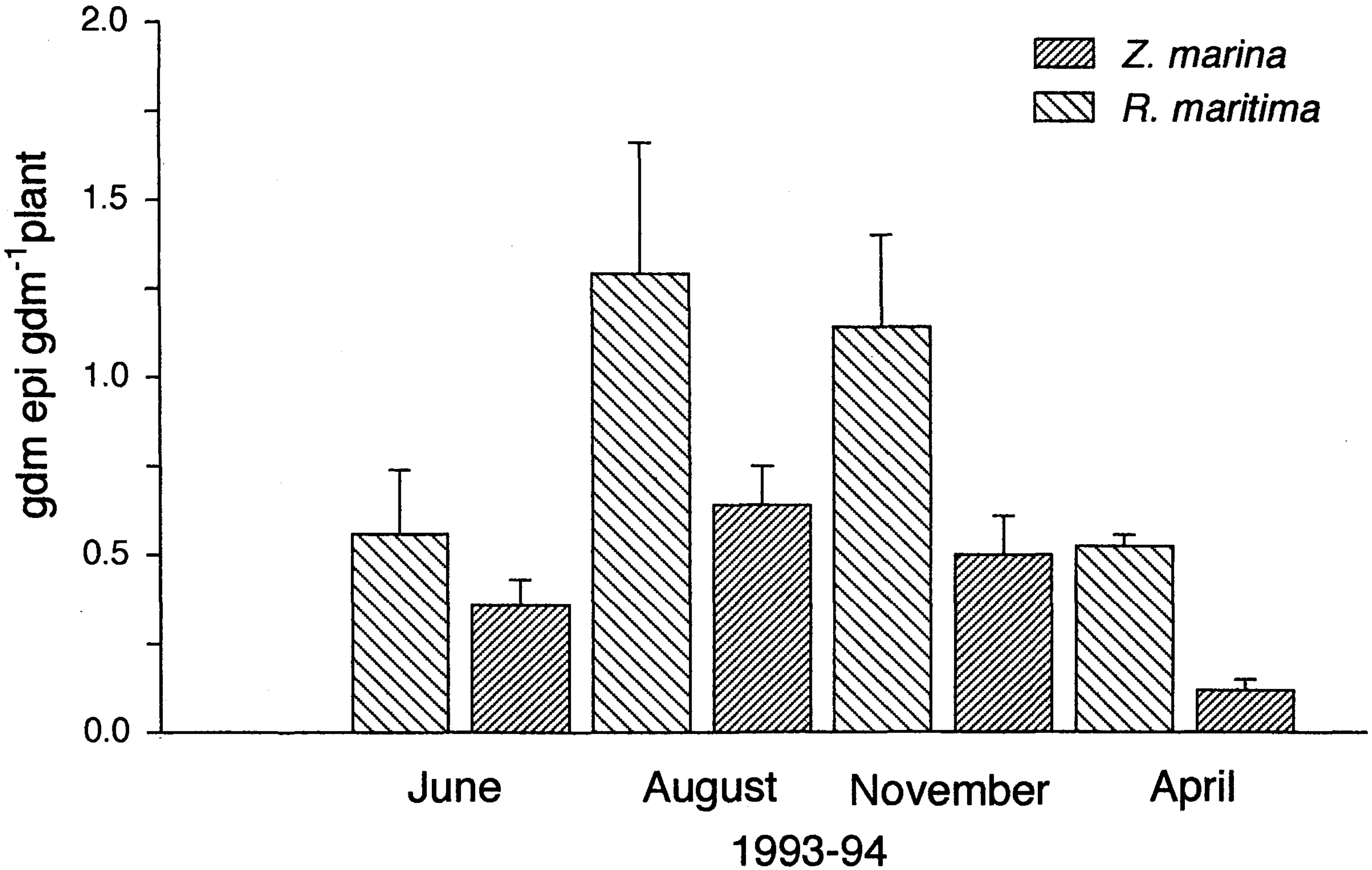
A7: SAV density by species at Goodwin Island, VA study site. Values are means of 10 replicates sampled in vicinity of stations 1 and 2.



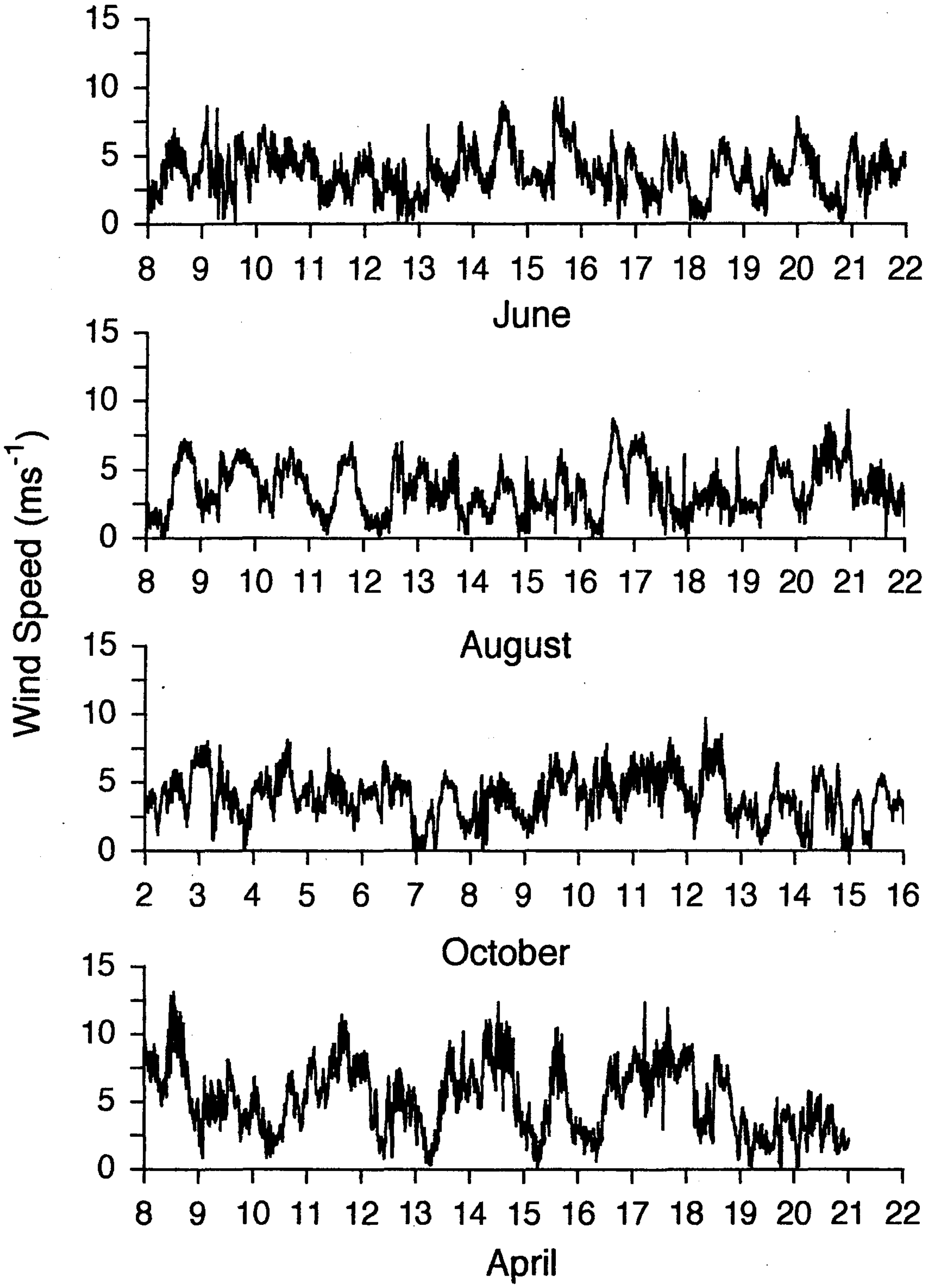
A8: Canopy height at Goodwin Island, VA study site. Values are means (+se) of 10 replicates sampled in vicinity of stations 1 and 2.



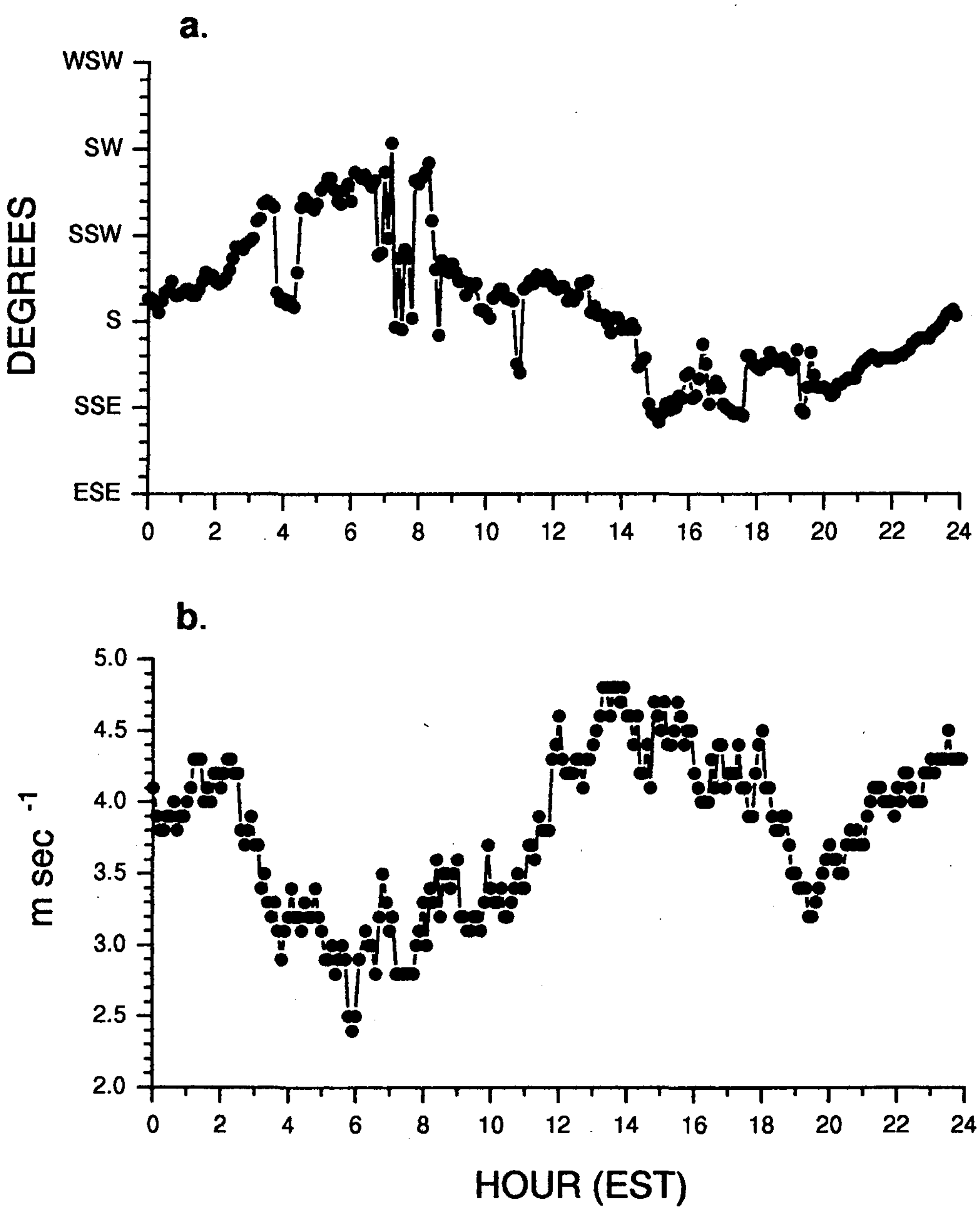
A9: Leaf Tissue specific mass of attached epiphytes at Goodwin Island, VA study site. Values are means (+se) of 10 replicates sampled in vicinity of stations 1 and 2. (gdm=grams dry mass)



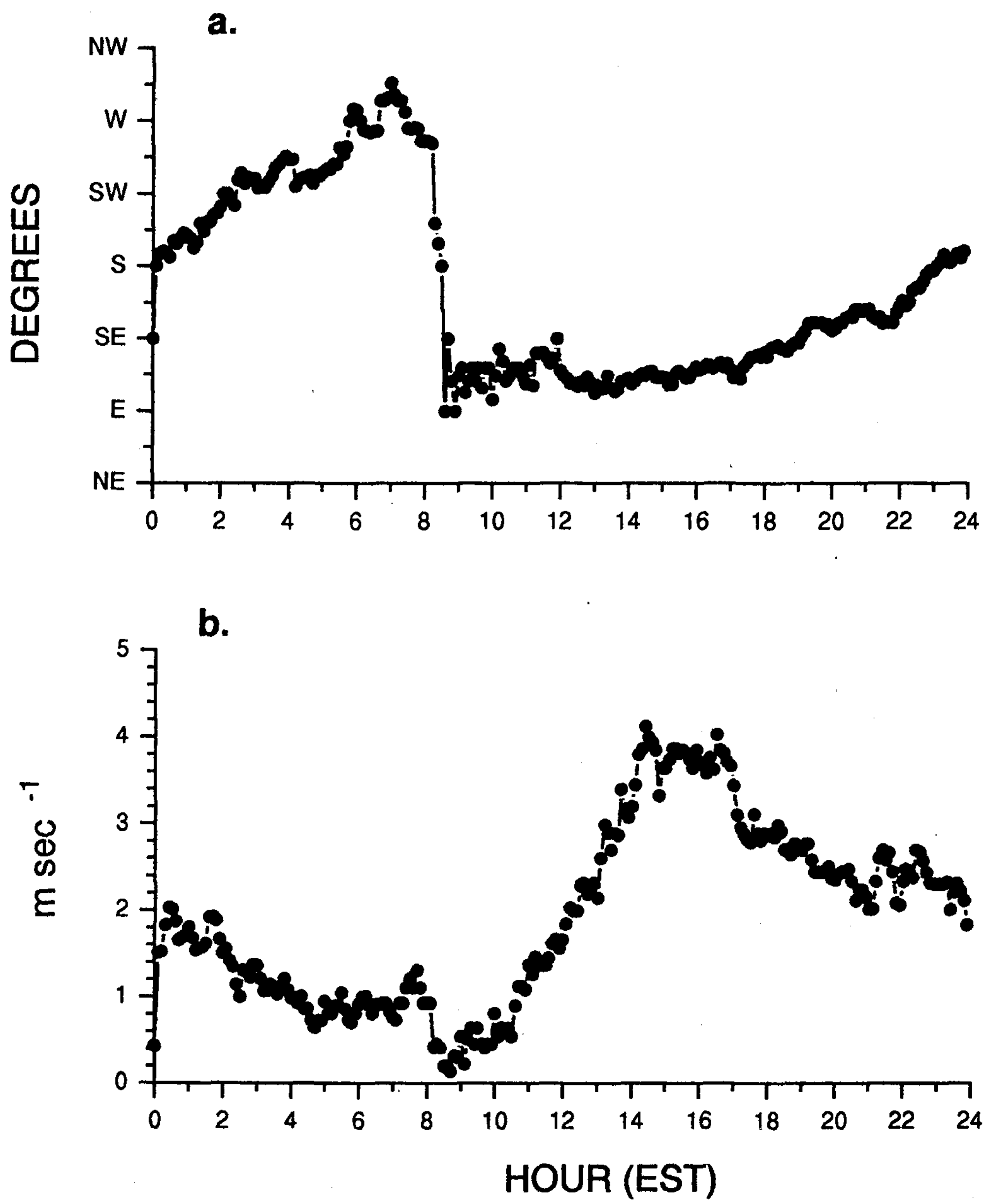
A10: Six minute, vector averaged wind speed at Gloucester Point meteorological station.



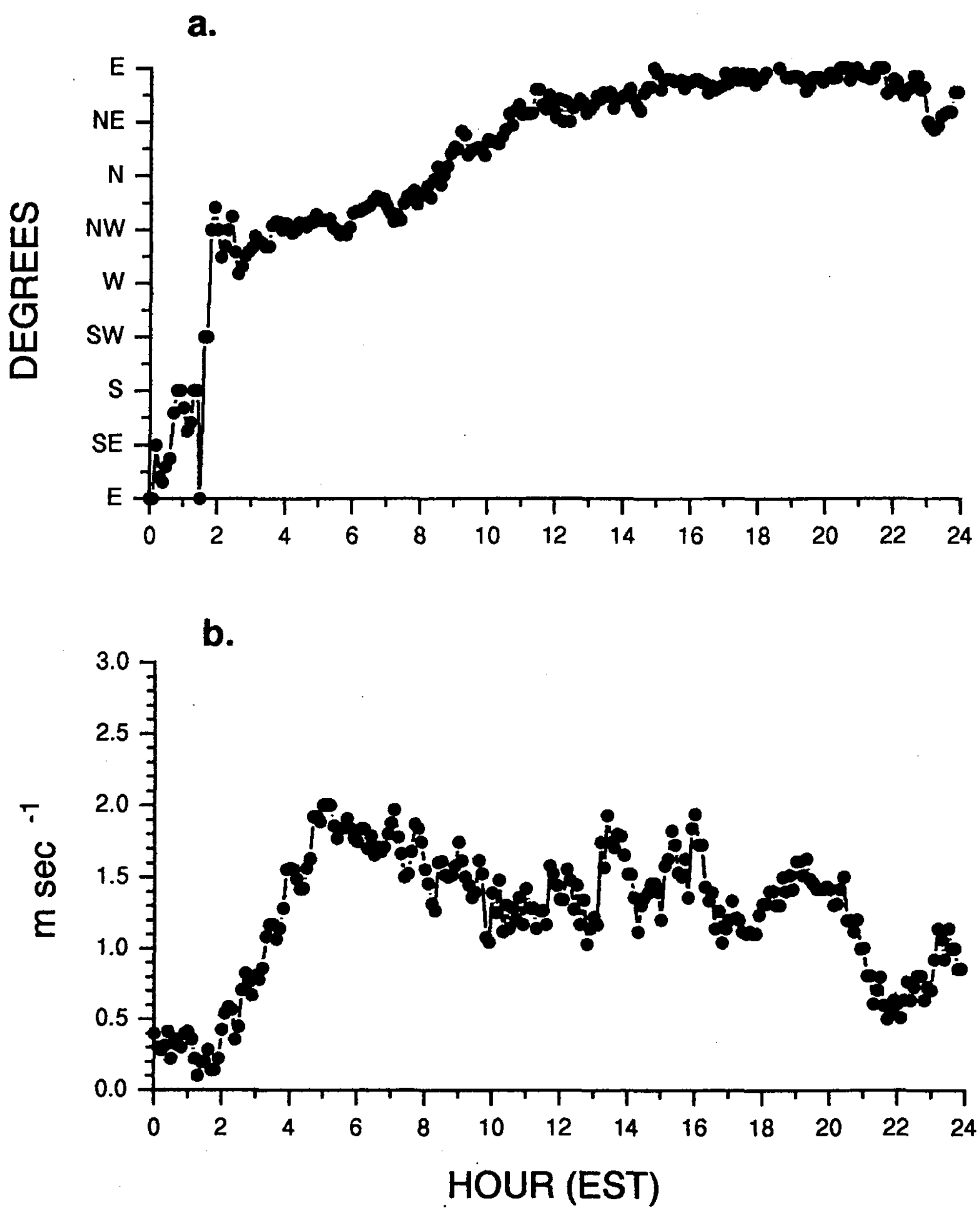
A11: Integrated six-minute, vector-averaged (a.) wind direction and (b.)velocity at Gloucester Point meteorological station, June 7-17, 1993.



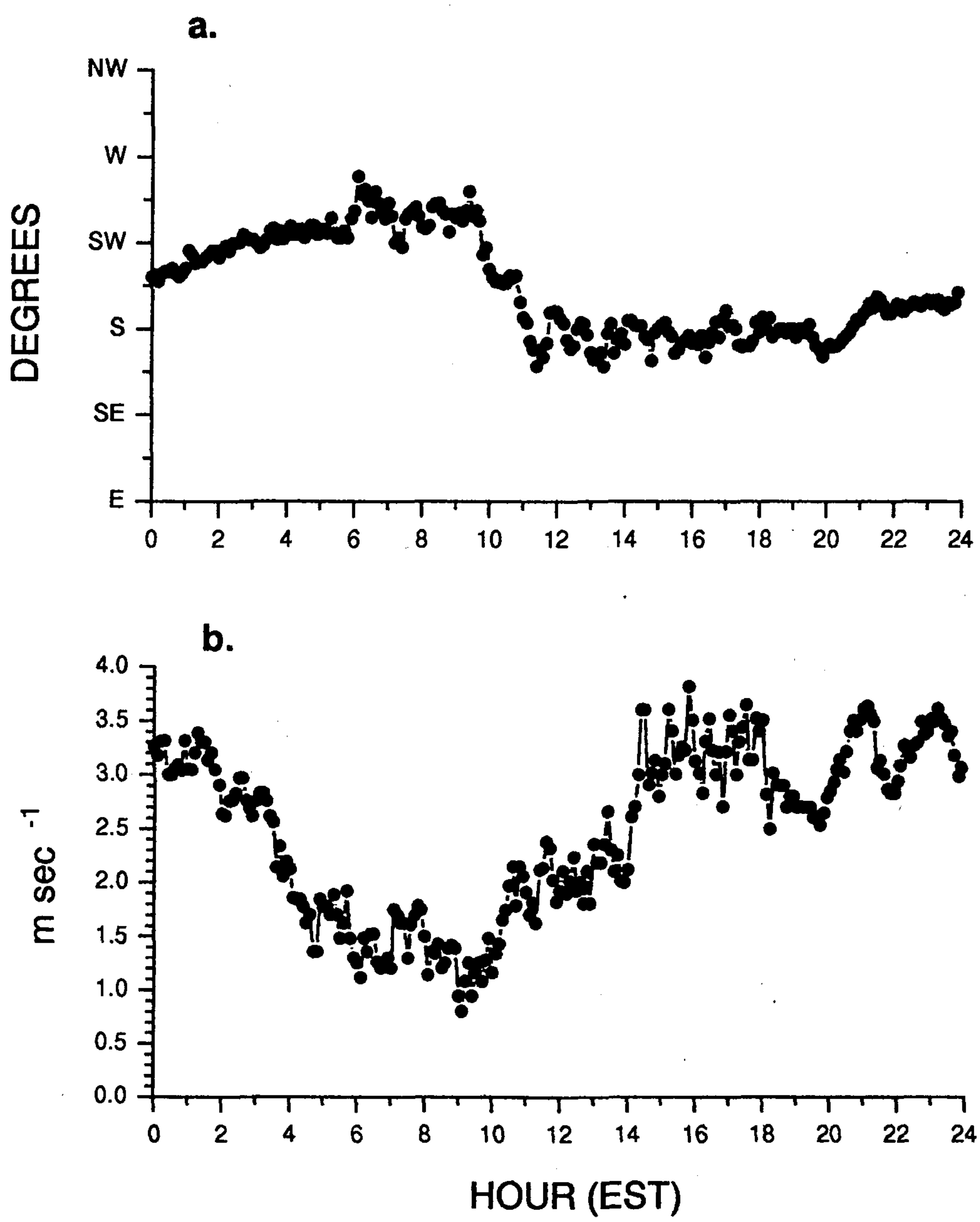
A12: Integrated six-minute, vector-averaged (a.) wind direction and (b.) velocity at Gloucester Point, Va. meteorological station, August 9-19, 1993.



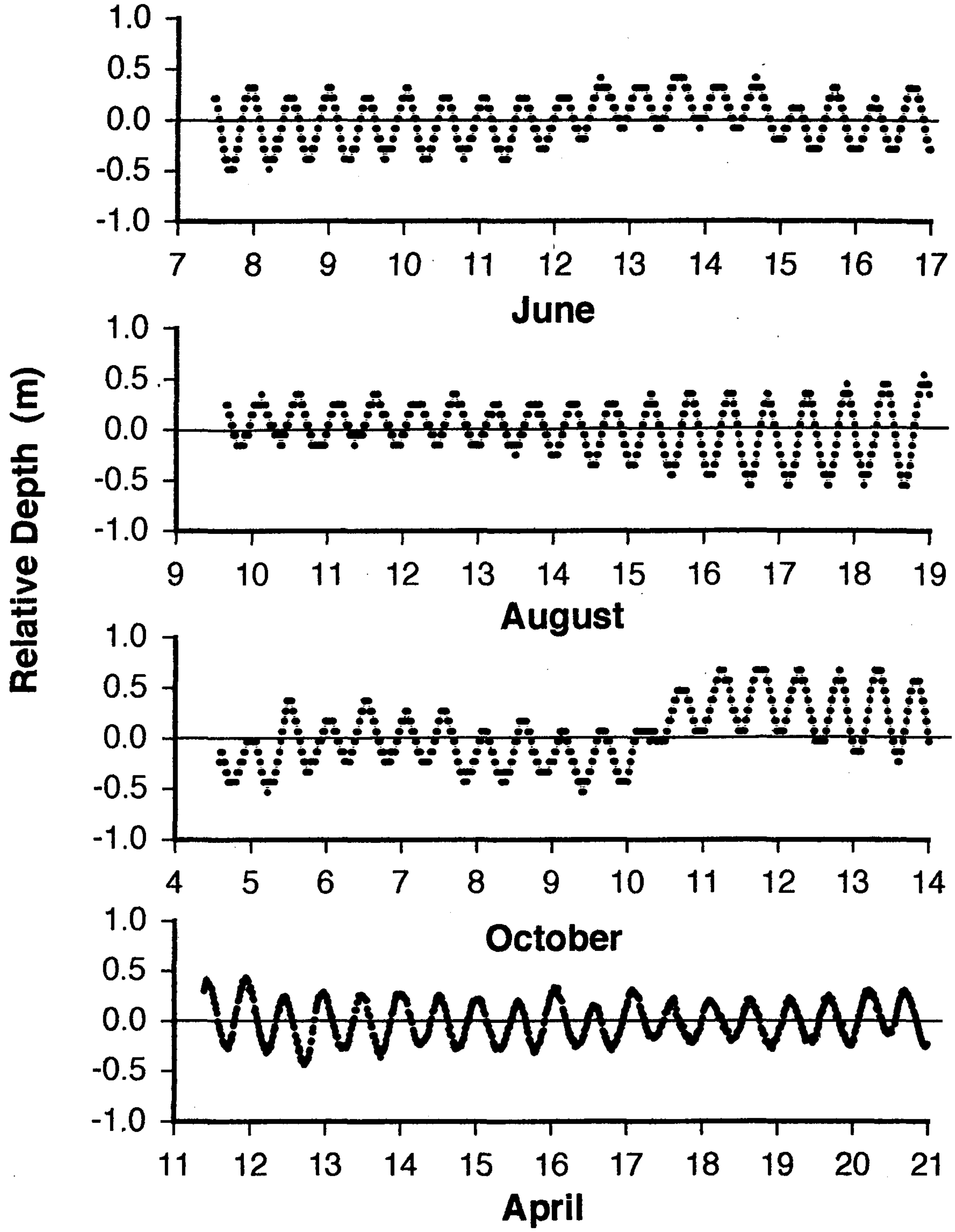
A13: Integrated six-minute, vector-averaged (a.) wind direction and (b.) velocity at Gloucester Point, Va. meteorological station, October 4-14, 1993.



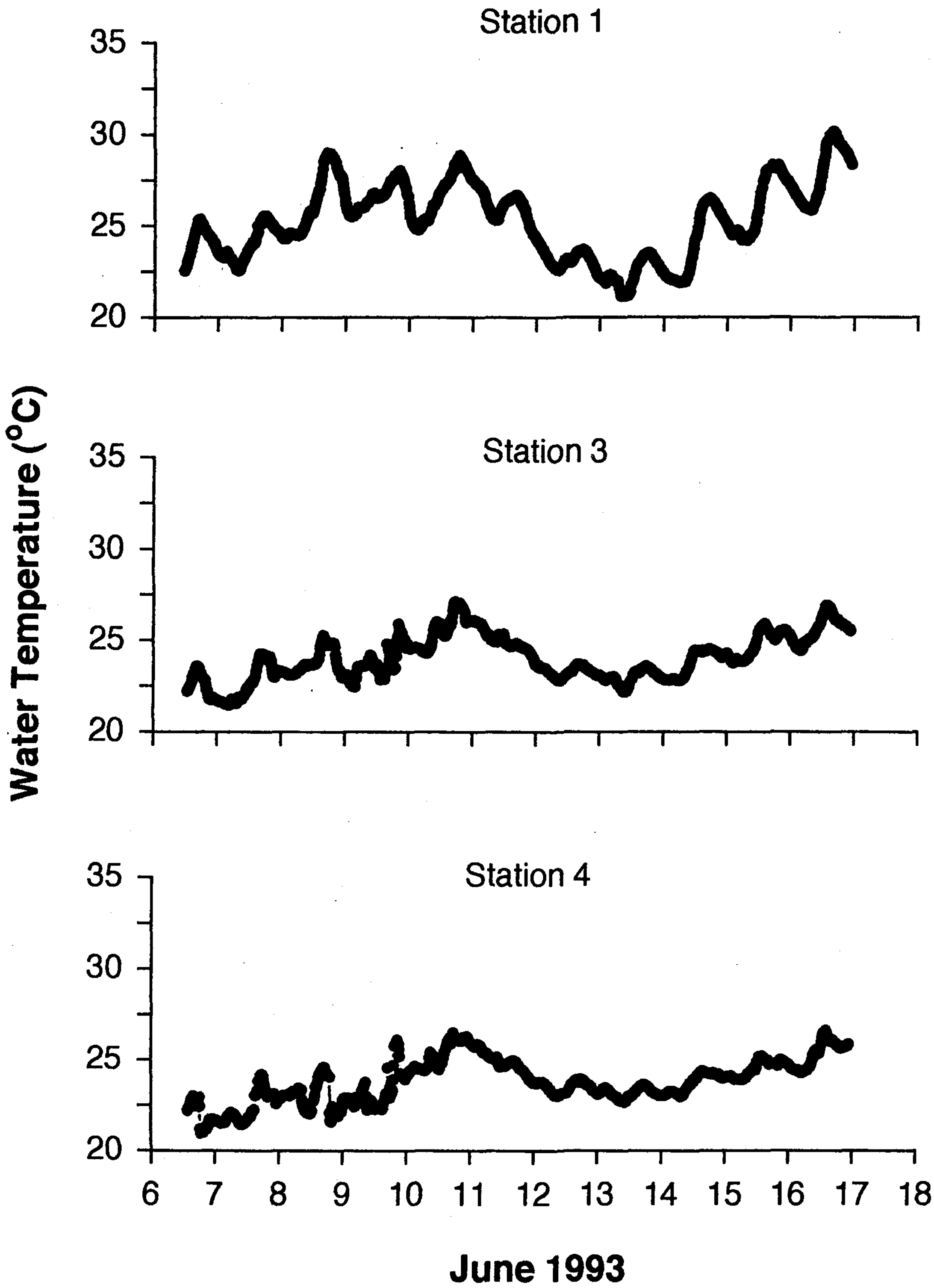
A14: Integrated six-minute, vector-averaged (a.) wind direction and (b.) velocity at Gloucester Point, Va. meteorological station, April 11-21, 1994.



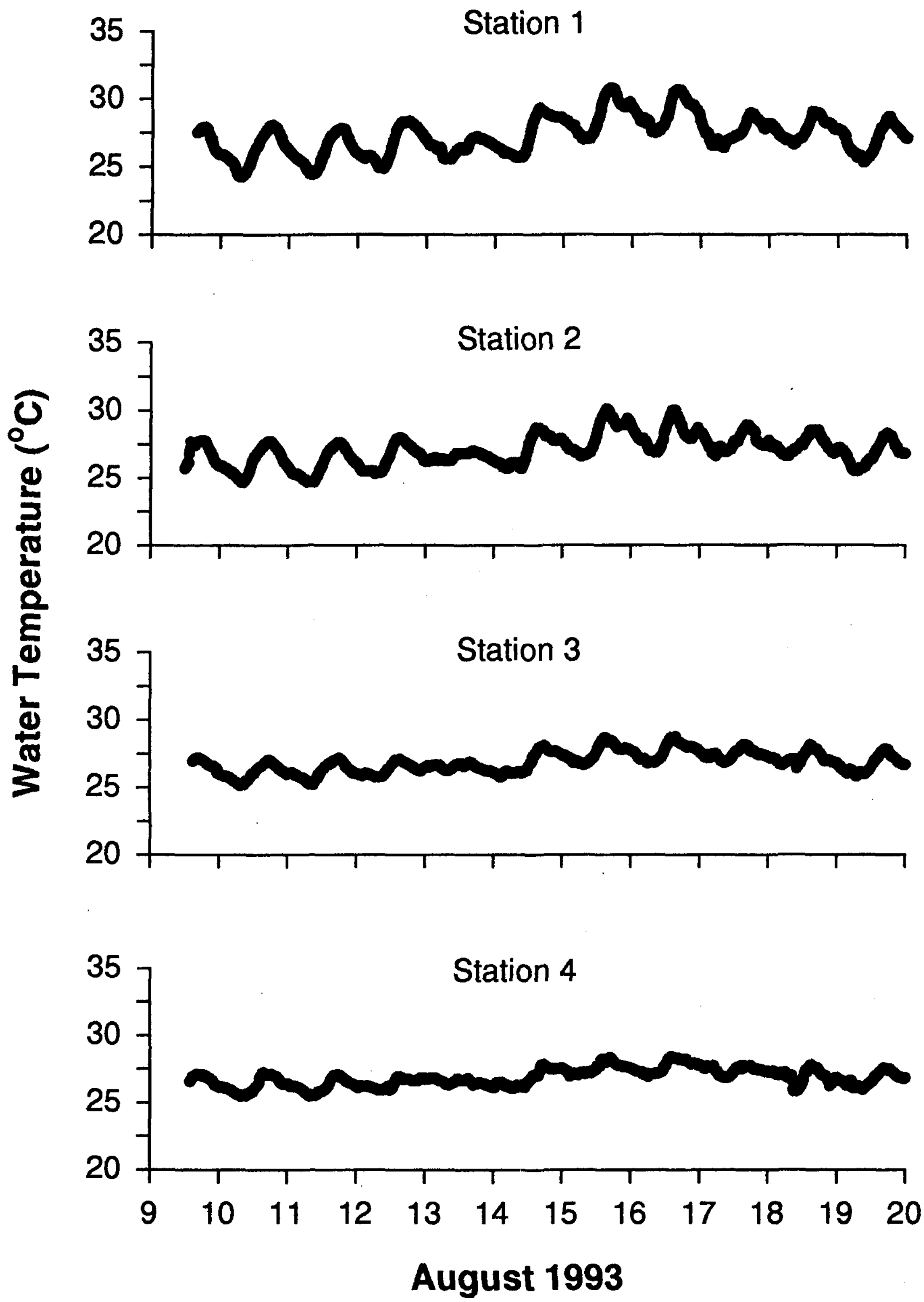
A15 : 15-minute relative tidal depths at Goodwin Island, VA.



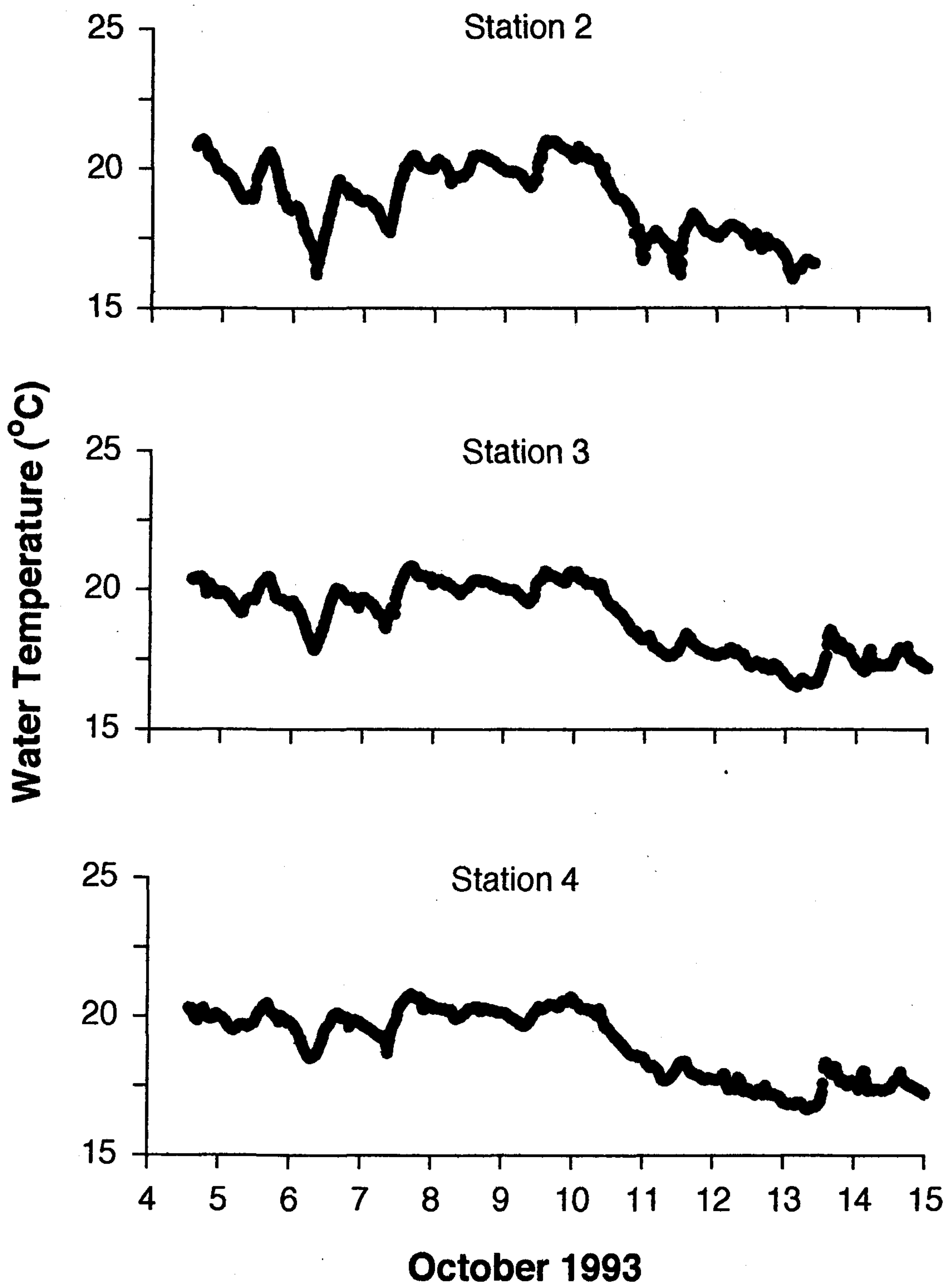
A16 : 15-minute water temperatures at Goodwin Island, VA. June 1993.



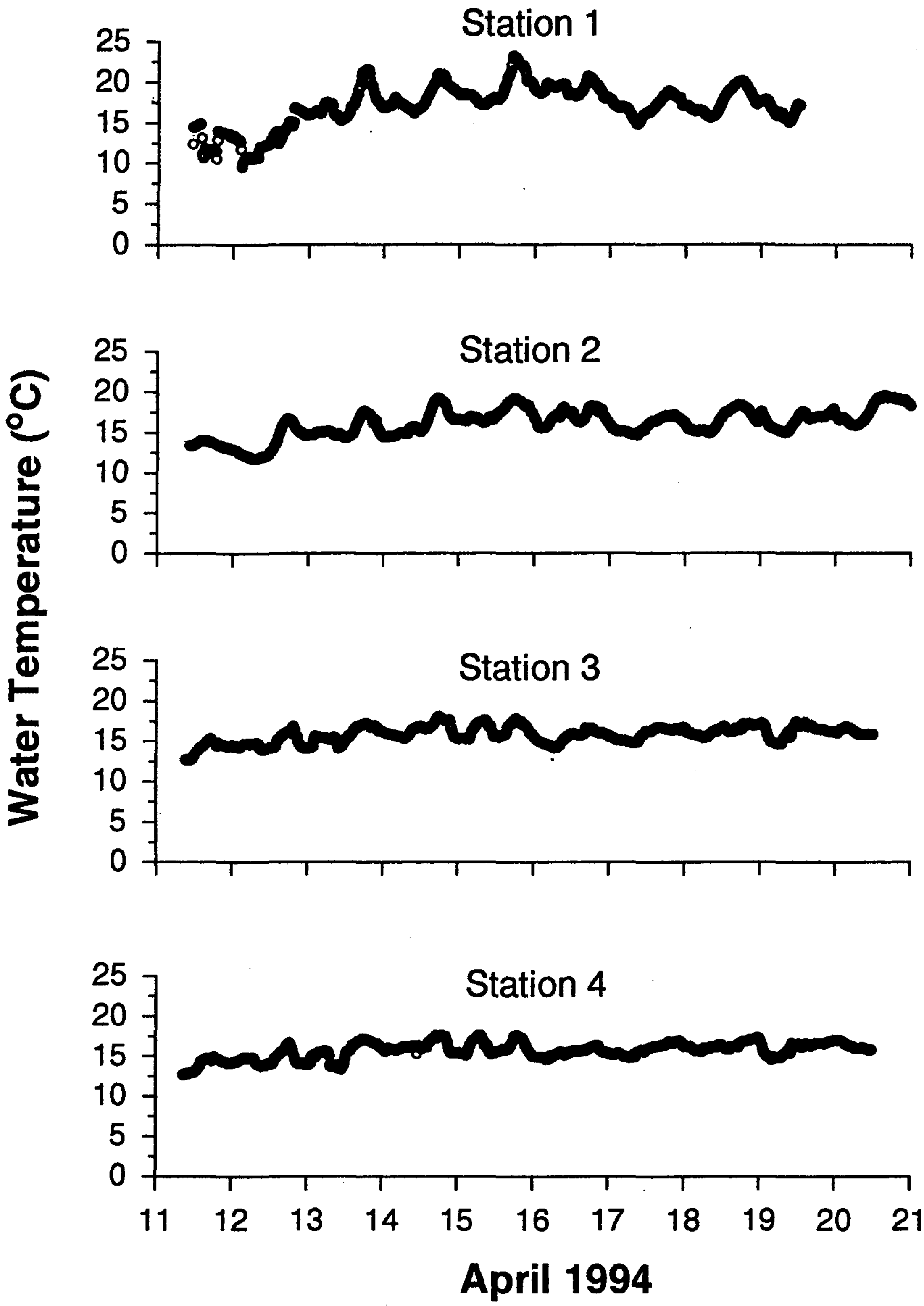
A17 : 15-minute water temperatures at Goodwin Island, VA. August 1993.



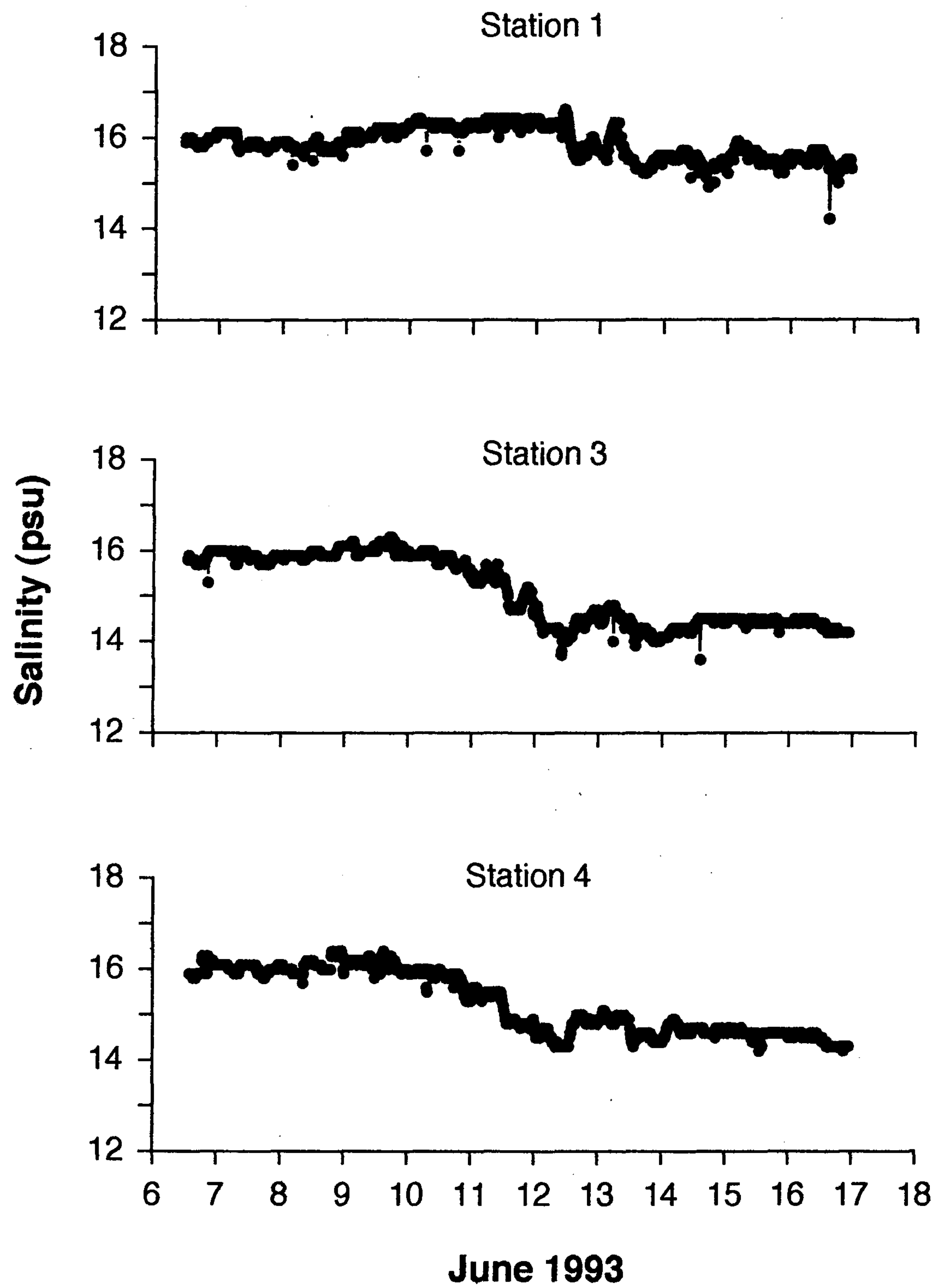
A18 : 15-minute water temperatures at Goodwin Island, VA. October 1993.



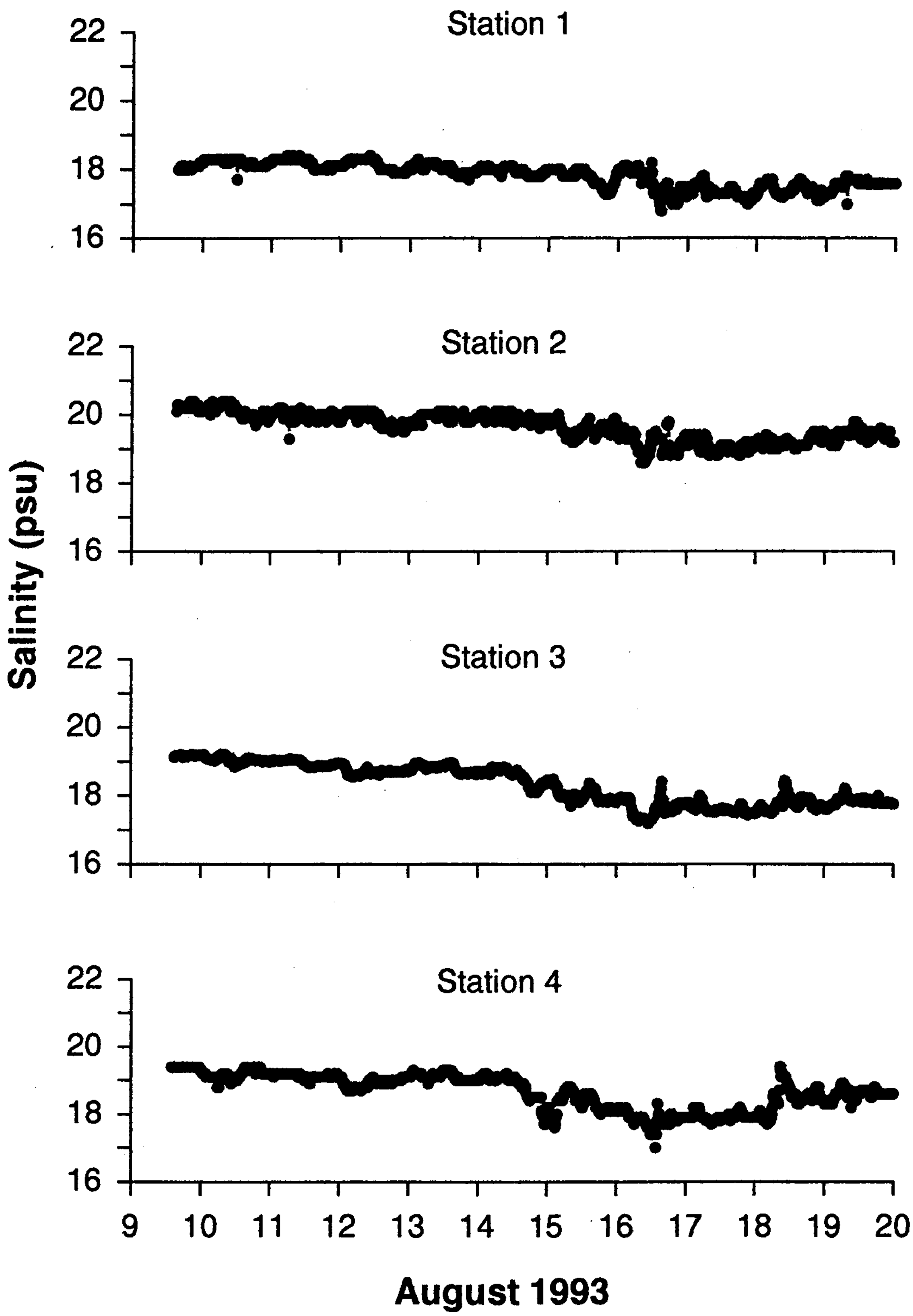
A19 : 15-minute water temperatures at Goodwin Island, VA. April 1994.



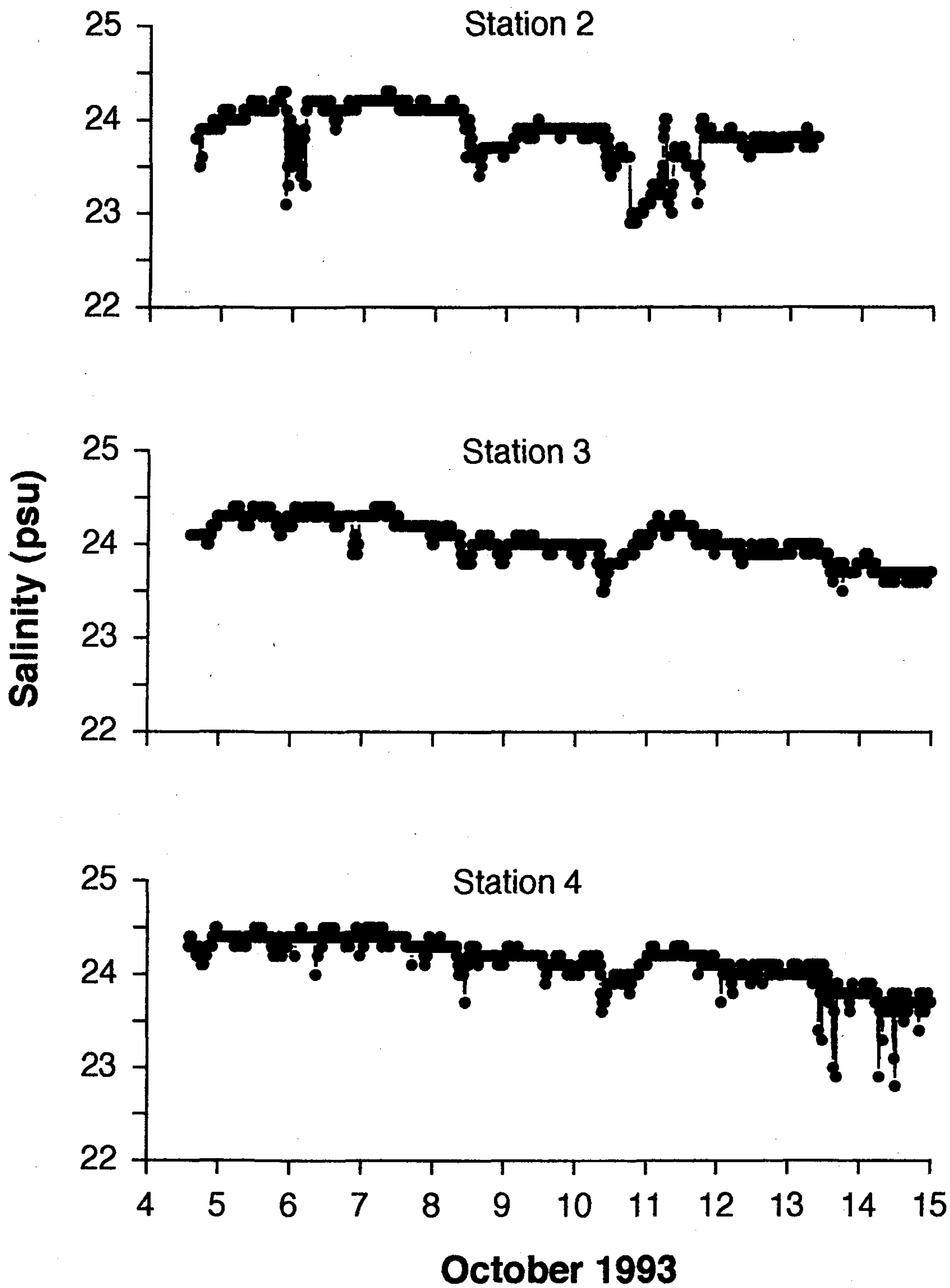
A20 : 15-minute salinities at Goodwin Island, VA. June 1993.



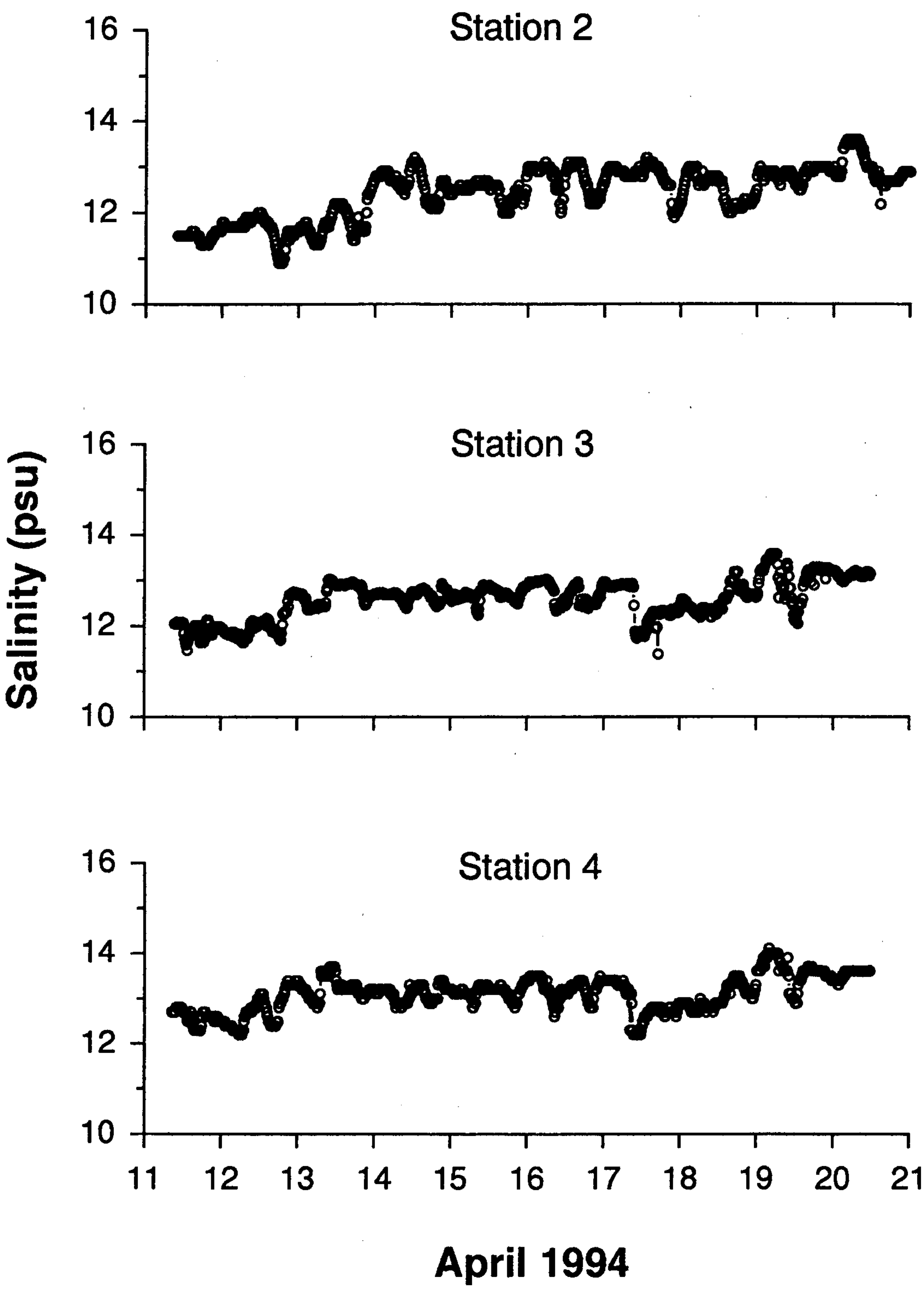
A21 : 15-minute salinities at Goodwin Island, VA. August 1993.



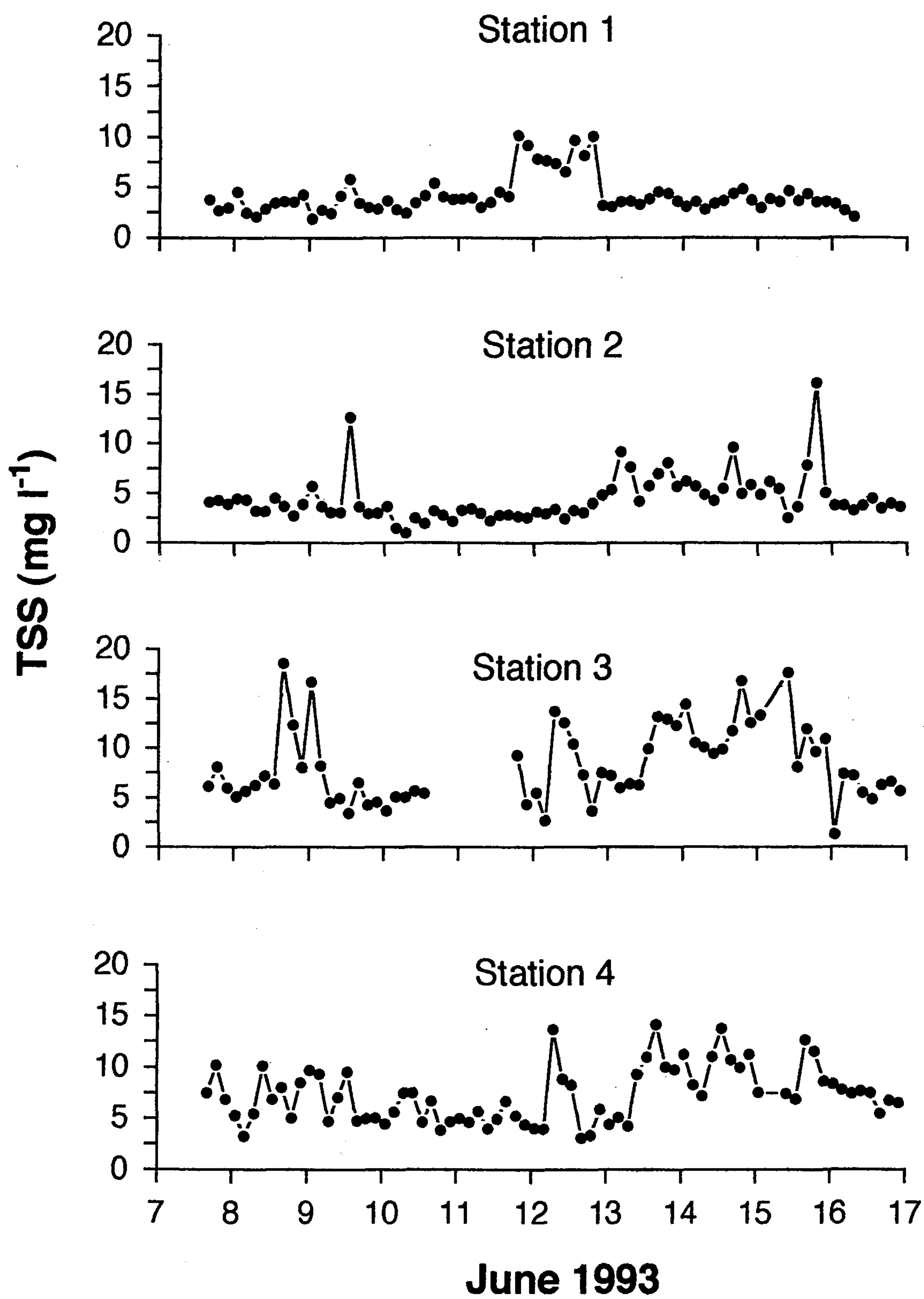
A22 : 15-minute salinities at Goodwin Island, VA. October 1993.



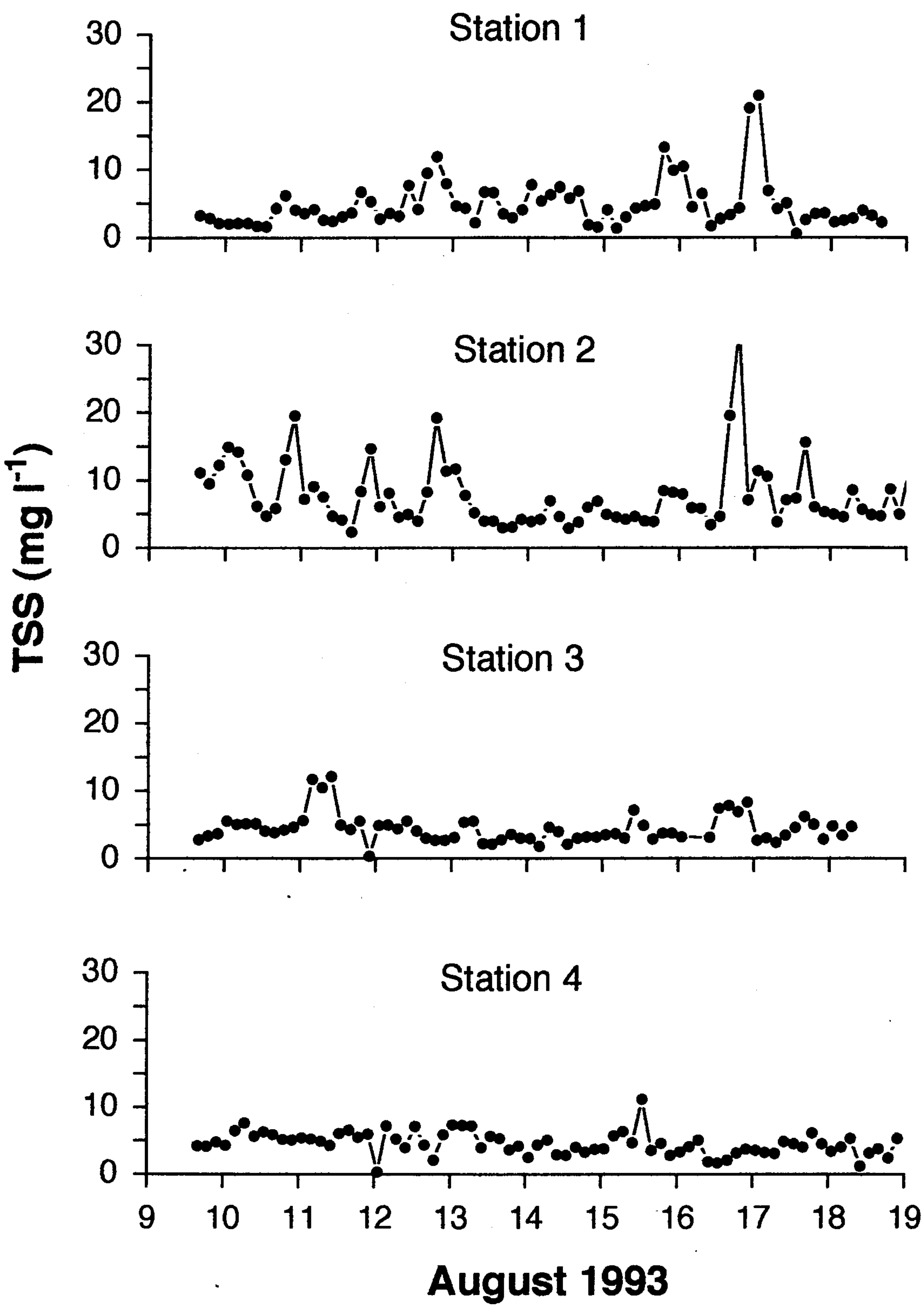
A23 : 15-minute salinities at Goodwin Island, VA. April 1994.



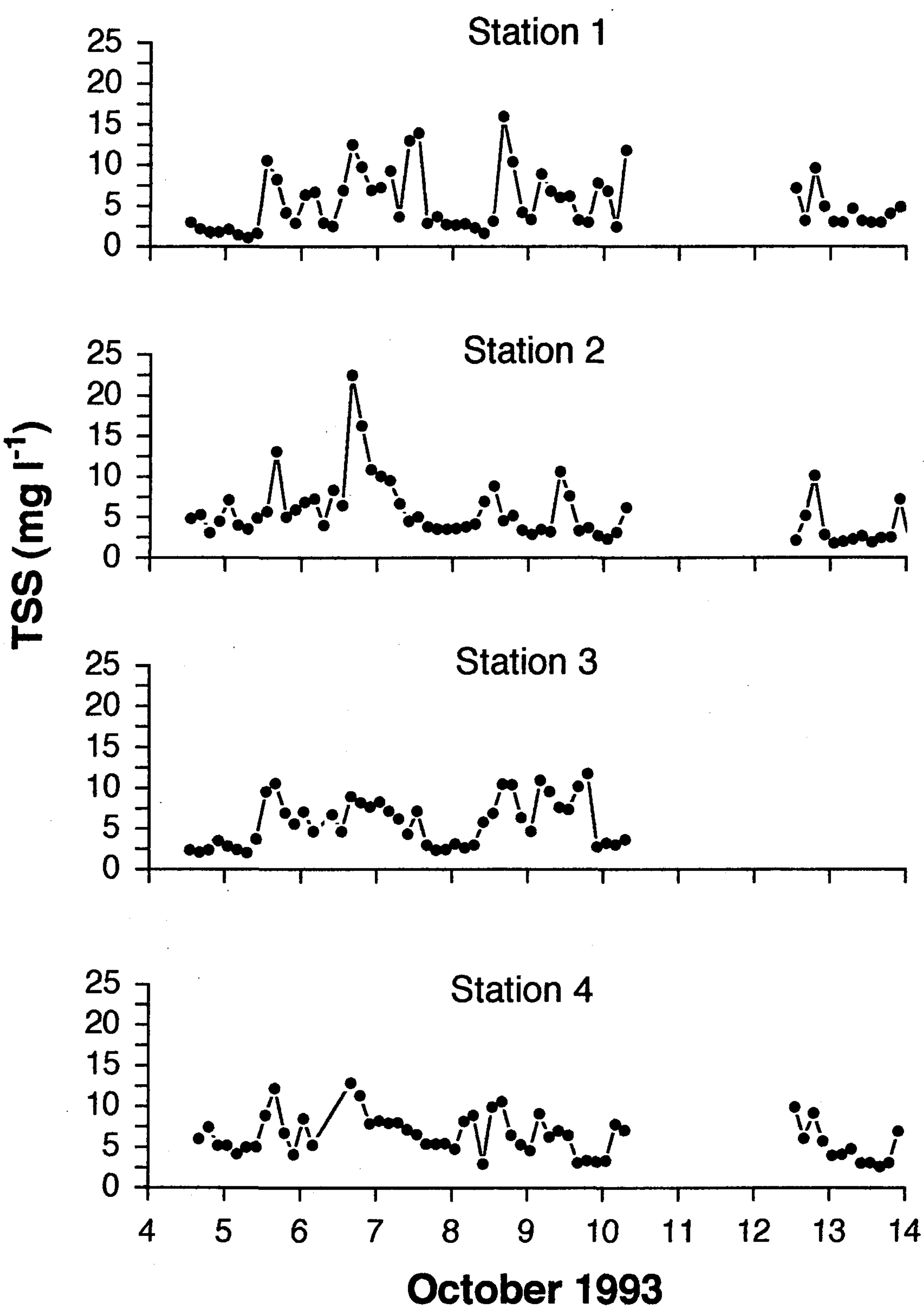
A24 : 3-hour total suspended solid (TSS) concentrations at Goodwin Island, VA. June 1993.



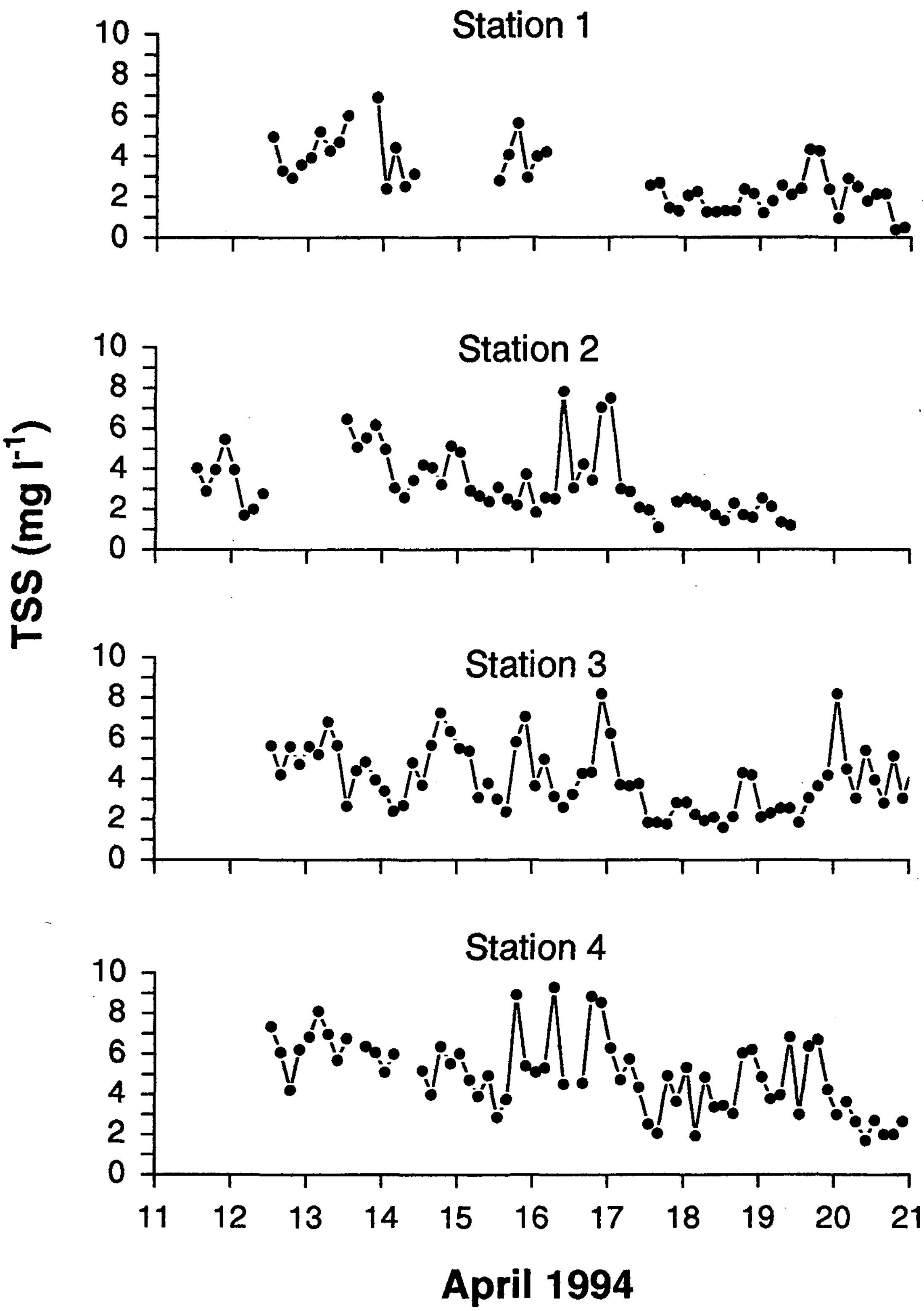
A25 : 3-hour total suspended solid (TSS) concentrations at Goodwin Island, VA. August 1993



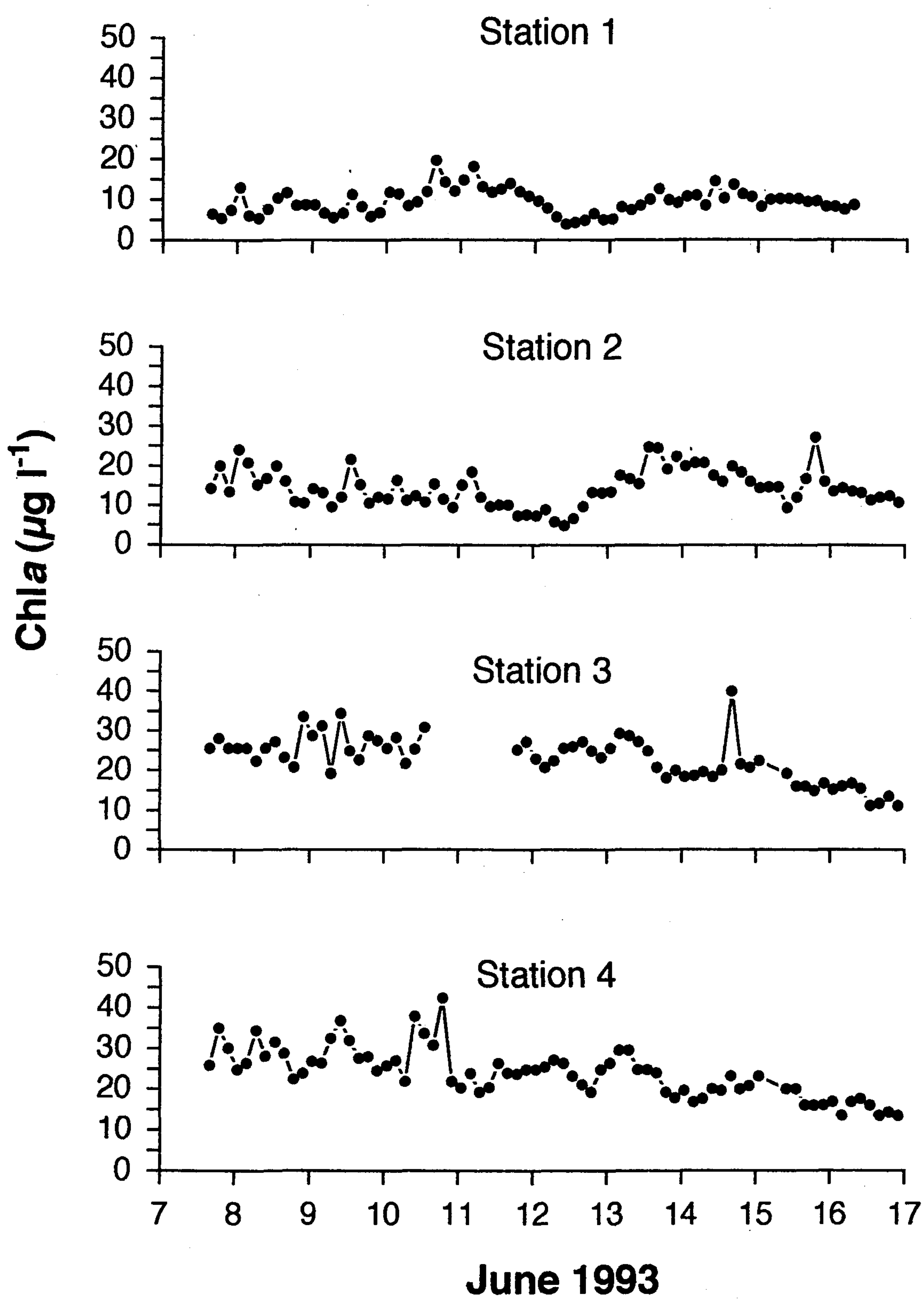
A26 : 3-hour total suspended solid (TSS) concentrations at Goodwin Island, VA. October 1993.



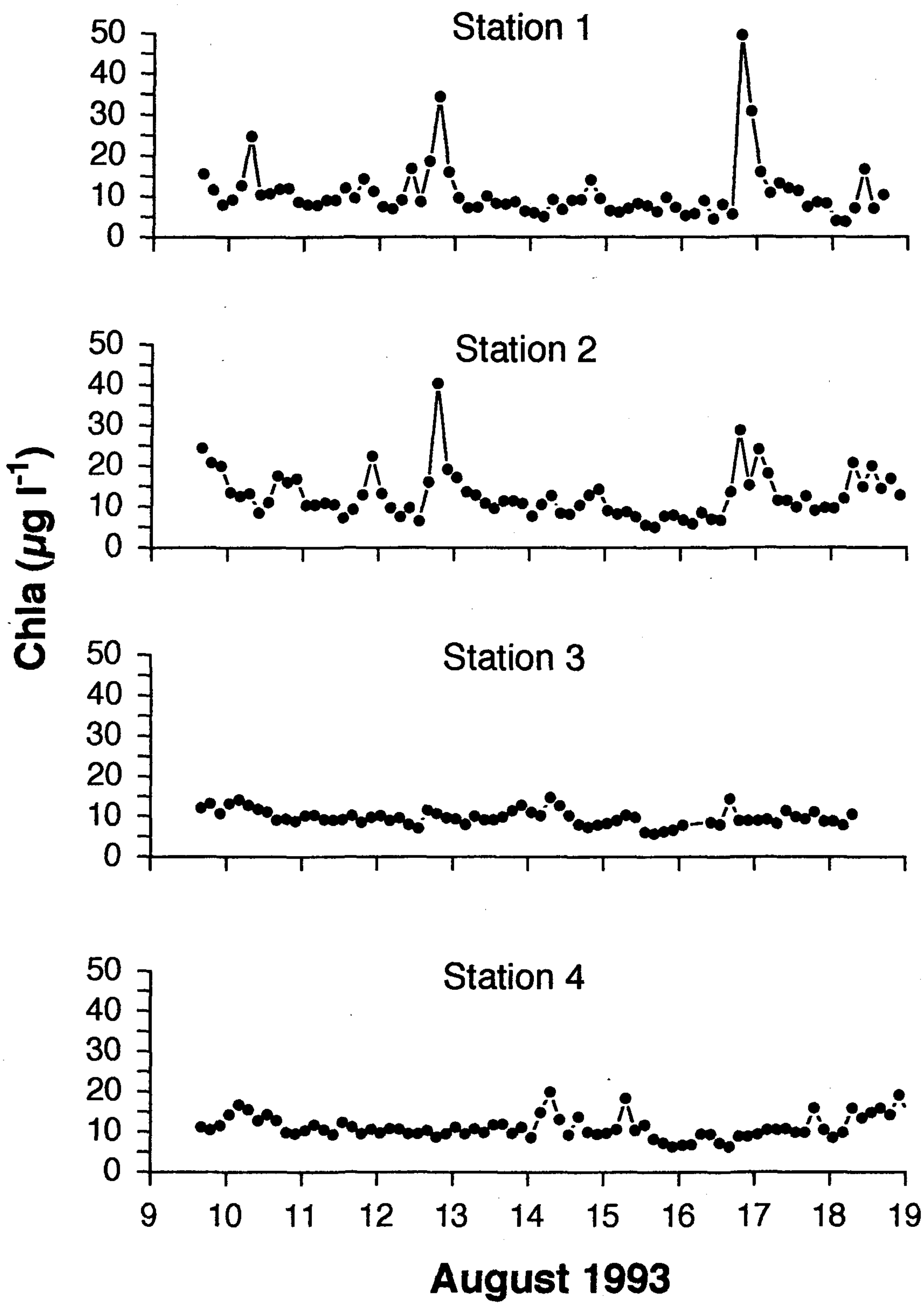
A27 : 3-hour total suspended solid (TSS) concentrations at Goodwin Island, VA. April 1994.



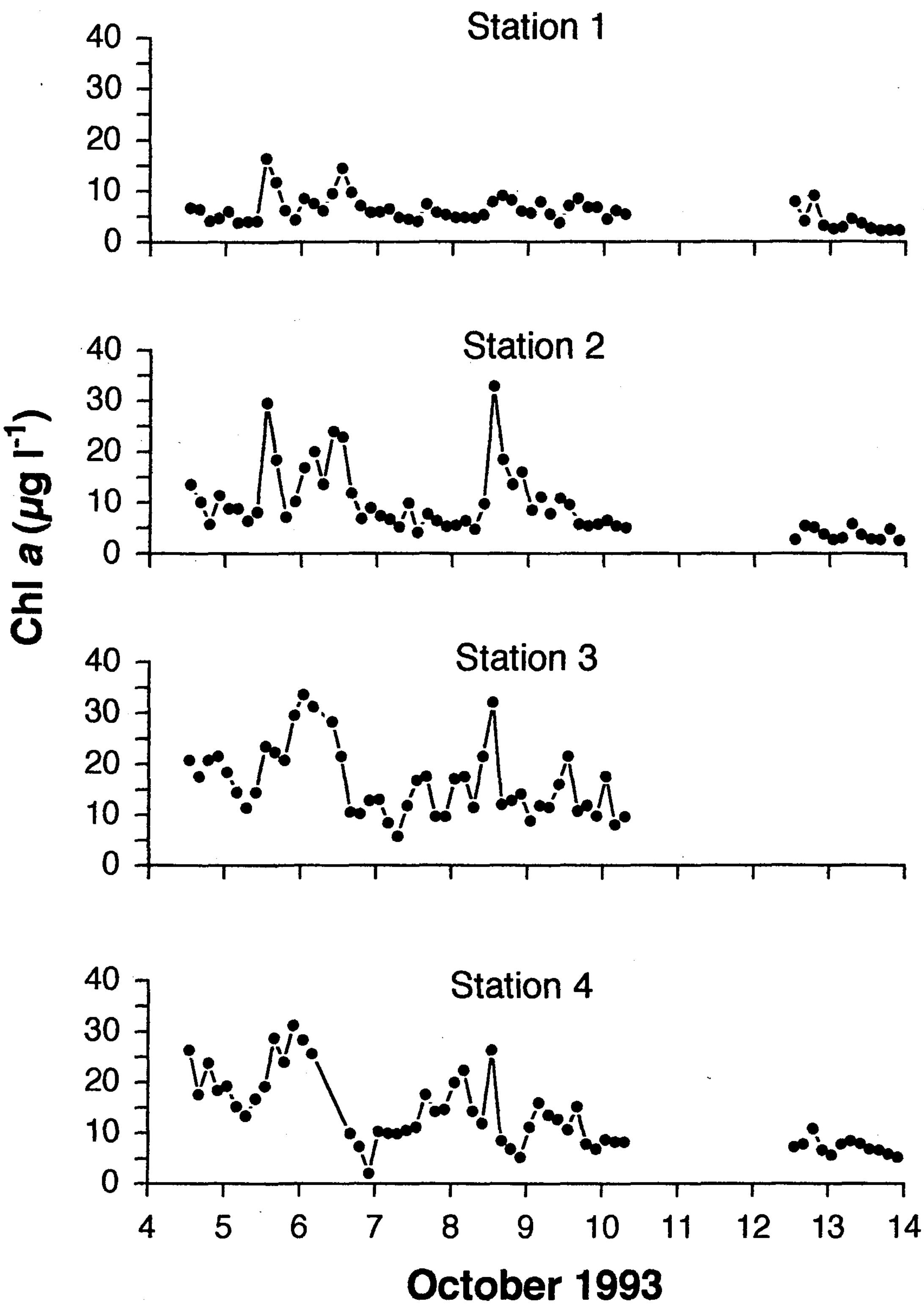
A28 : 3-hour chlorophyll *a* at Goodwin Island, VA. June 1993.



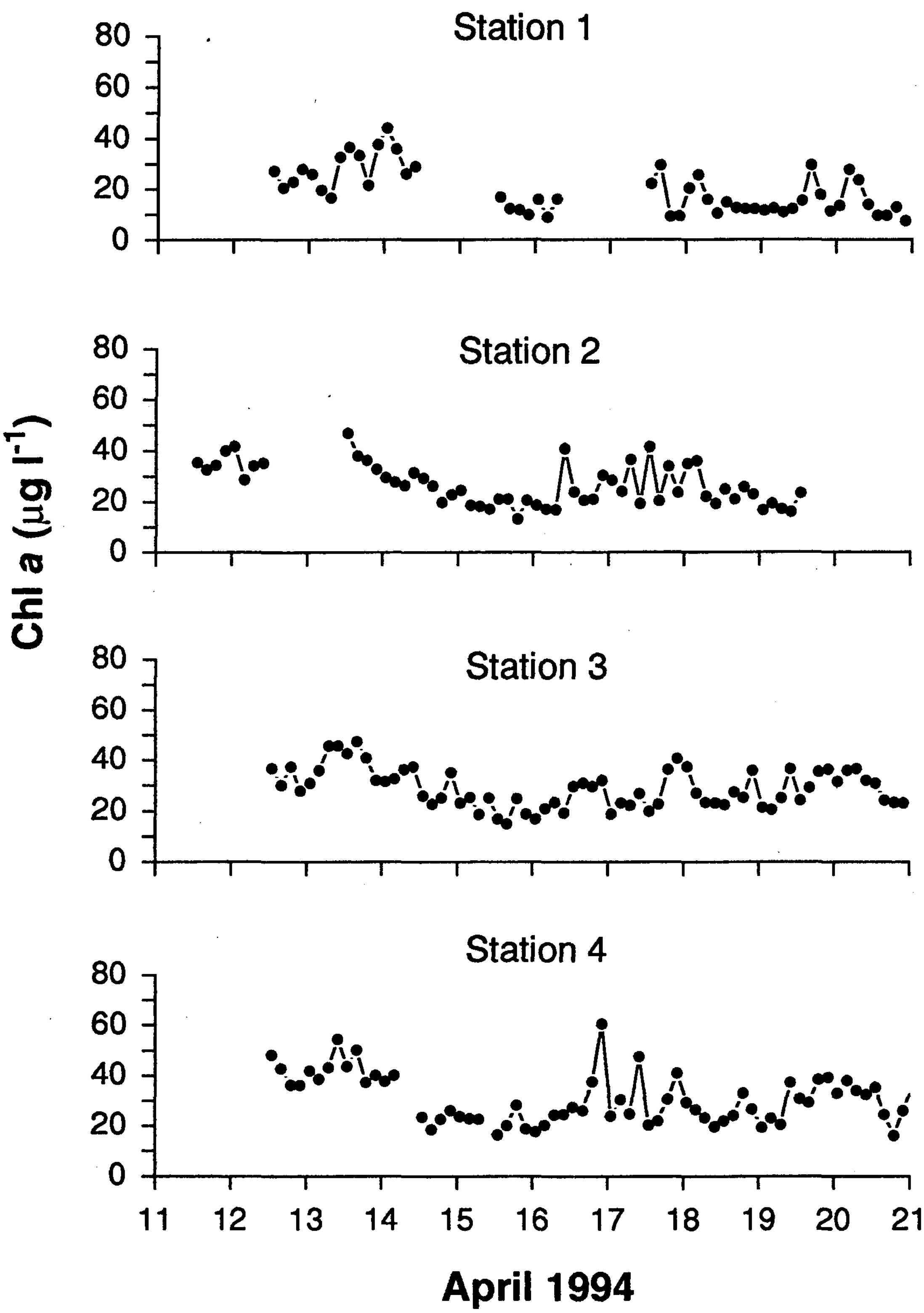
A29 : 3-hour chlorophyll *a* concentrations at Goodwin Island, VA. August 1993.



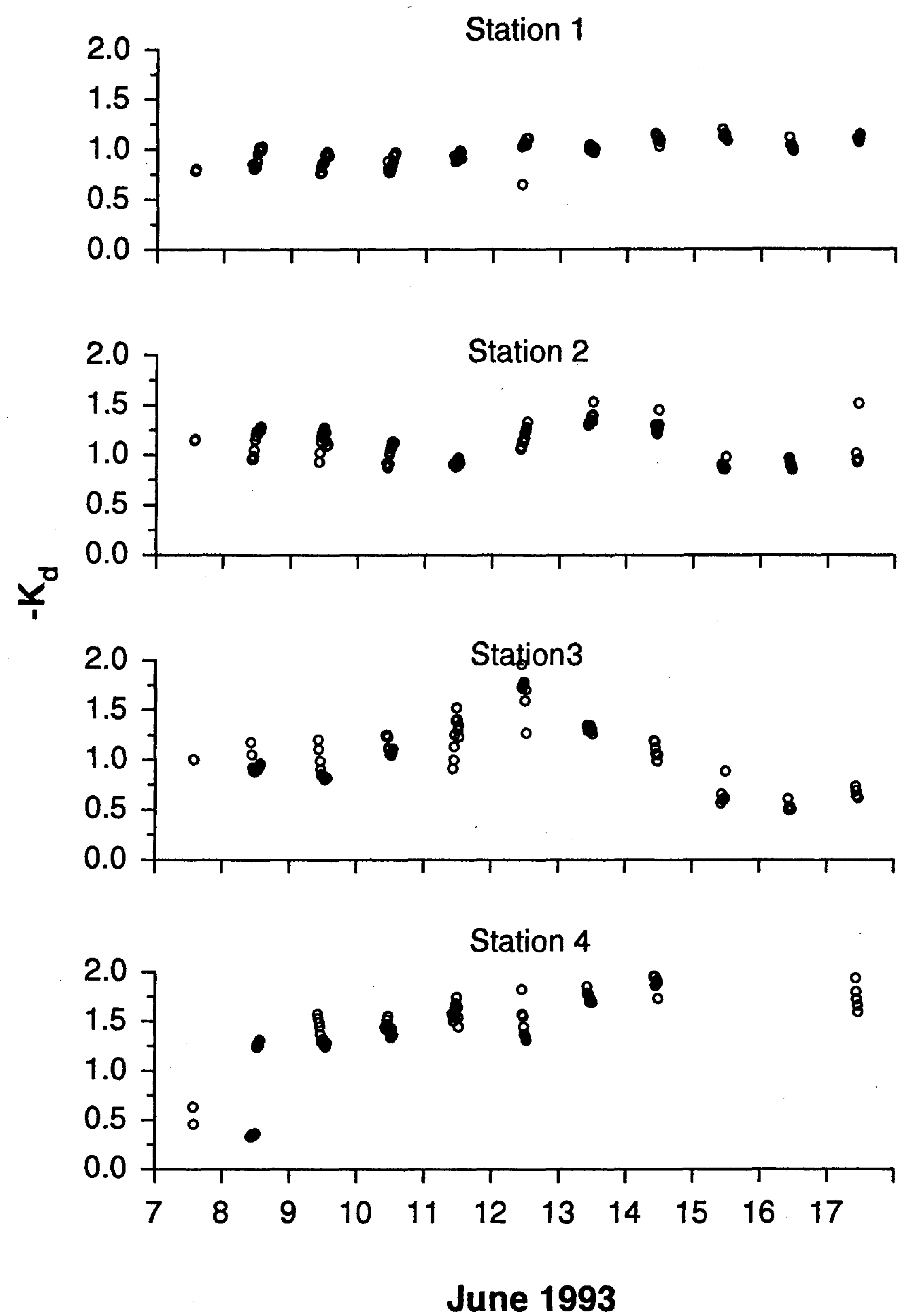
A30 : 3-hour chlorophyll *a* concentrations at Goodwin Island, VA. October 1993.



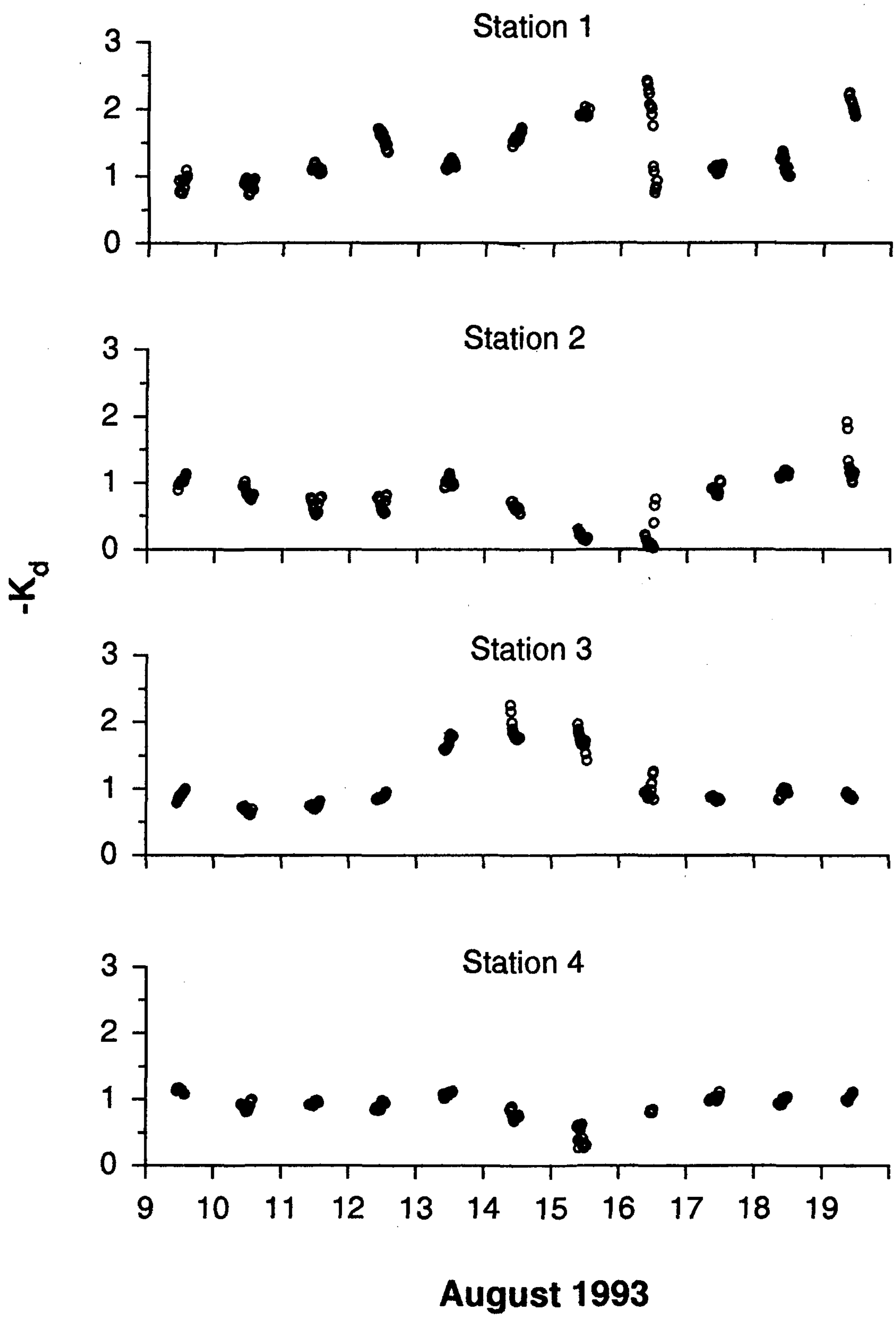
A31 : 3-hour chlorophyll *a* concentrations at Goodwin Island, VA. April 1994.



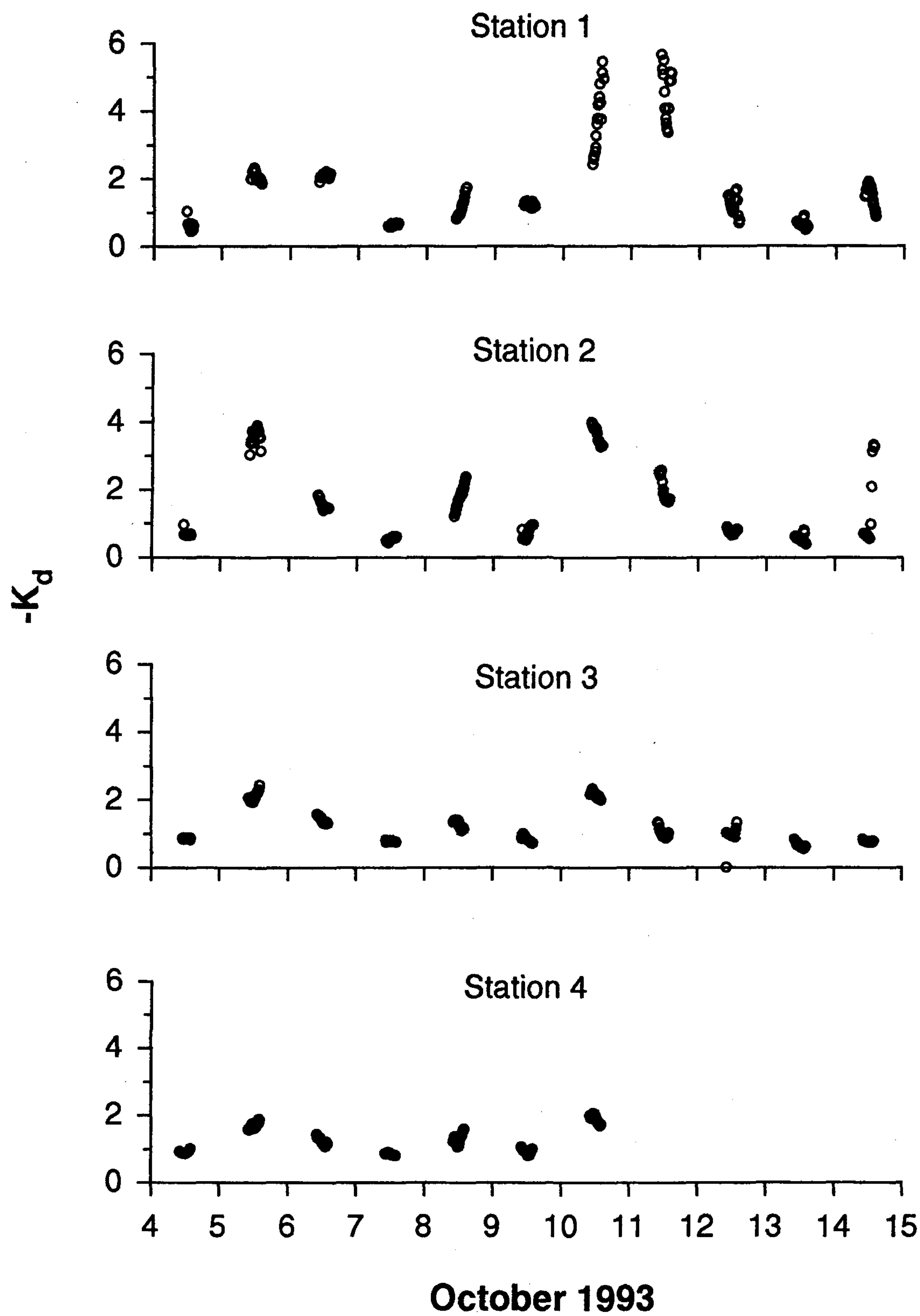
A32 : 15-minute integrated light attenuation ($-K_d$) at Goodwin Island, VA. June 1993.



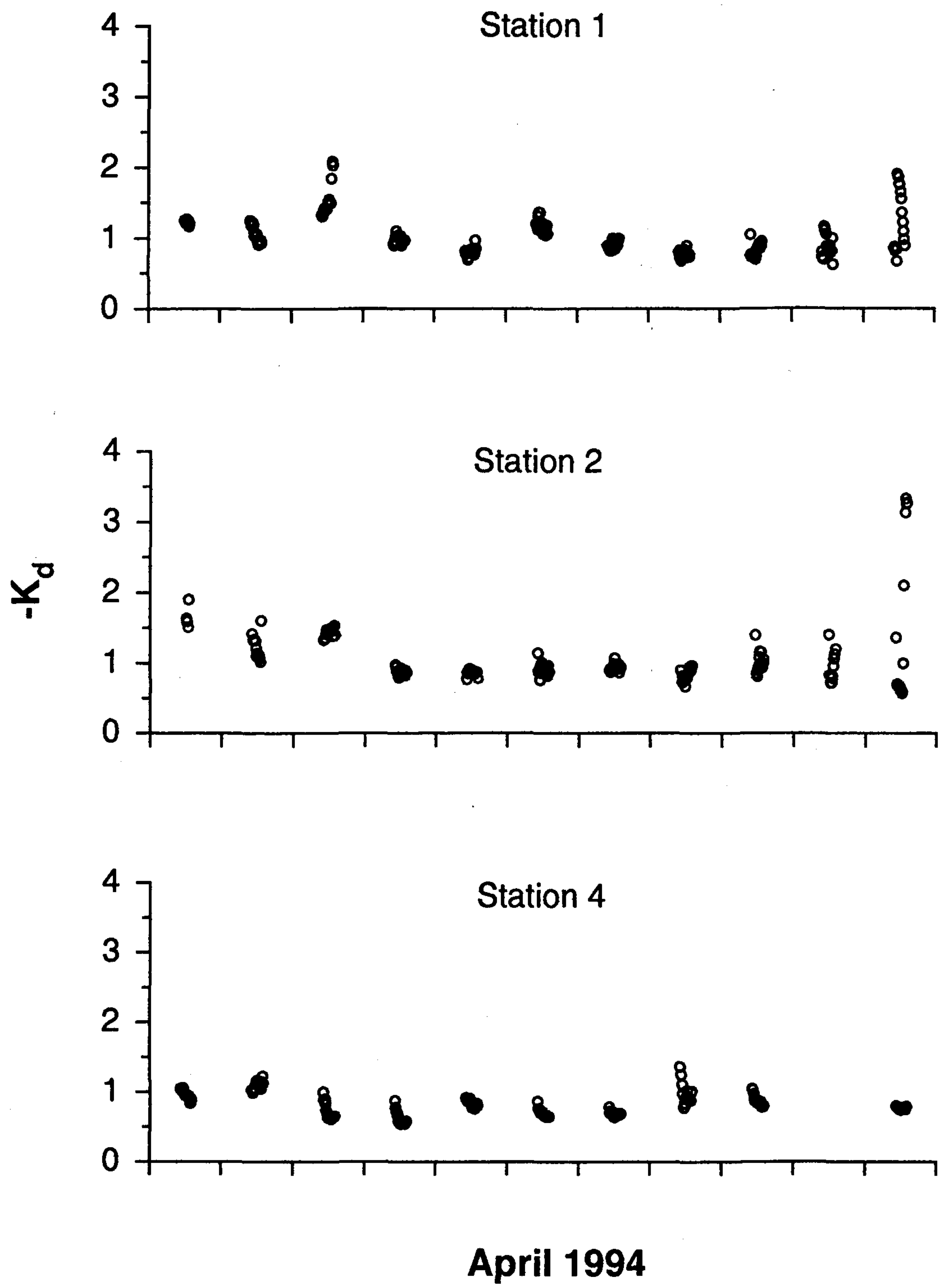
A33 : 15-minute integrated light attenuation (-K_d) at Goodwin Island, VA. August 1993.



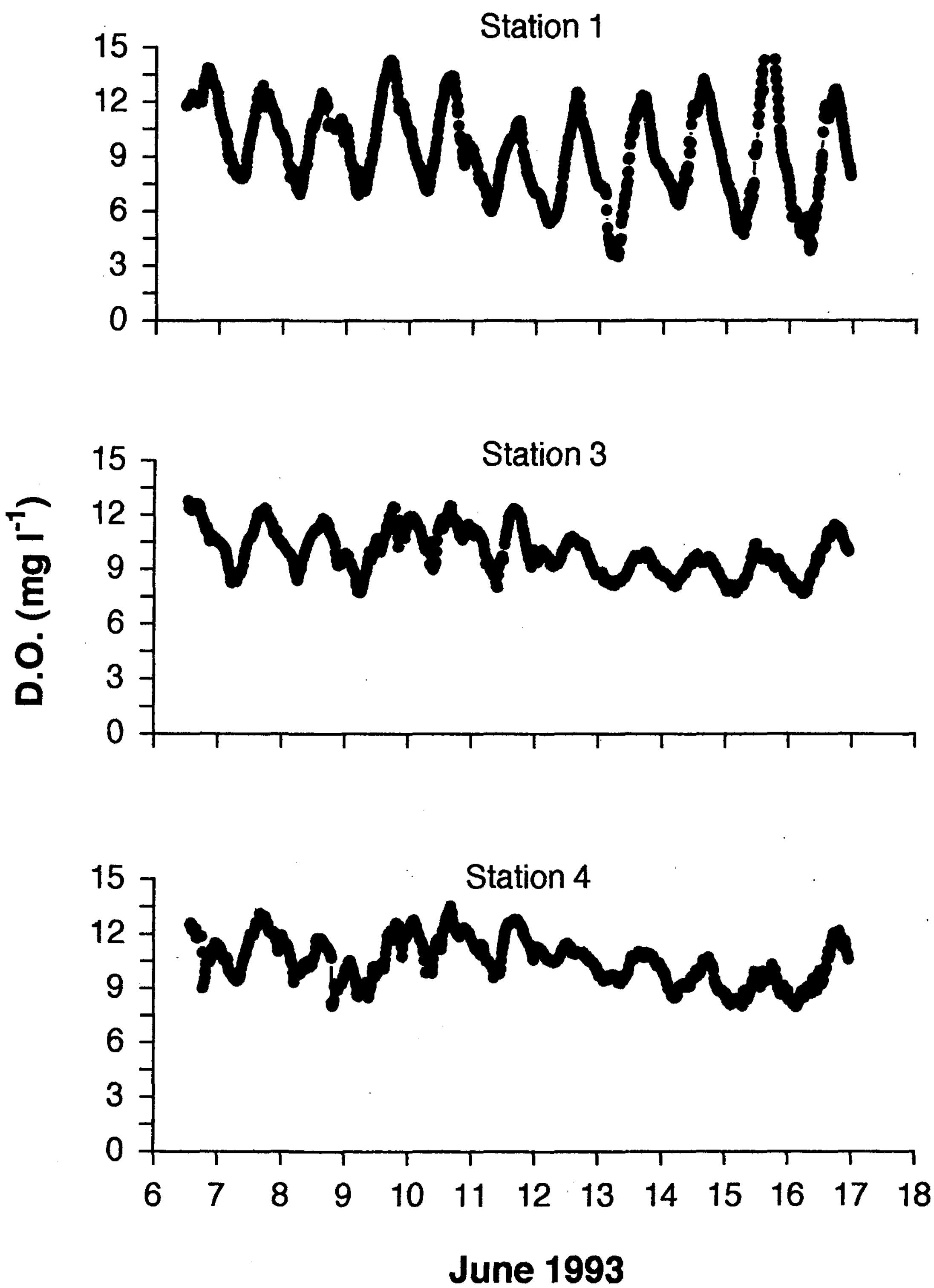
A34 : 15-minute integrated light attenuation ($-K_d$) at Goodwin Island, VA. October 1993.



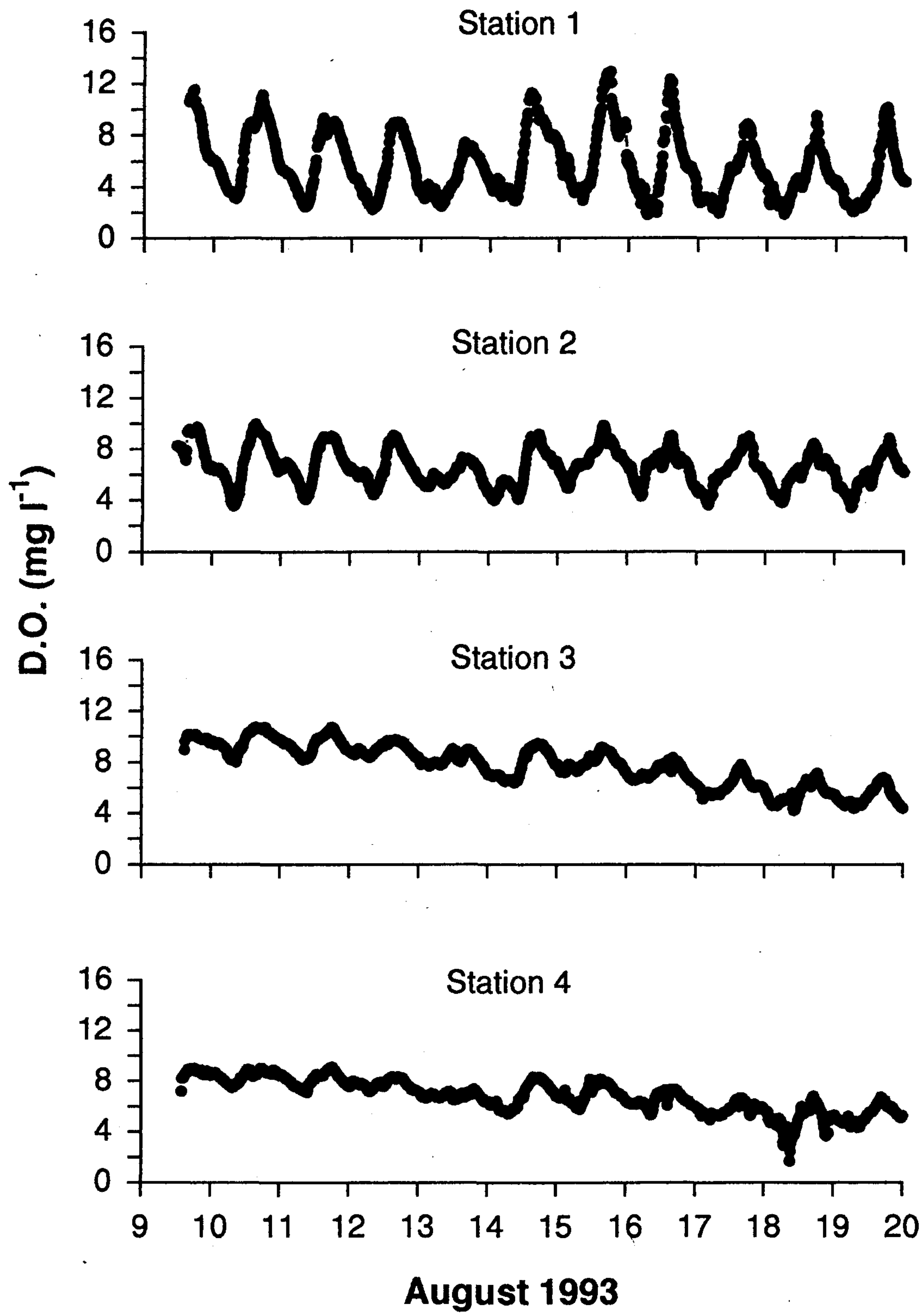
A35 : 15-minute integrated light attenuation ($-K_d$) at Goodwin Island, VA. April 1994.



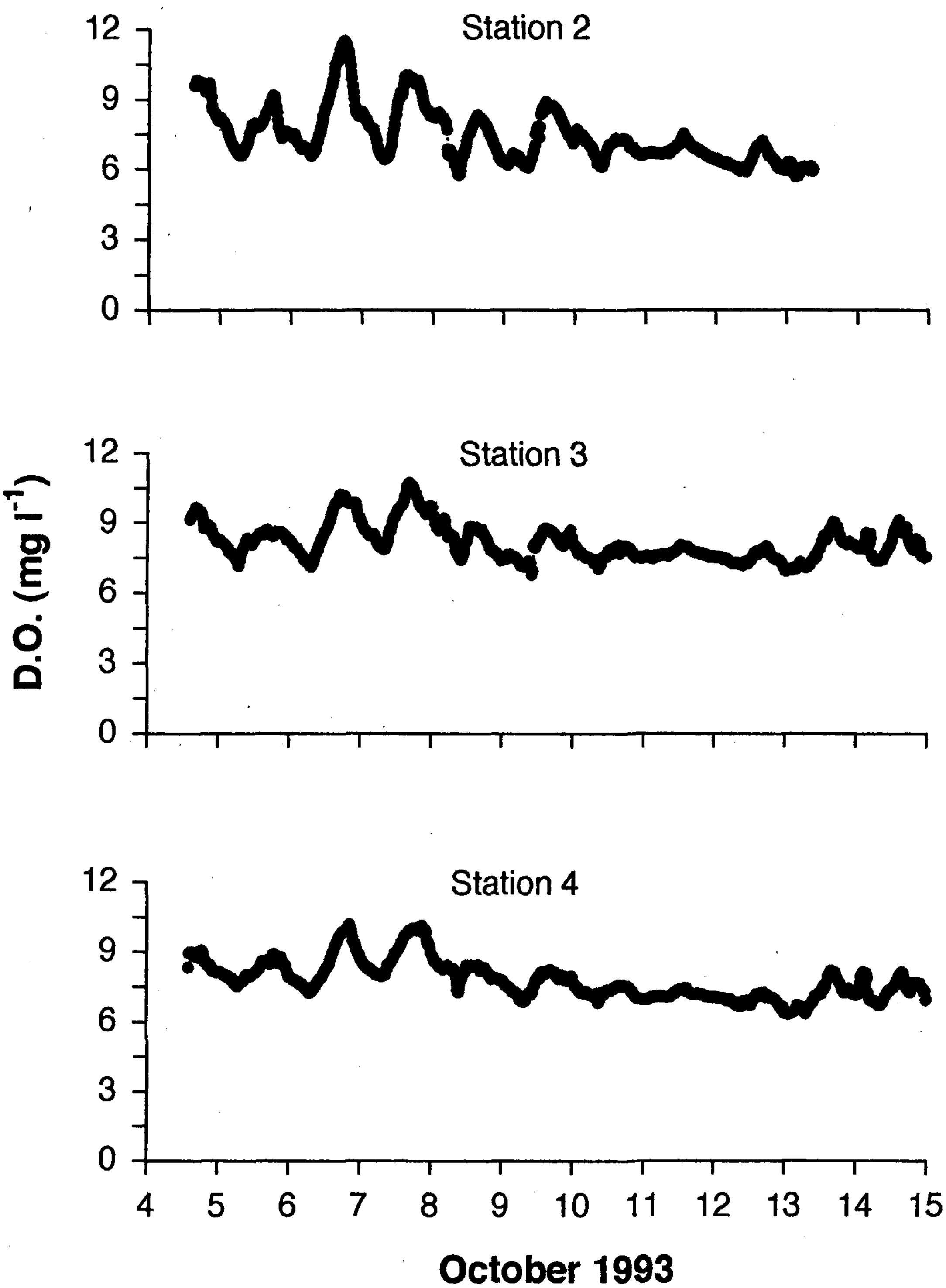
A36 : 15-minute dissolved oxygen (D.O.) at Goodwin Island, VA. June 1993.



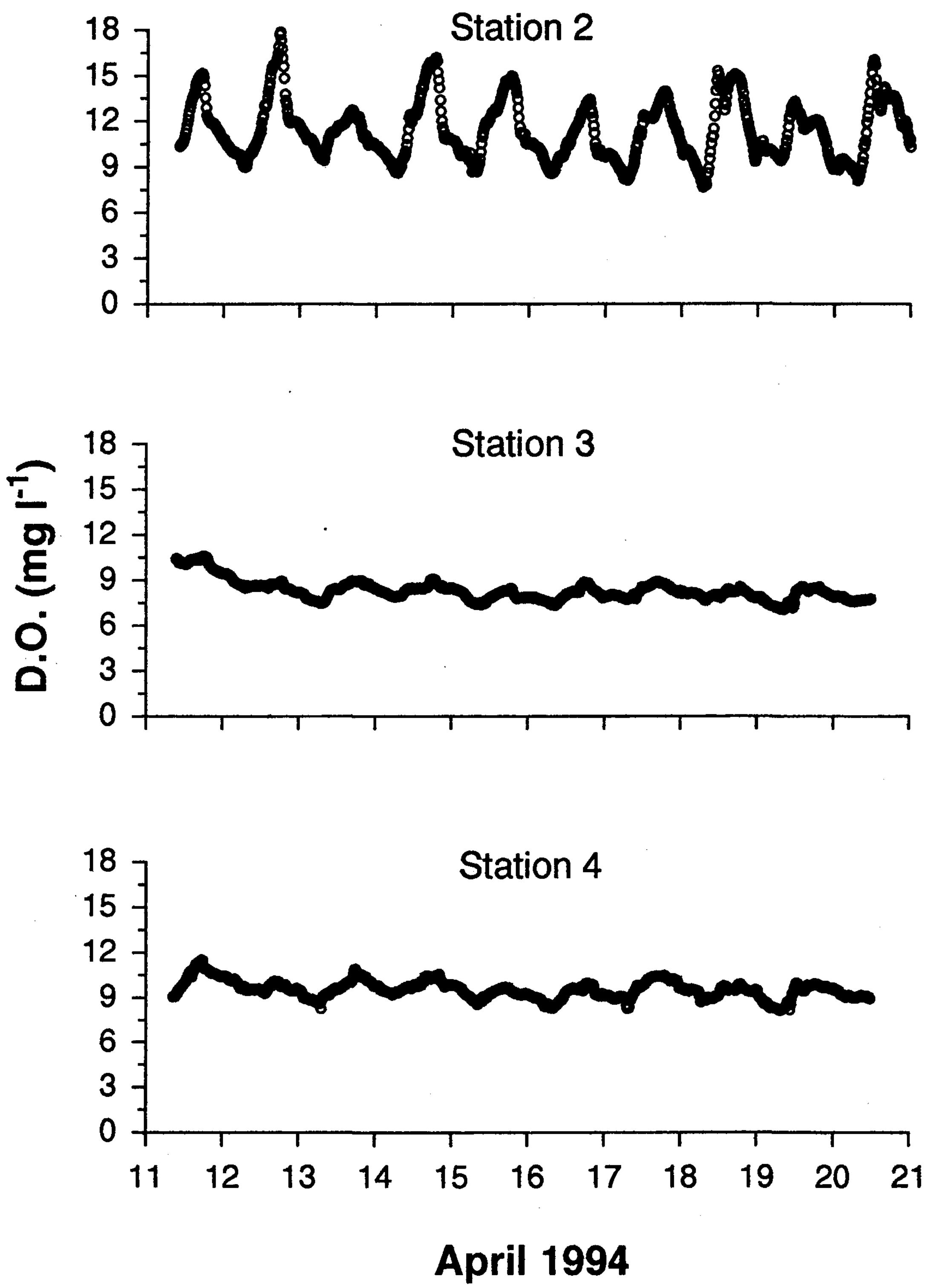
A37 : 15-minute dissolved oxygen (D.O.) at Goodwin Island, VA. August 1993.



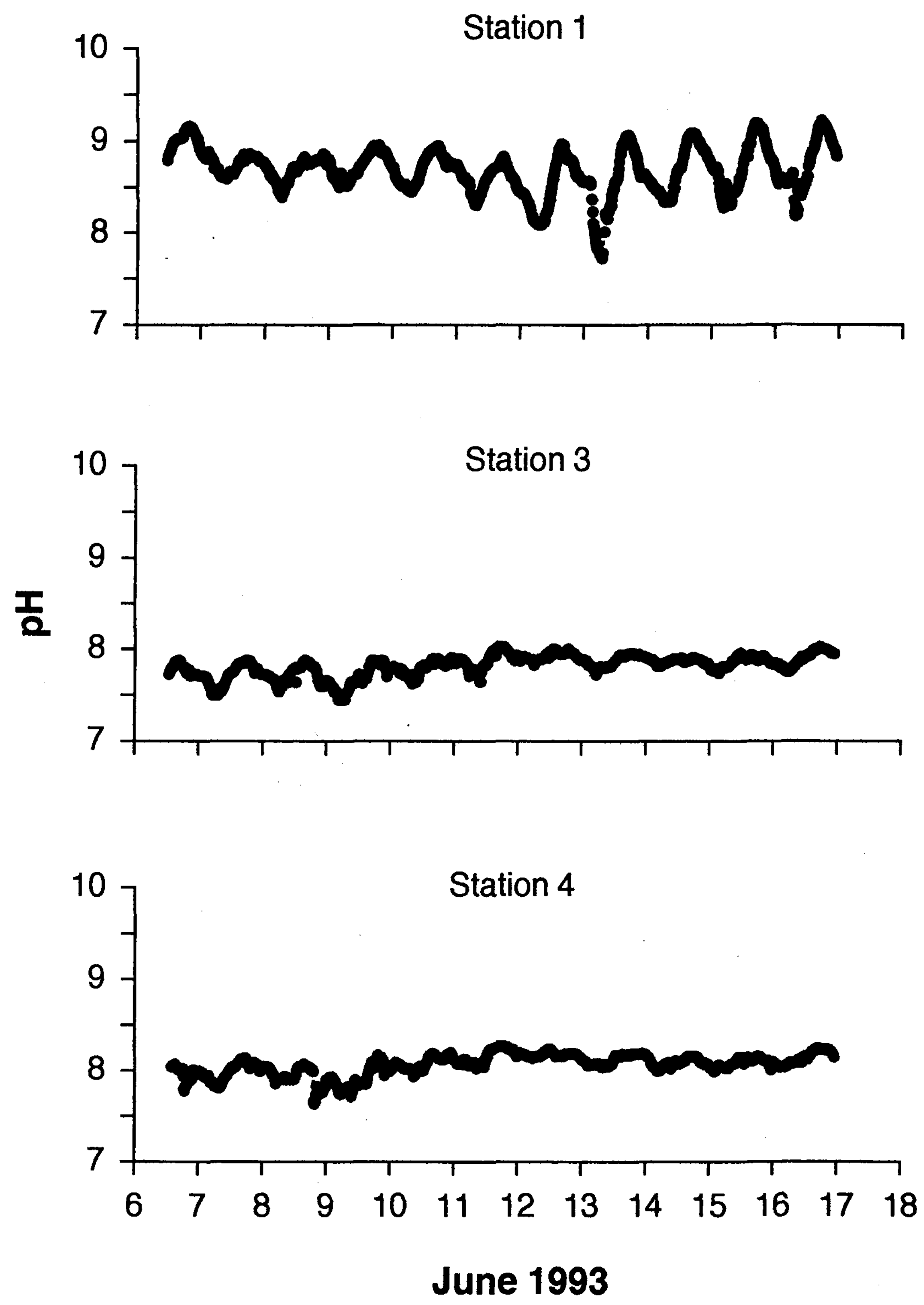
A38 : 15-minute dissolved oxygen (D.O.) at Goodwin Island, VA. October 1993.



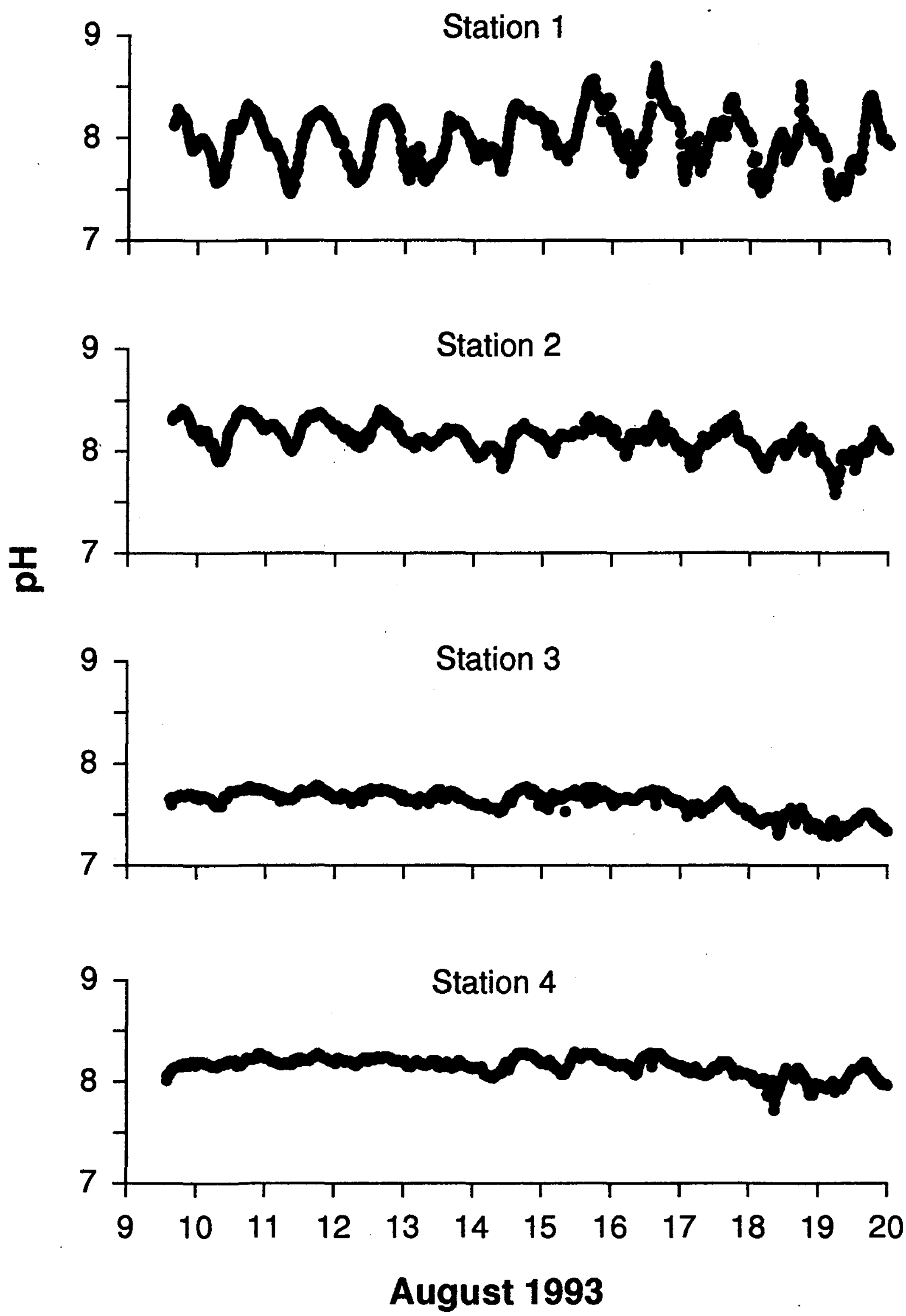
A39 : 15-minute dissolved oxygen (D.O.) at Goodwin Island, VA. April 1994.



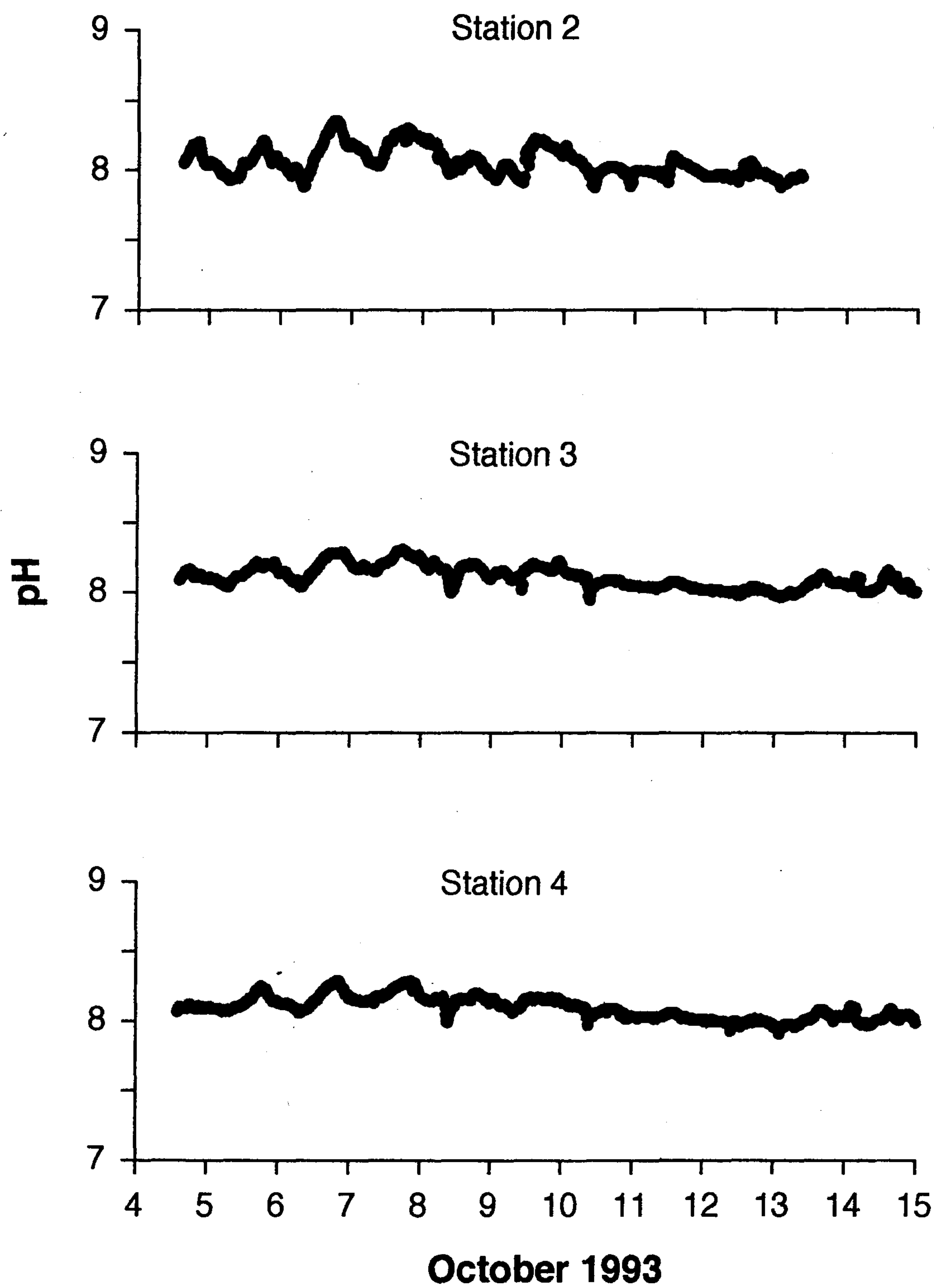
A40 : 15-minute pH measurements at Goodwin Island, VA. June 1993.



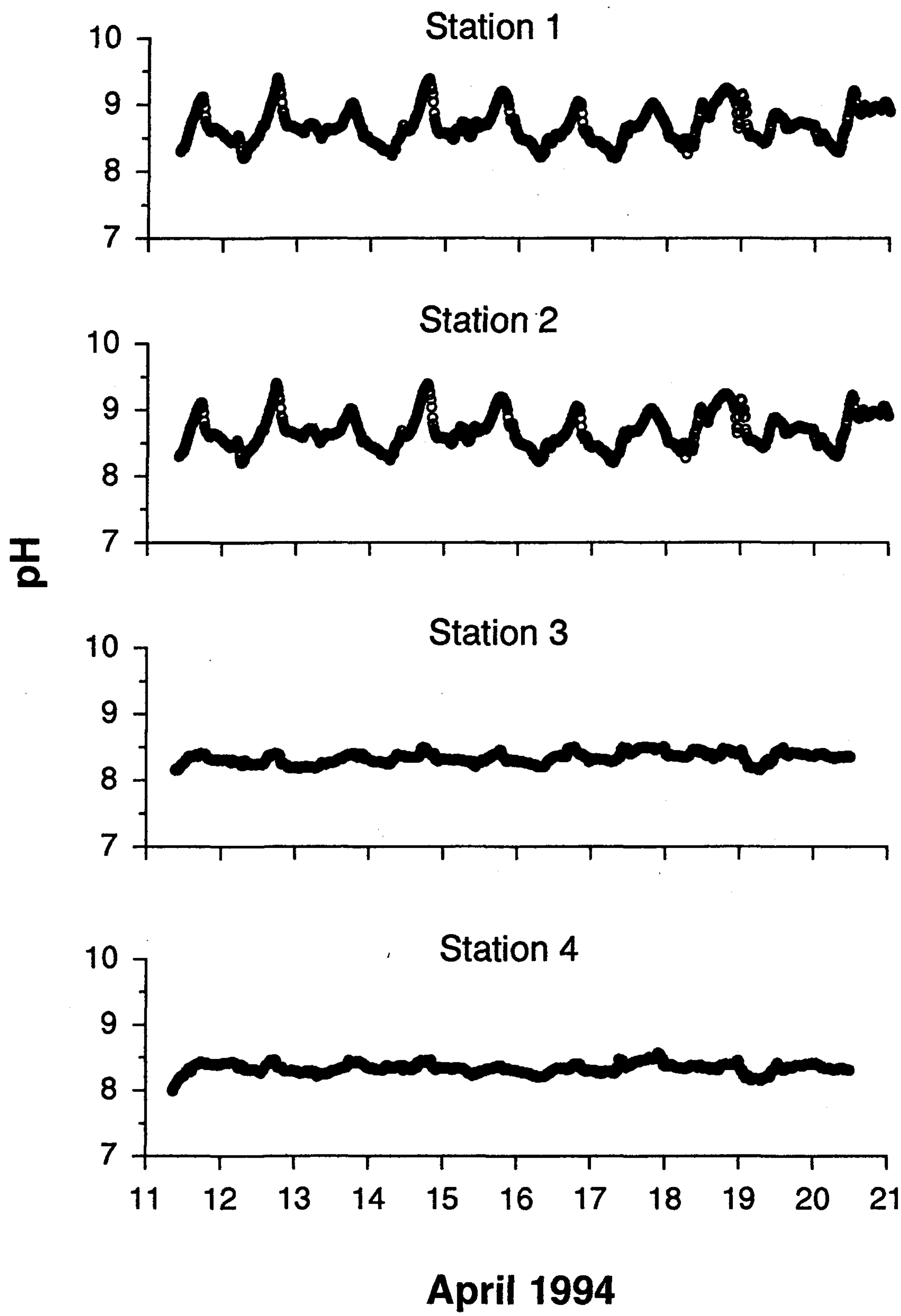
A41 : 15-minute pH measurements at Goodwin Island, VA. August 1993.



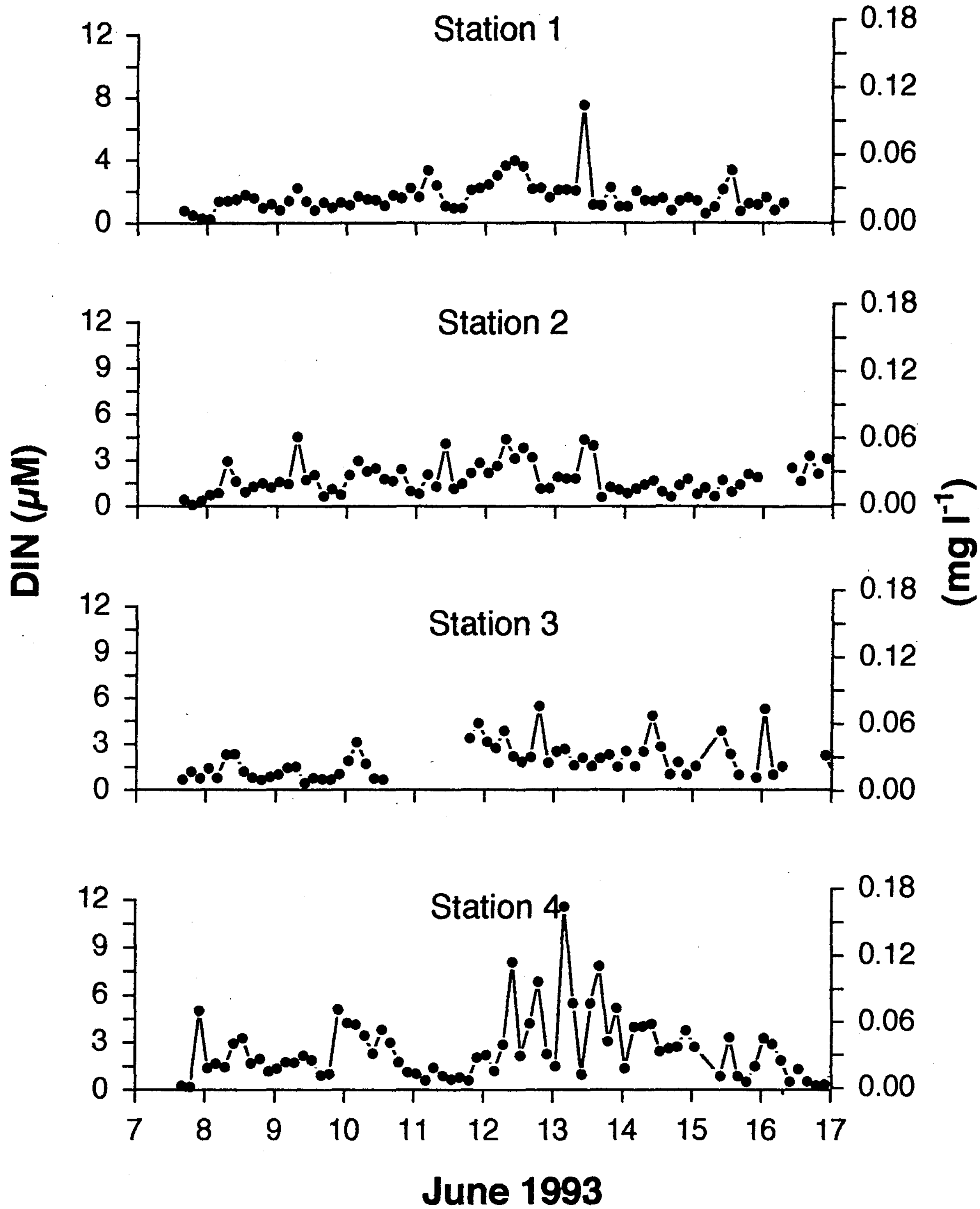
A42 : 15-minute pH measurements at Goodwin Island, VA. October 1993.



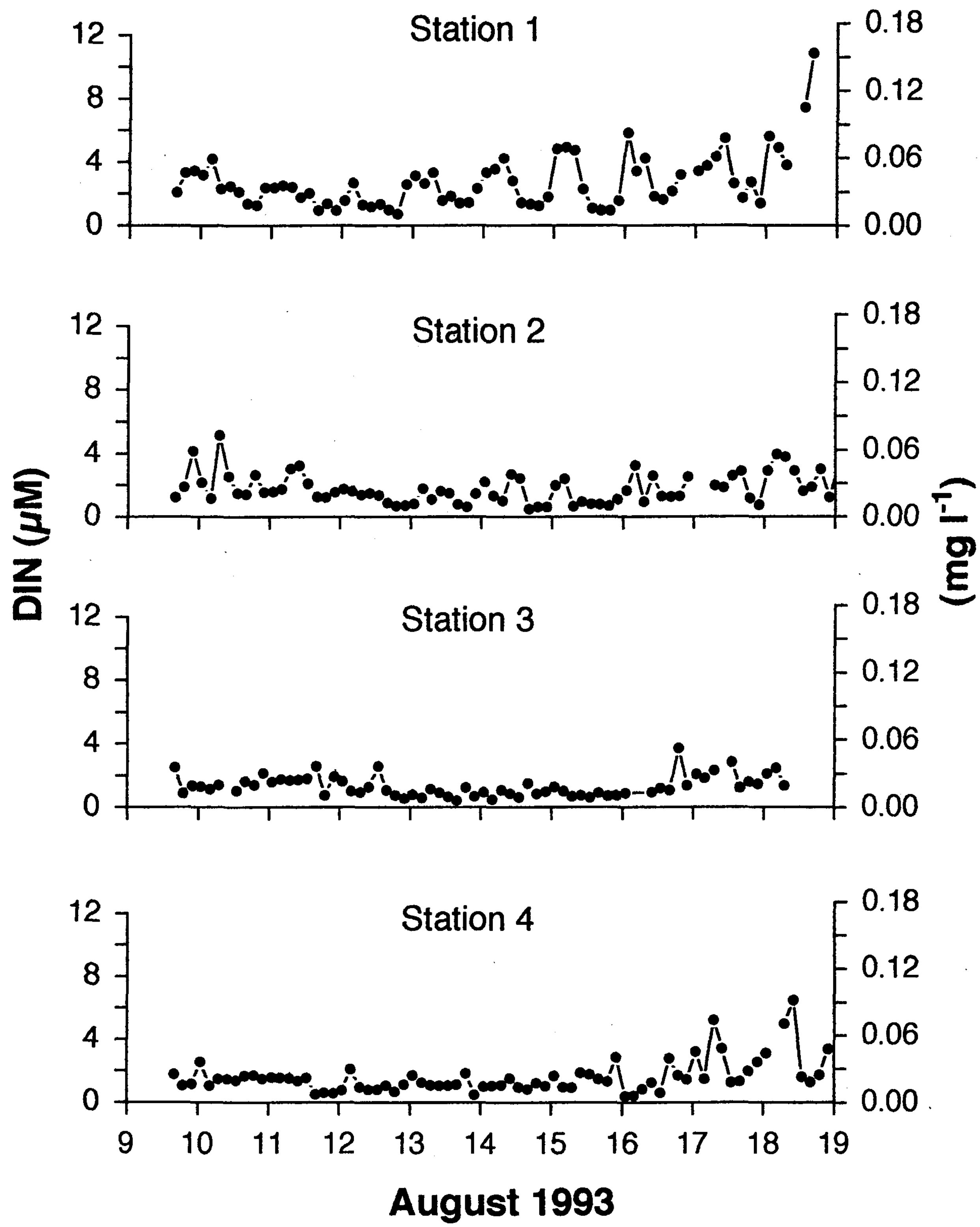
A43 : 15-minute pH measurements at Goodwin Island, VA. April 1994.



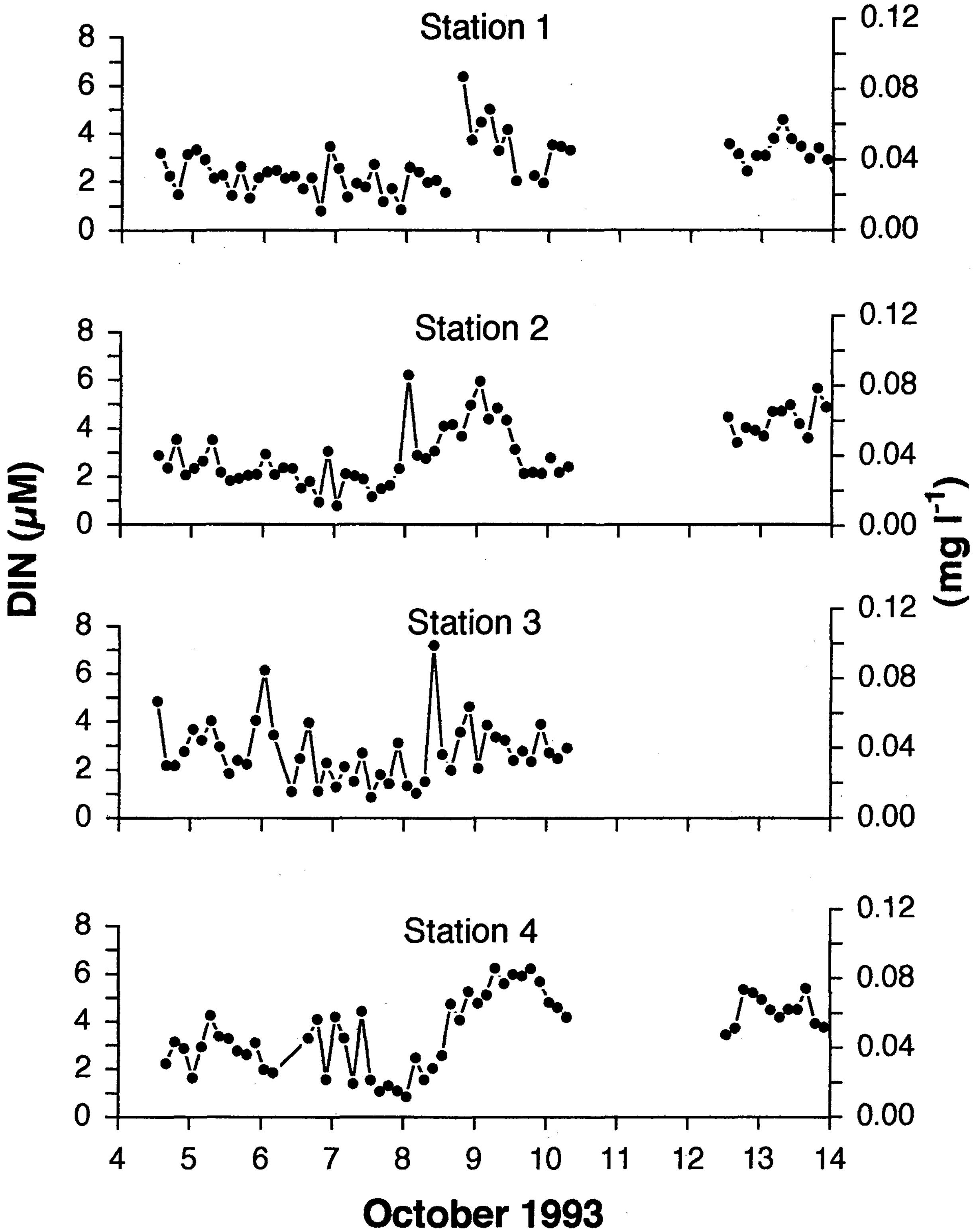
A44 : 3-hour dissolved inorganic nitrogen (DIN) at Goodwin Island, VA. June 1993.



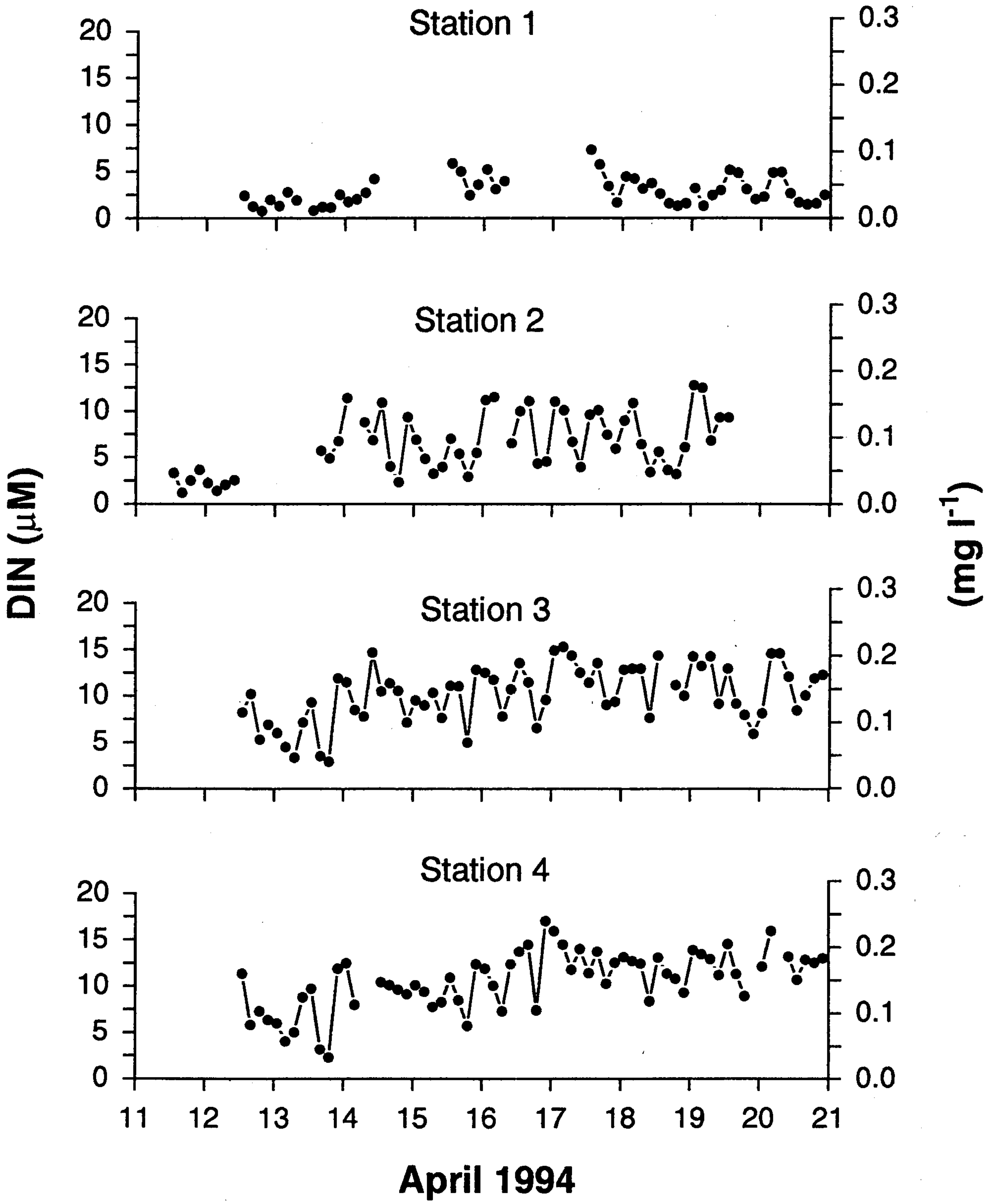
A45 : 3-hour dissolved inorganic nitrogen (DIN) at Goodwin Island, VA. August 1993.



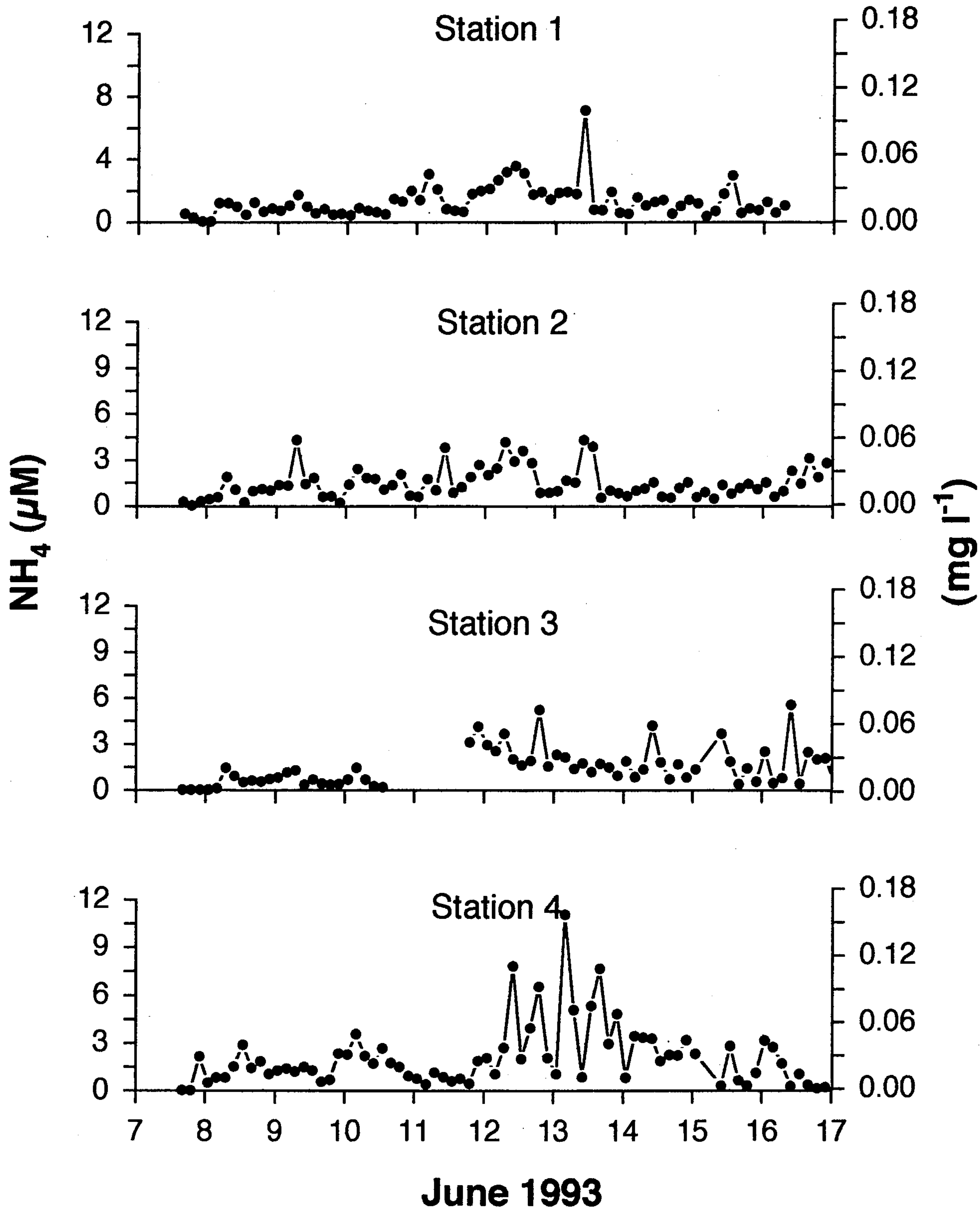
A46 : 3-hour dissolved inorganic nitrogen (DIN) at Goodwin Island, VA. October 1993.



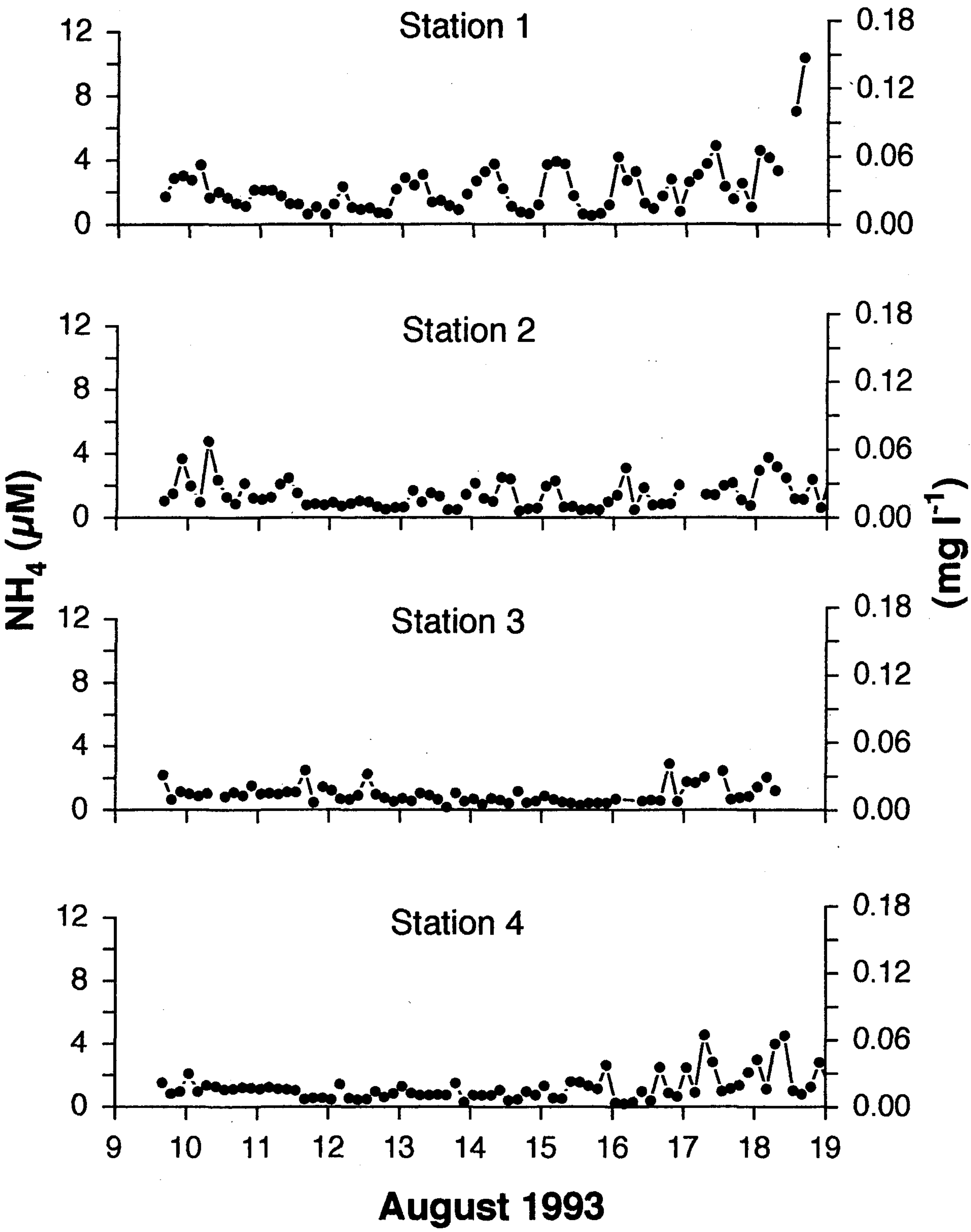
A47 : 3-hour dissolved inorganic nitrogen (DIN) at Goodwin Island, VA. April 1994.



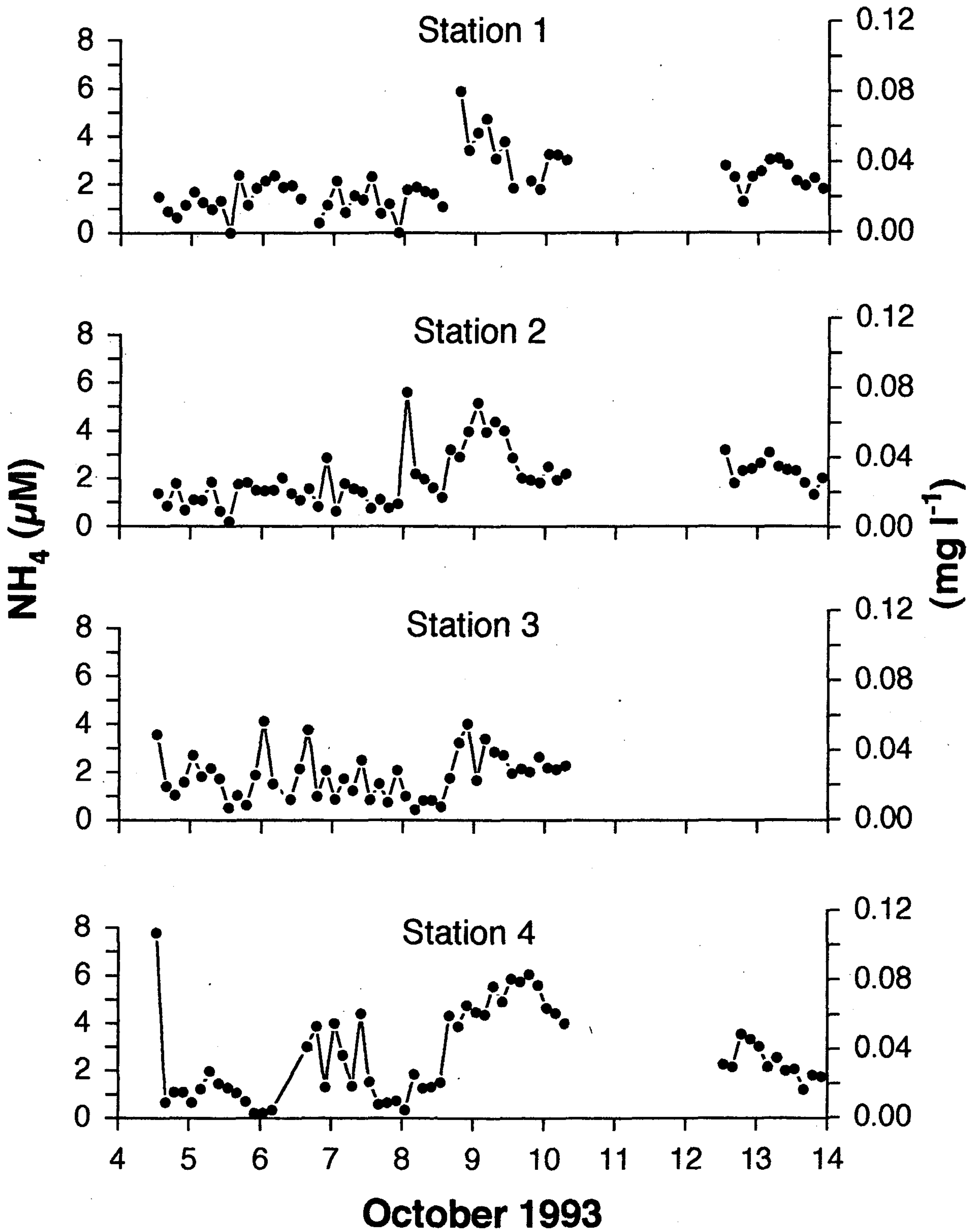
A48 : 3-hour ammonium (NH_4) at Goodwin Island, VA. June 1993.



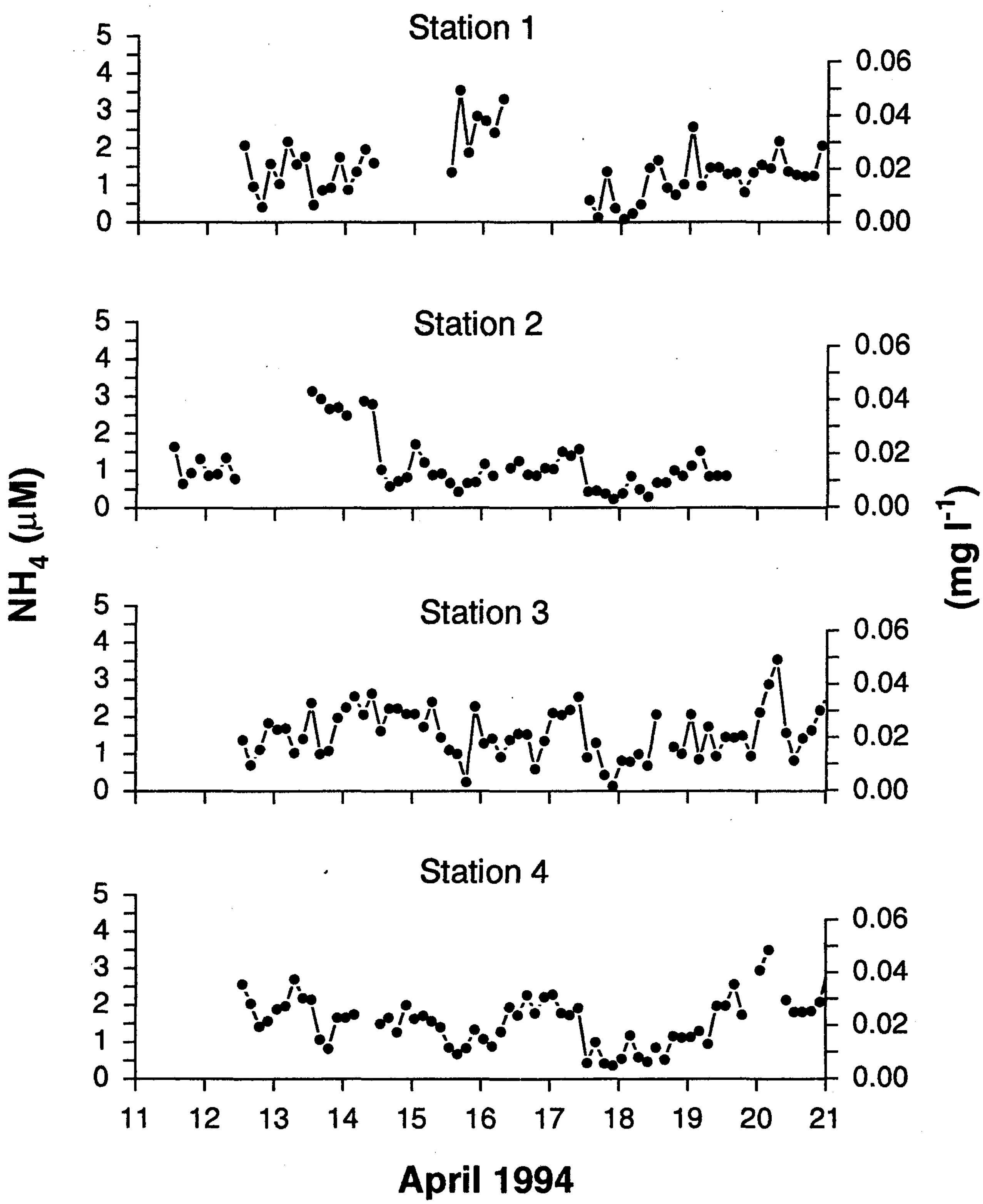
A49 : 3-hour ammonium (NH_4) at Goodwin Island, VA. August 1993.



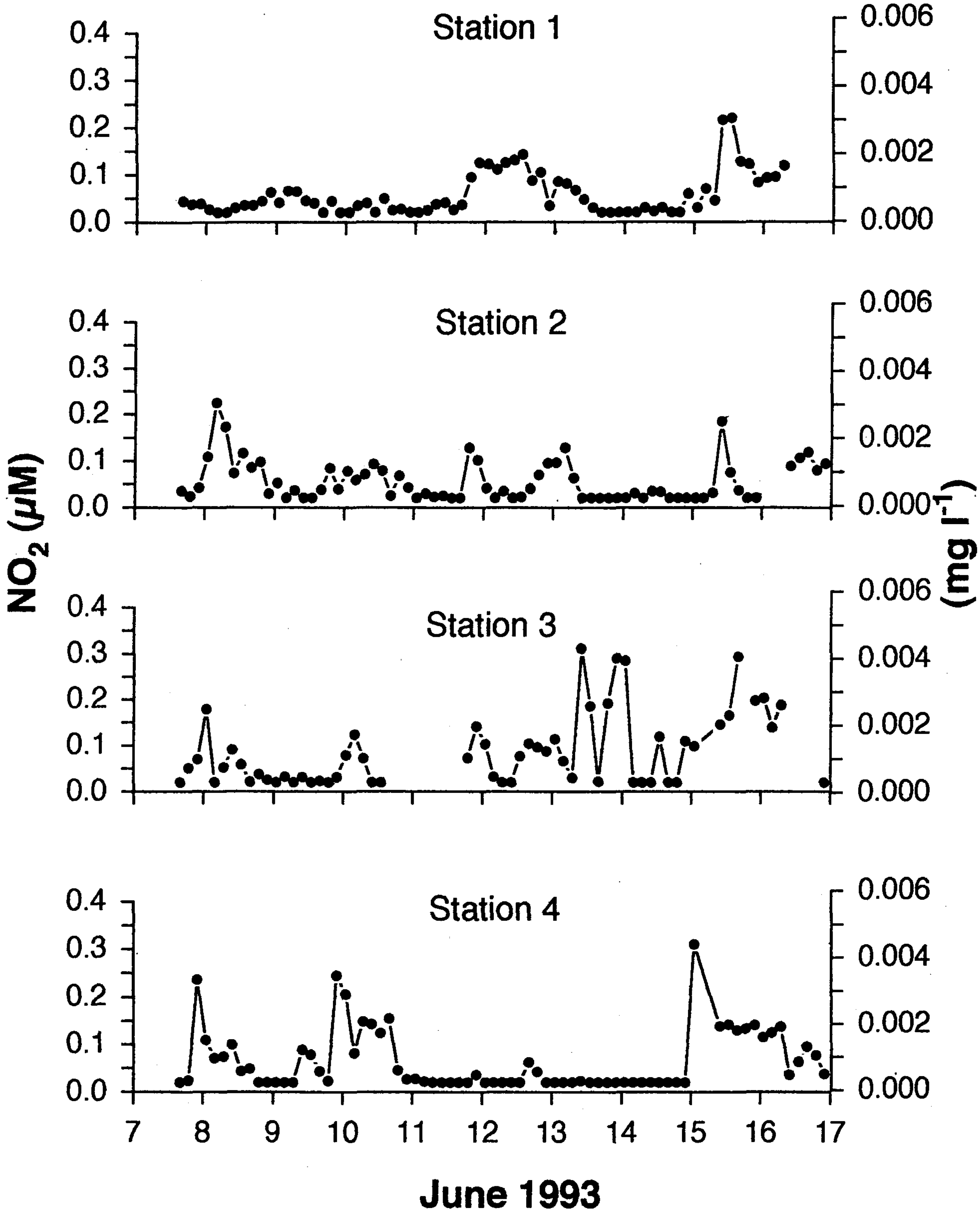
A50 : 3-hour ammonium (NH_4) at Goodwin Island, VA. October 1993.



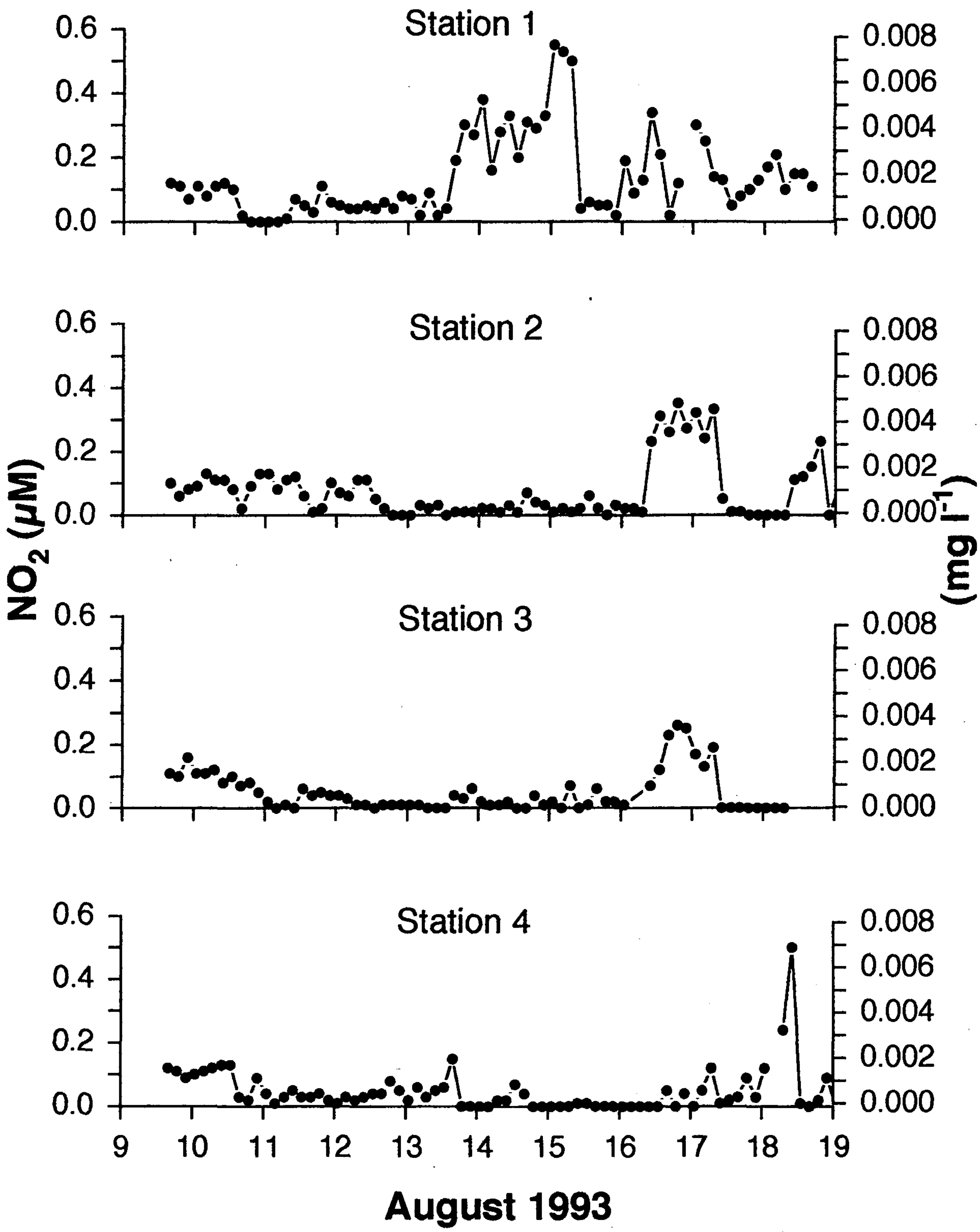
A51 : 3-hour ammonium (NH_4) at Goodwin Island, VA. April 1994.



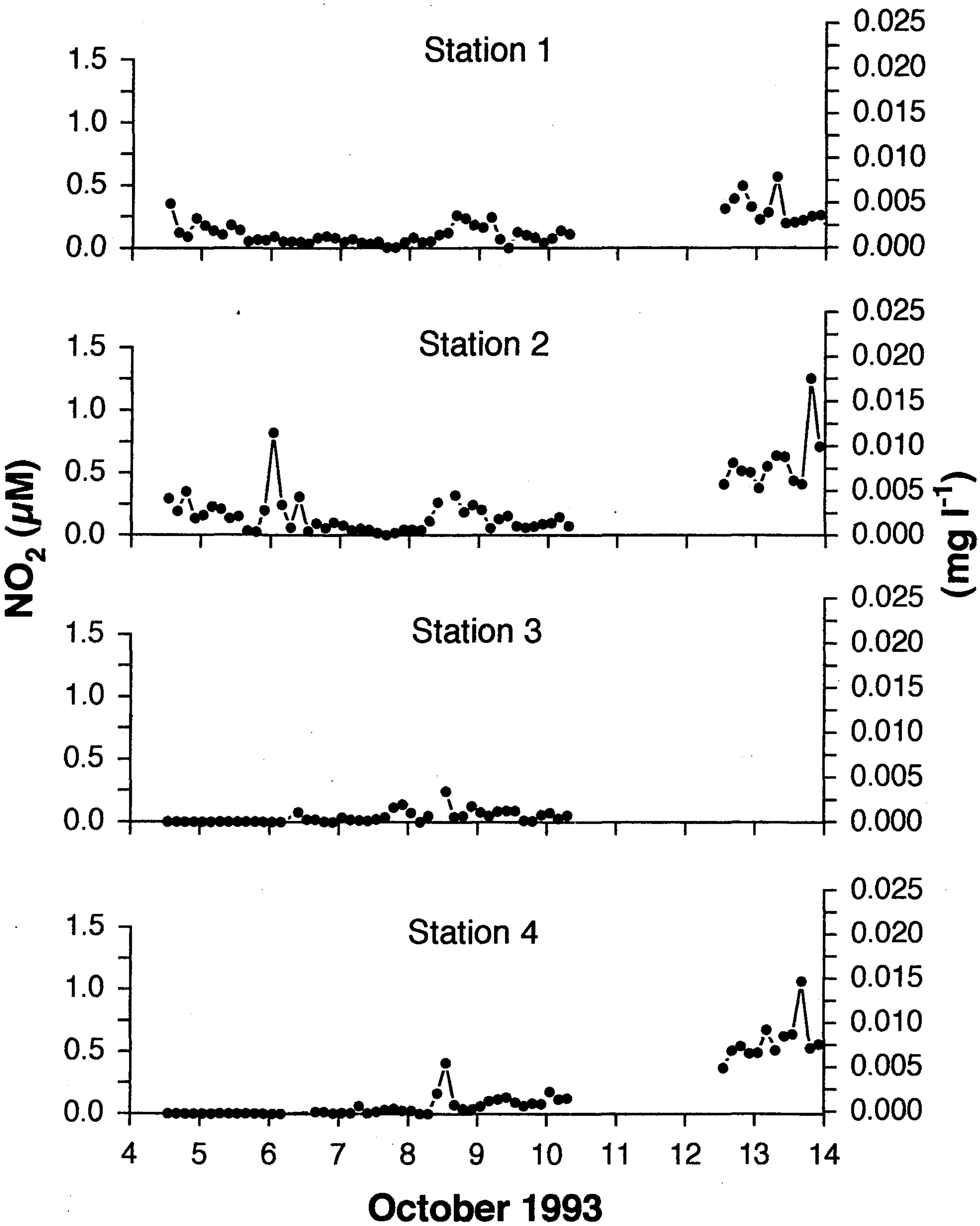
A52 : 3-hour nitrite (NO_2) at Goodwin Island, VA. June 1993.



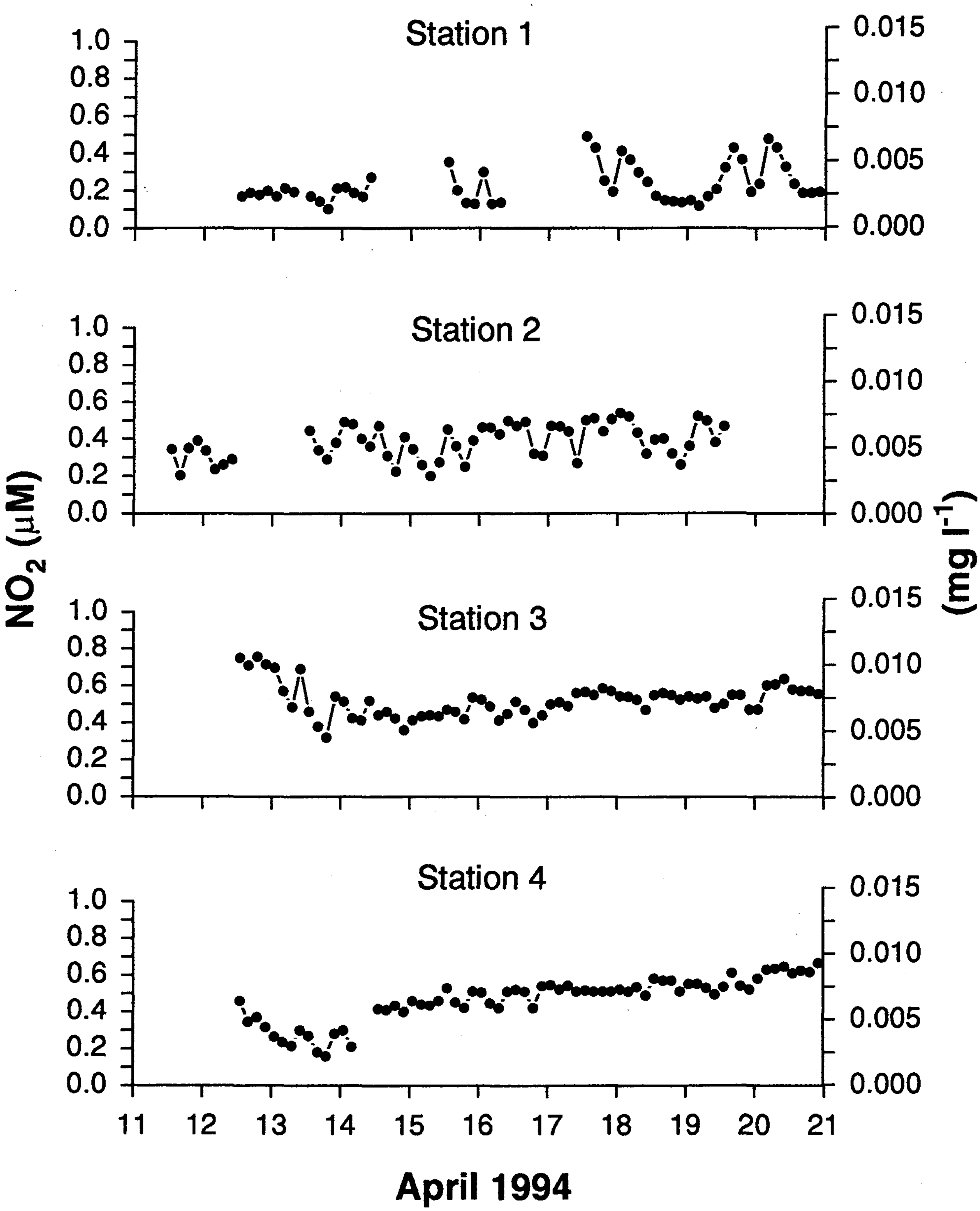
A53 : 3-hour nitrite (NO_2) at Goodwin Island, VA. August 1993.



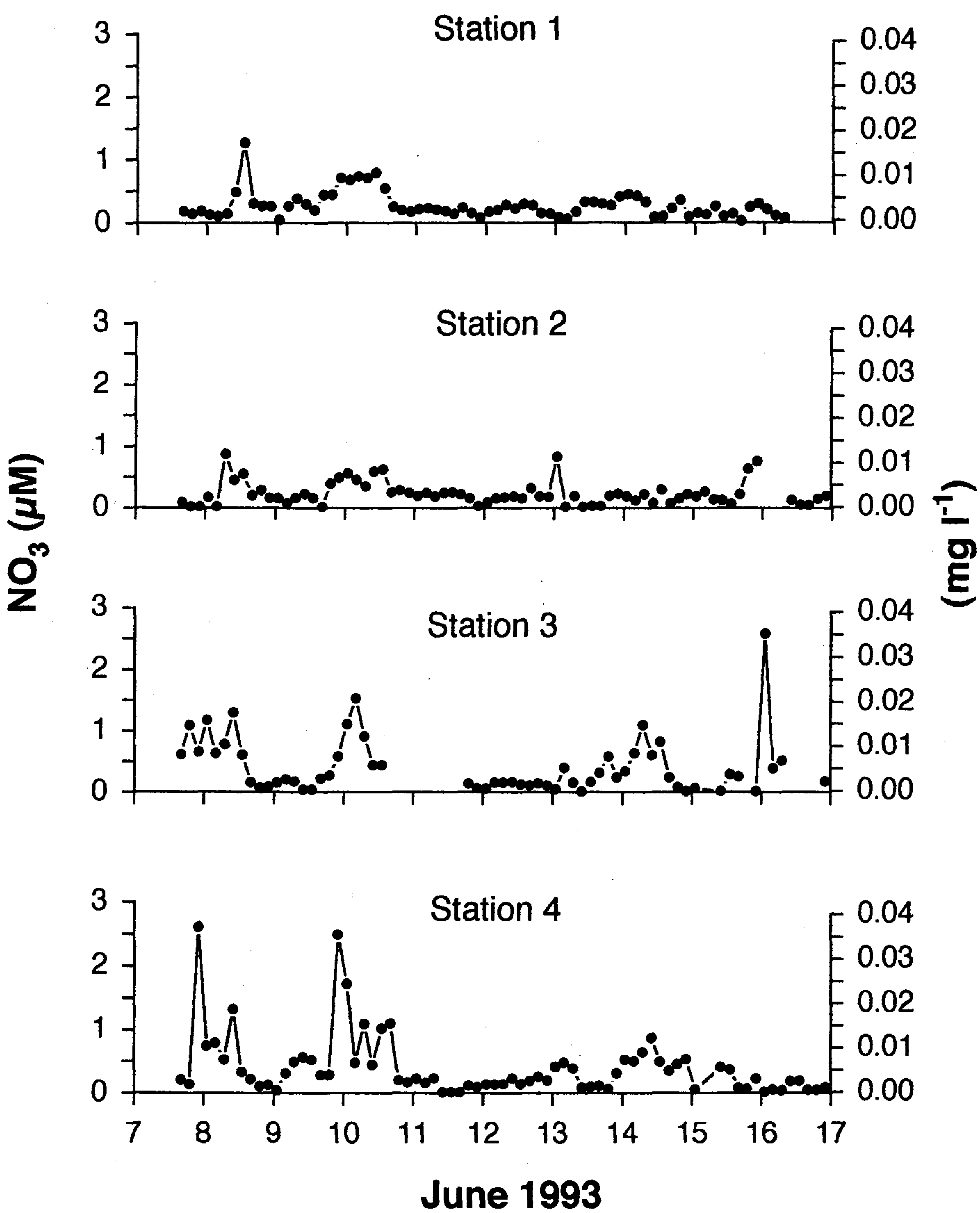
A54 : 3-hour nitrite (NO_2) at Goodwin Island, VA. October 1993.



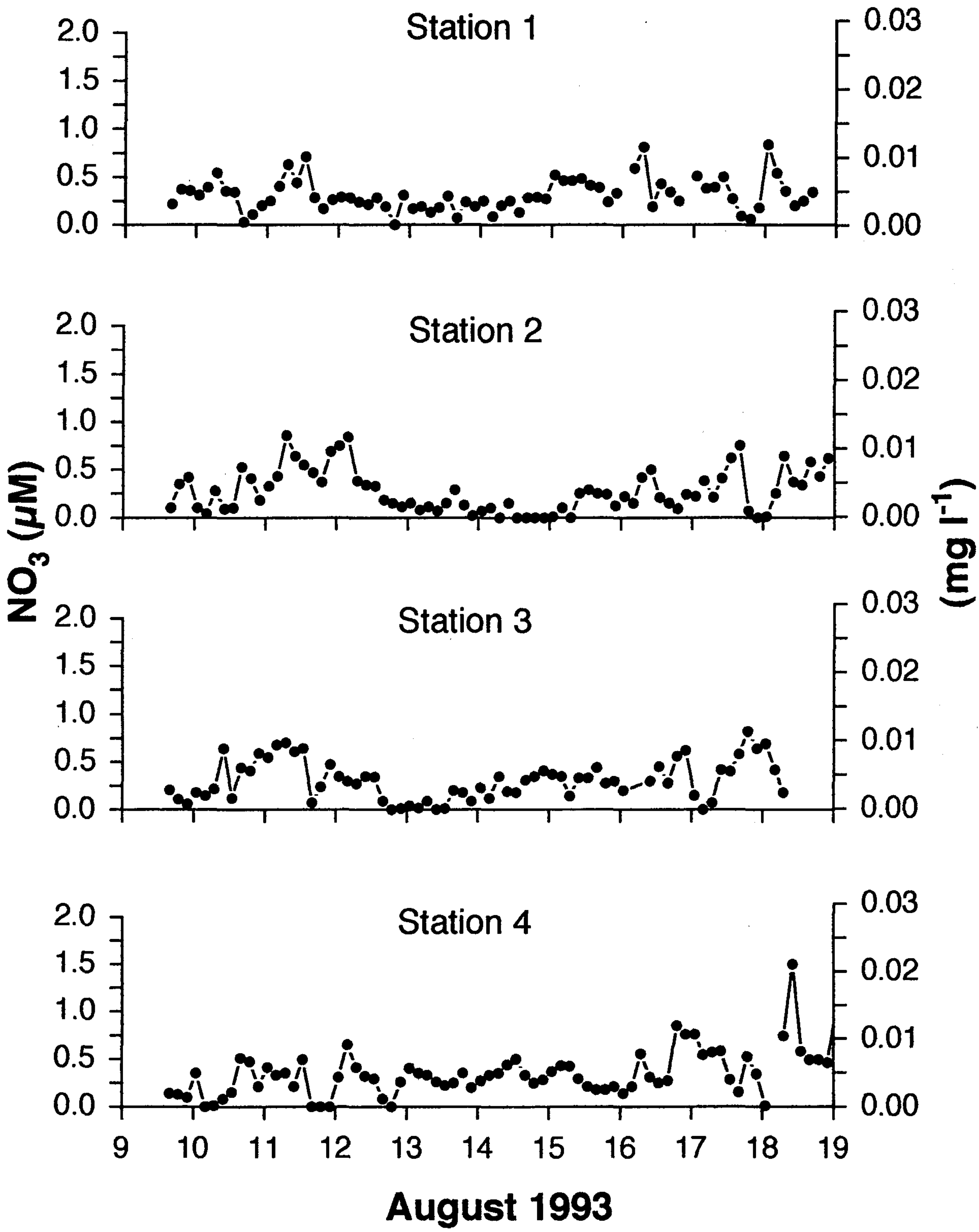
A55 : 3-hour nitrite (NO_2) at Goodwin Island, VA. April 1994.



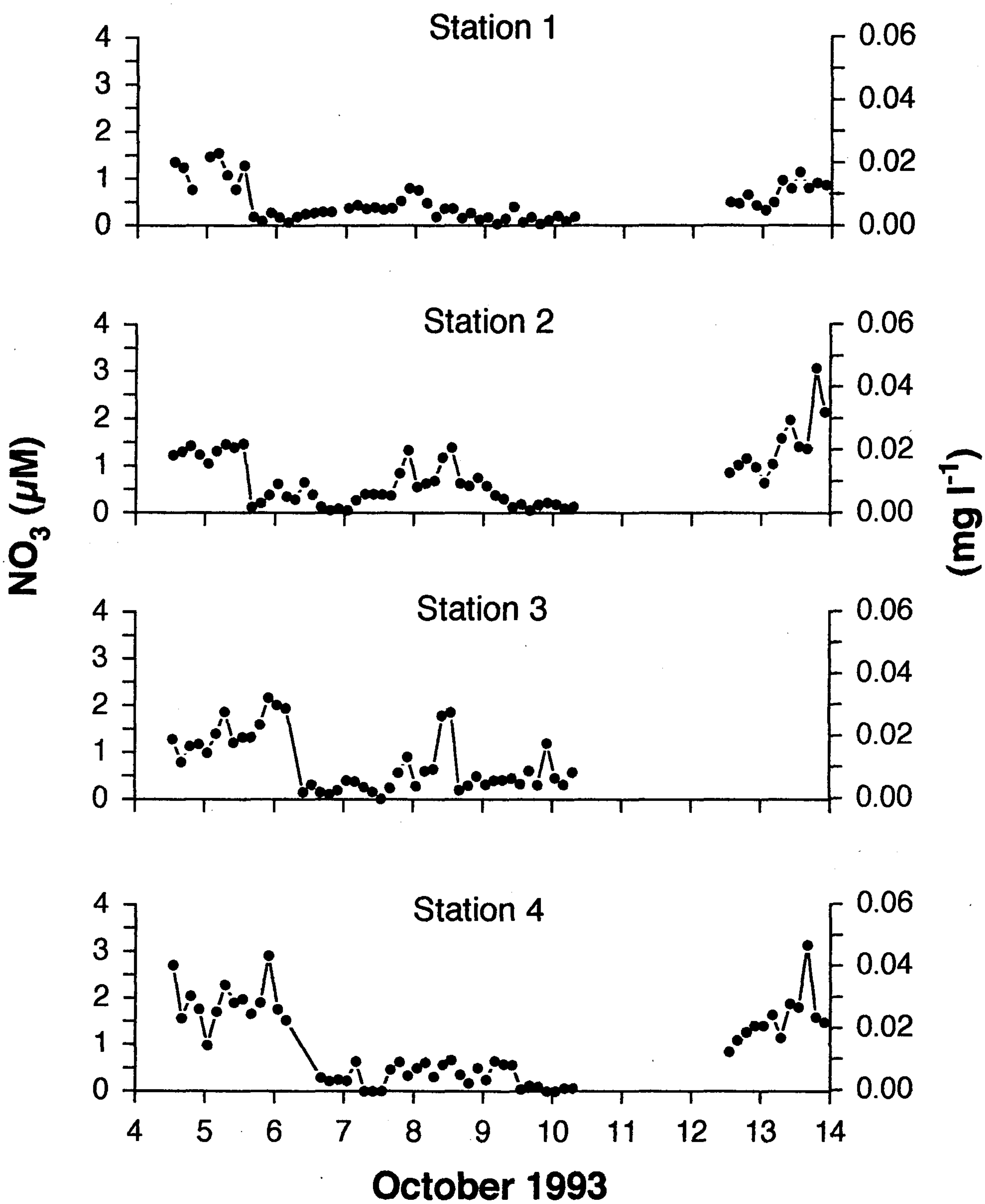
A56 : 3-hour nitrate (NO_3) at Goodwin Island, VA. June 1993.



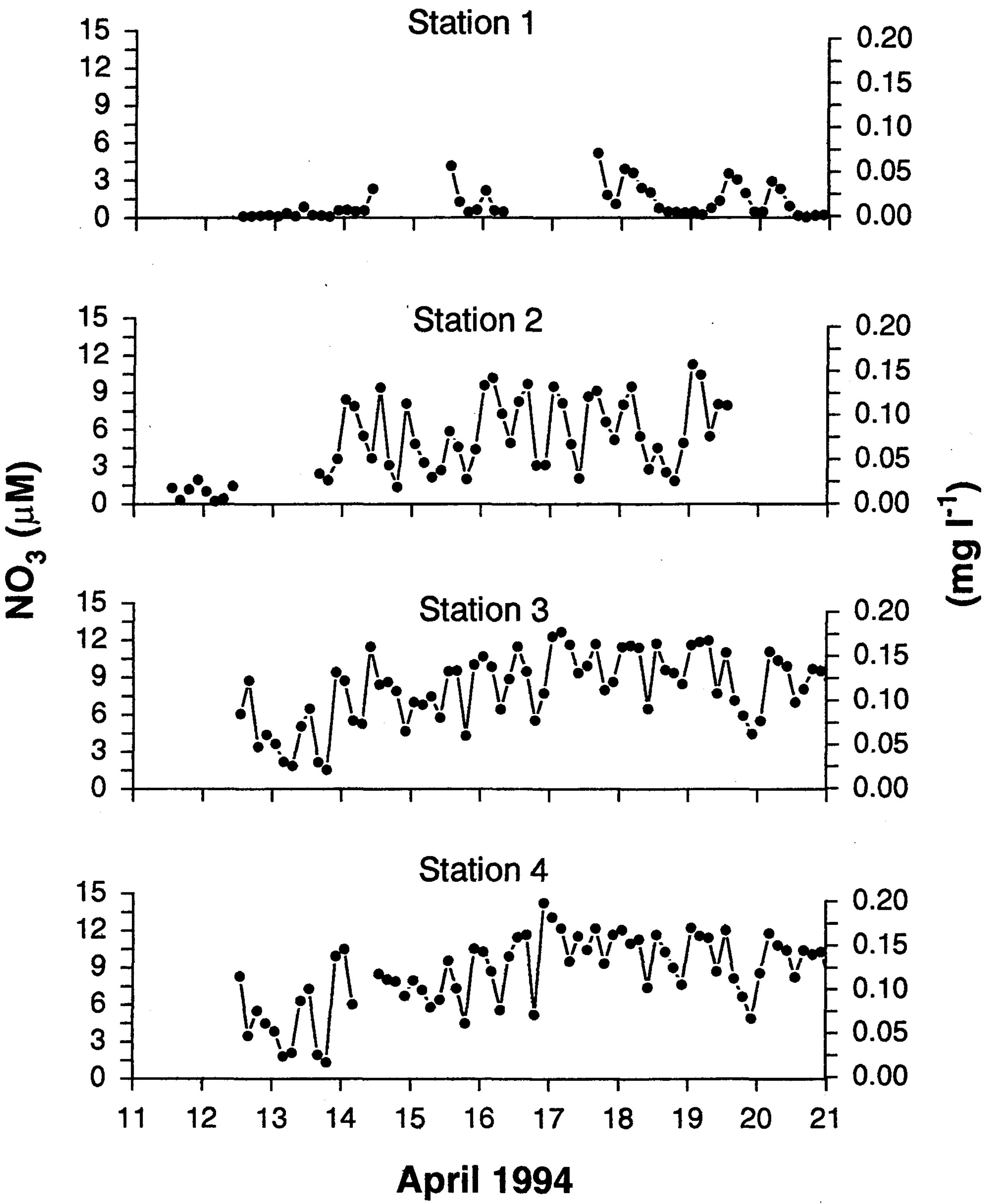
A57 : 3-hour nitrate (NO_3) at Goodwin Island, VA. August 1993.



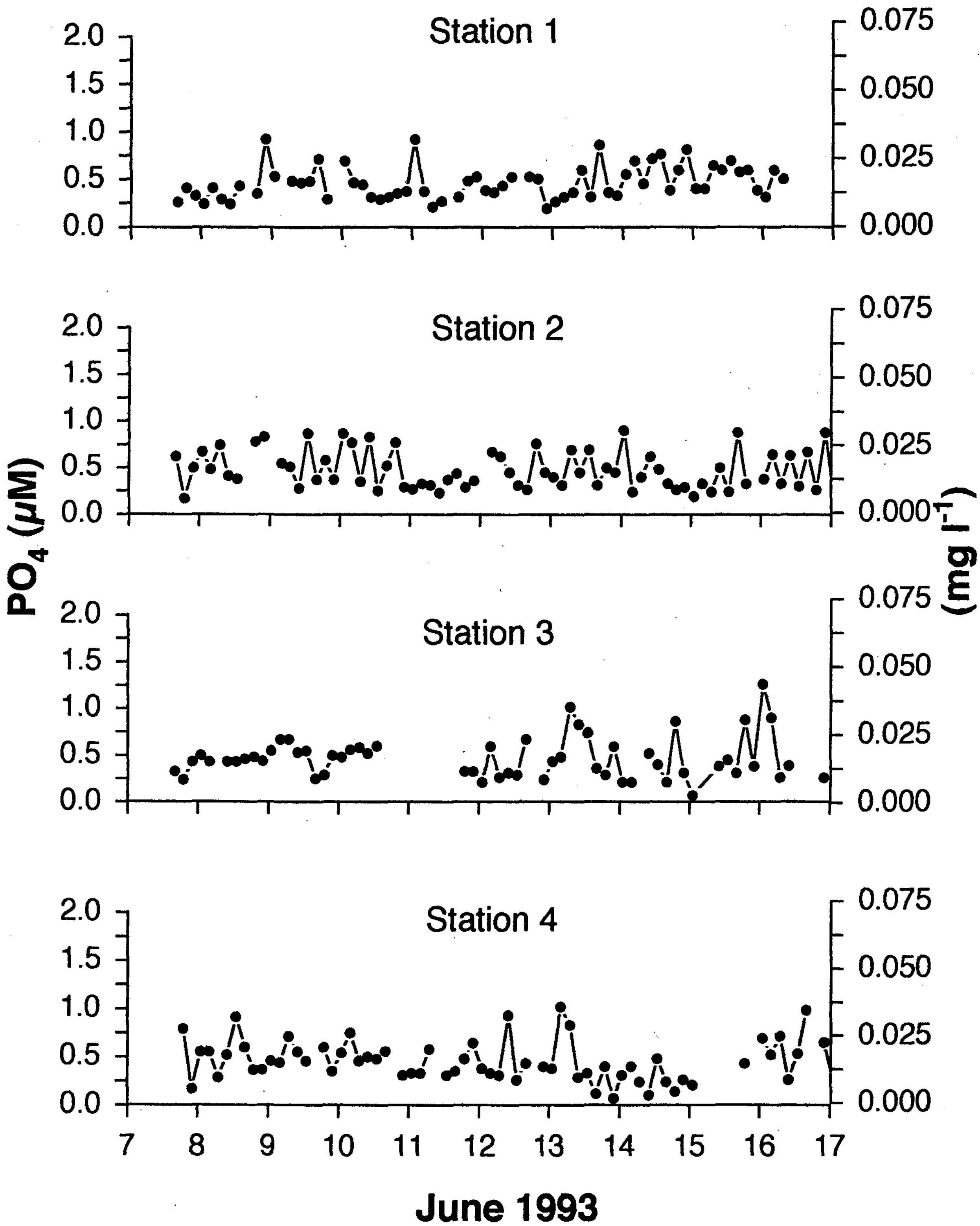
A58 : 3-hour nitrate (NO_3) at Goodwin Island, VA. October 1993



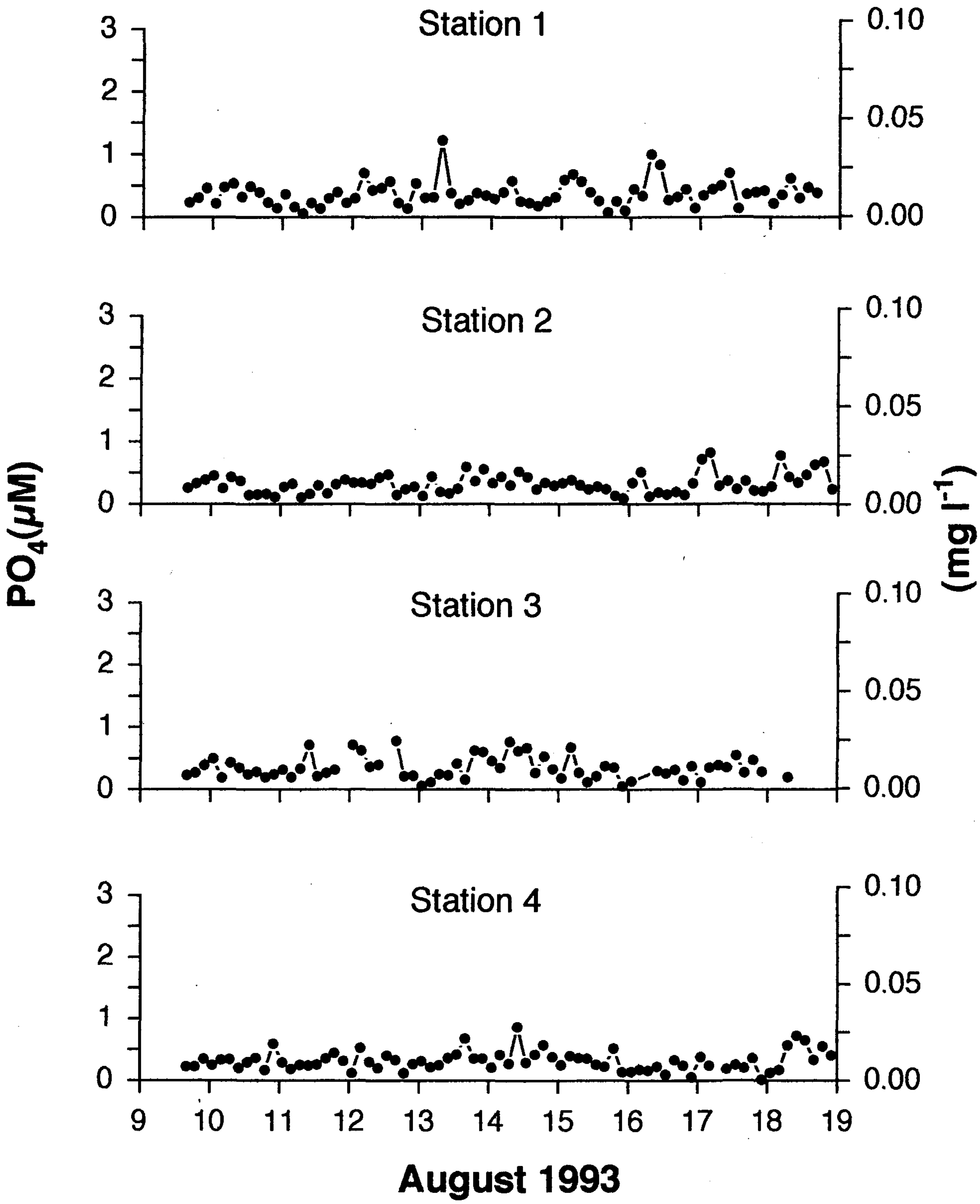
A59 : 3-hour nitrate (NO_3) at Goodwin Island, VA. April 1994.



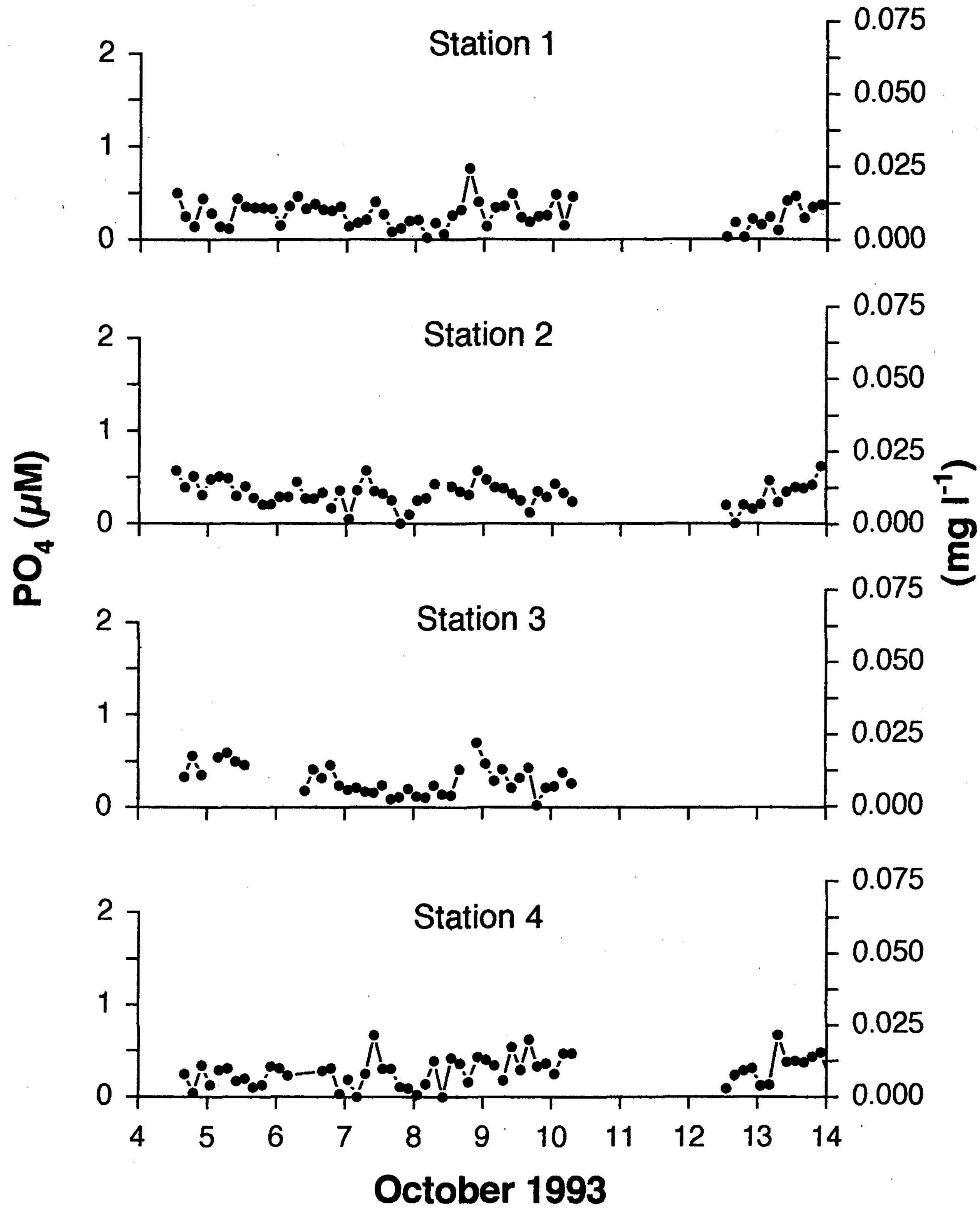
A60 : 3-hour orthophosphate (PO_4) at Goodwin Island, VA. June 1993.



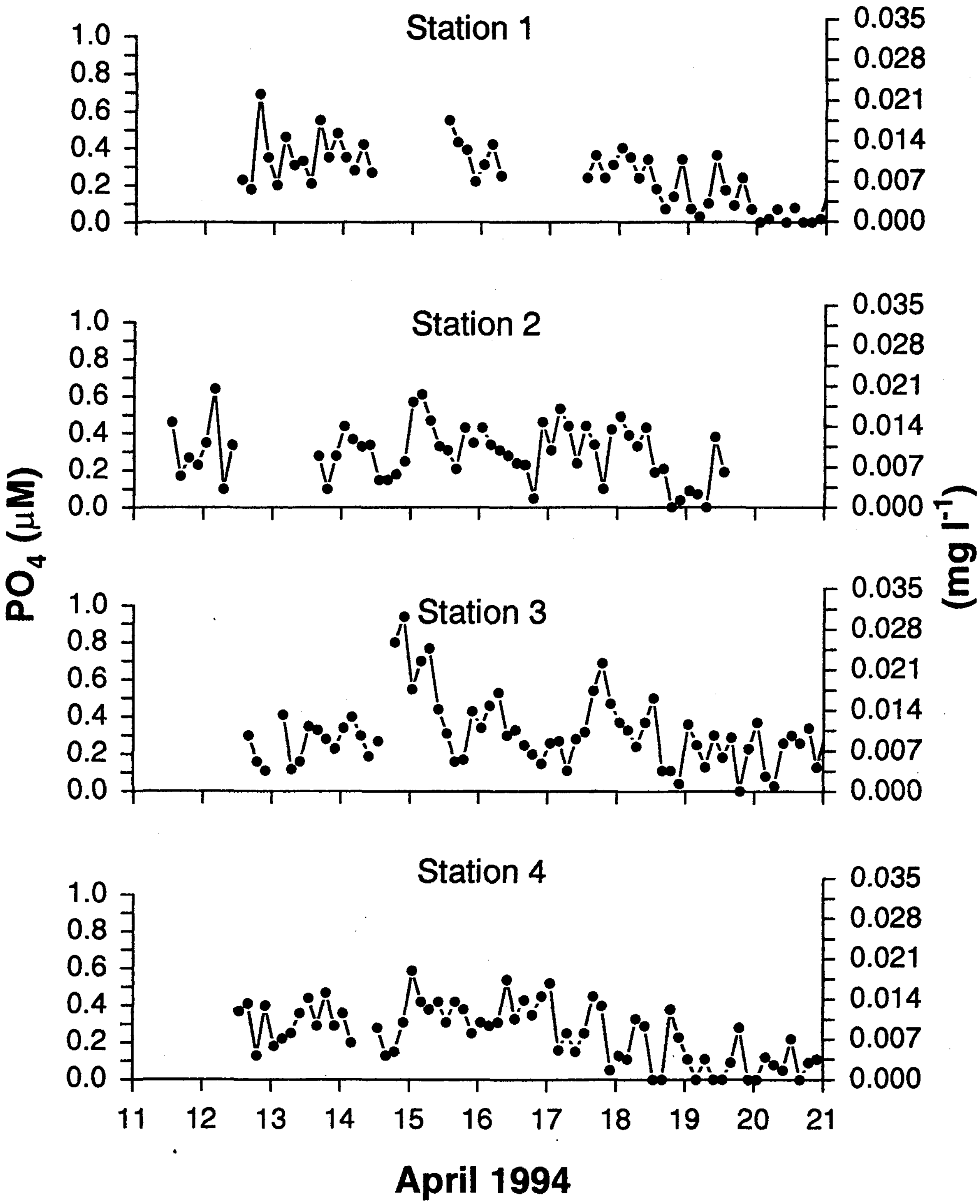
A61 : 3-hour orthophosphate (PO_4) at Goodwin Island, VA. August 1993.



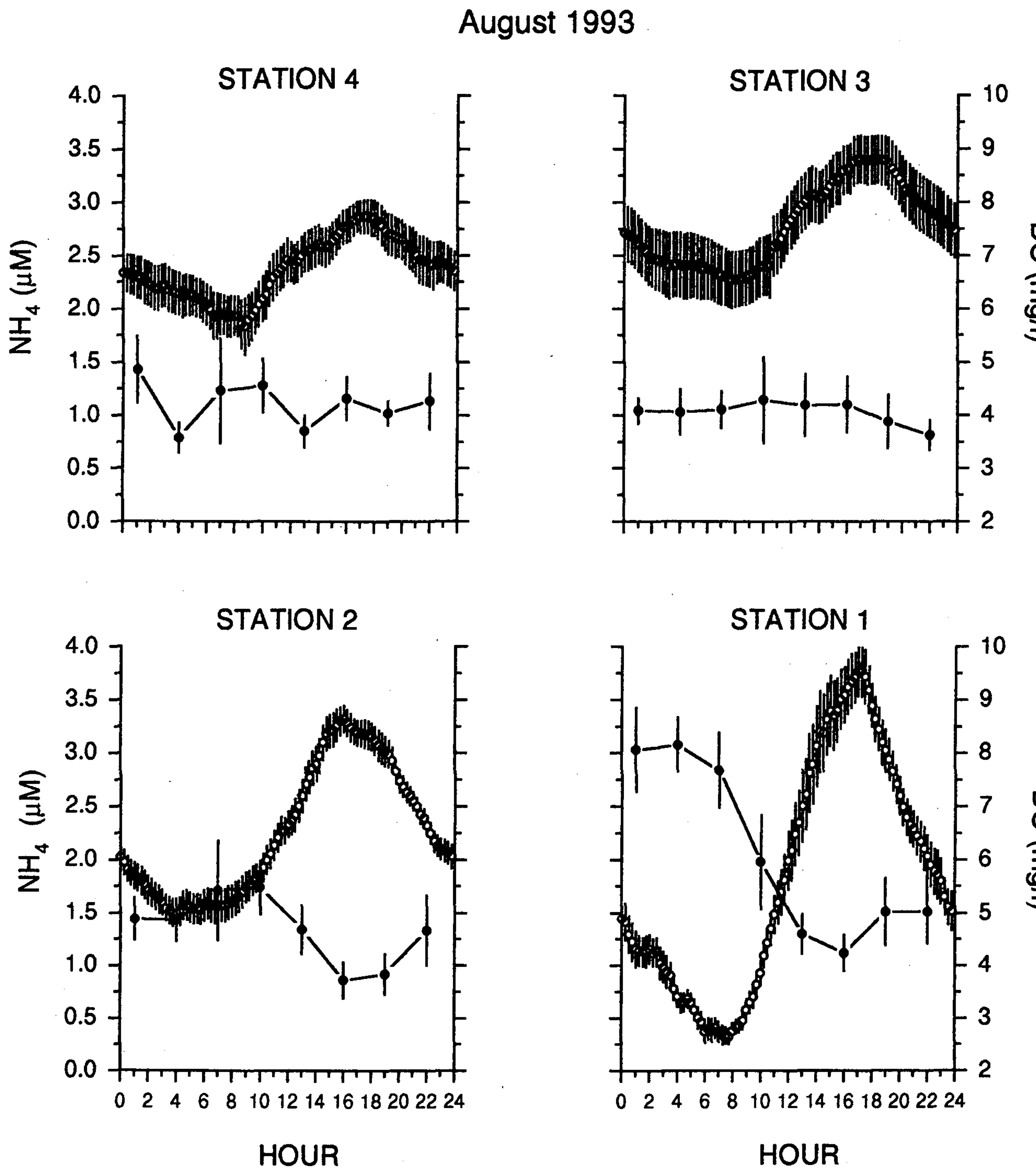
A62 : 3-hour orthophosphate (PO_4) at Goodwin Island, VA. October 1993.



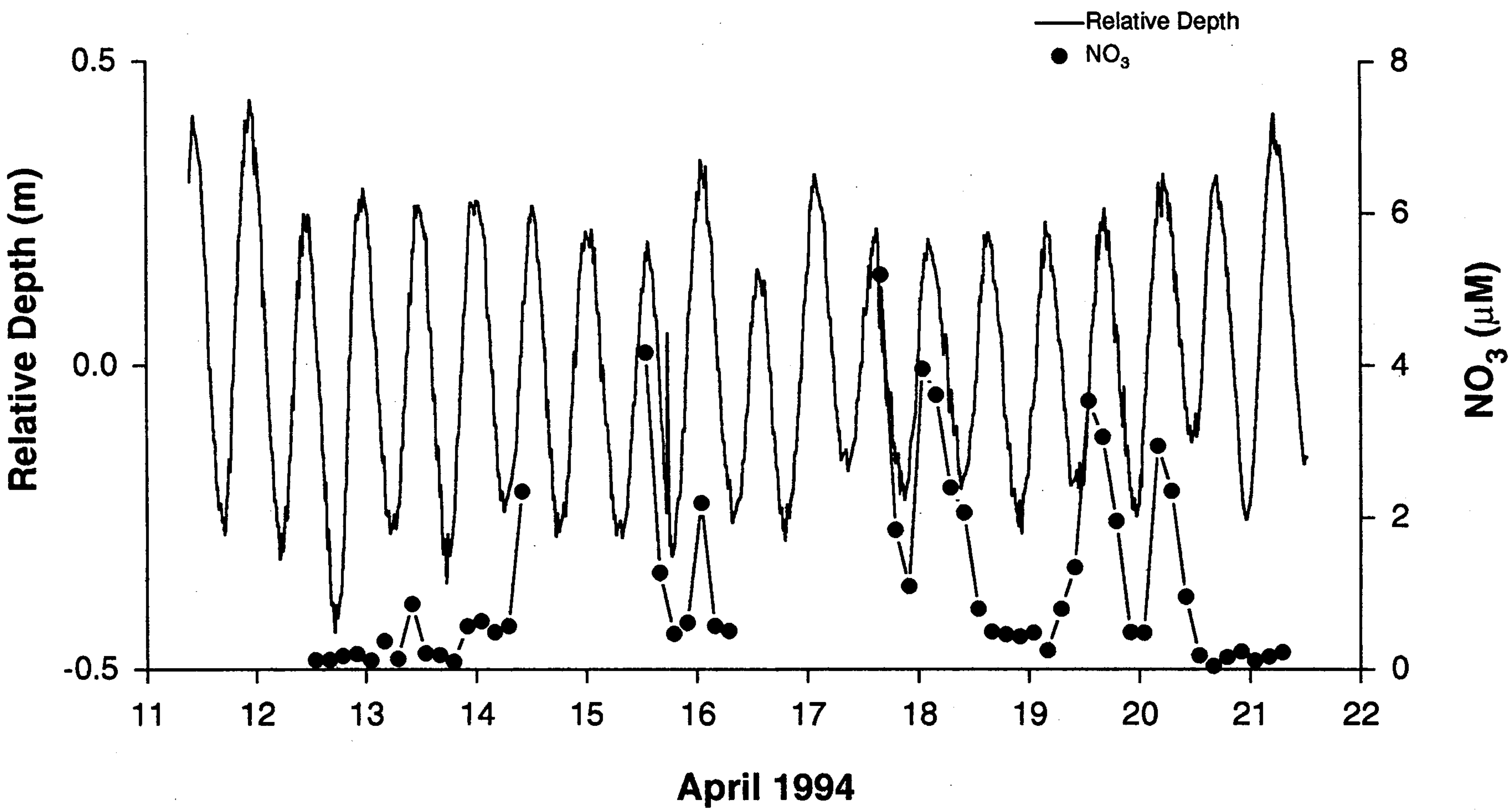
A63 : 3-hour orthophosphate (PO_4) at Goodwin Island, VA. April 1994.



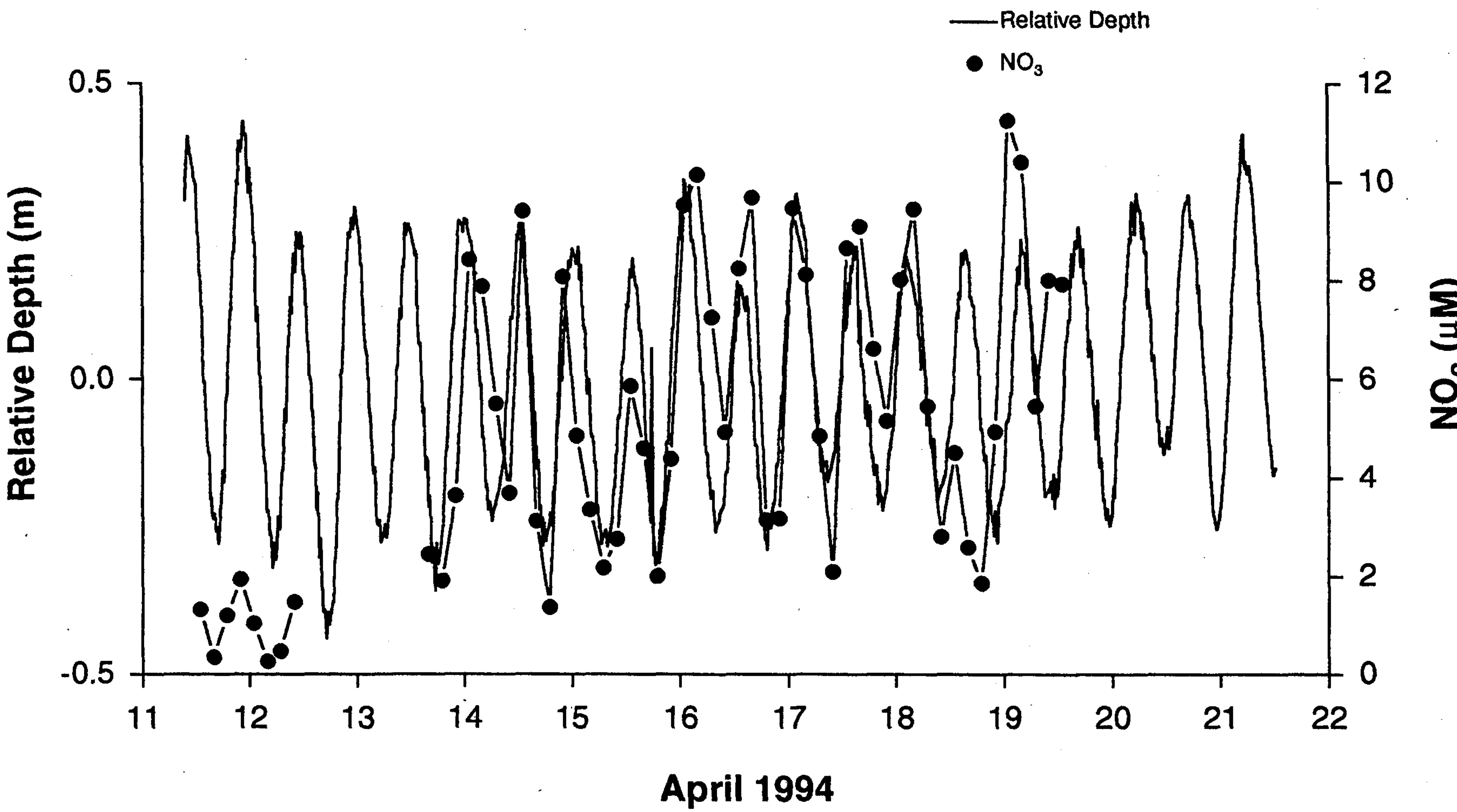
A64: Mean dissolved oxygen and ammonium (NH_4) concentrations aggregated over a diel cycle for stations 1 through 4 in August 1993.



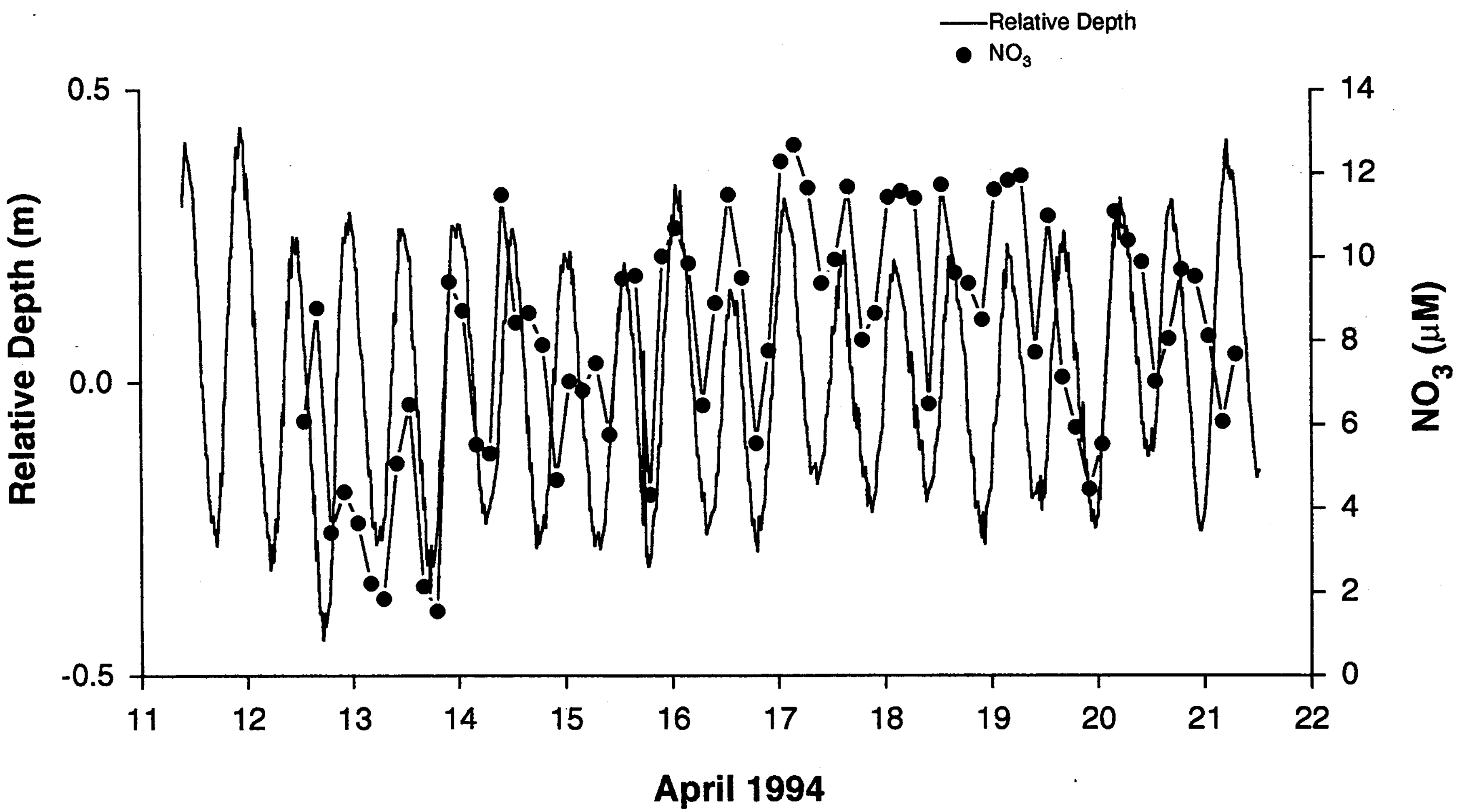
A65 : 3-hour nitrate (NO_3) and 15-minute relative tidal depth. Station 1. Goodwin Island, VA. April 1994.



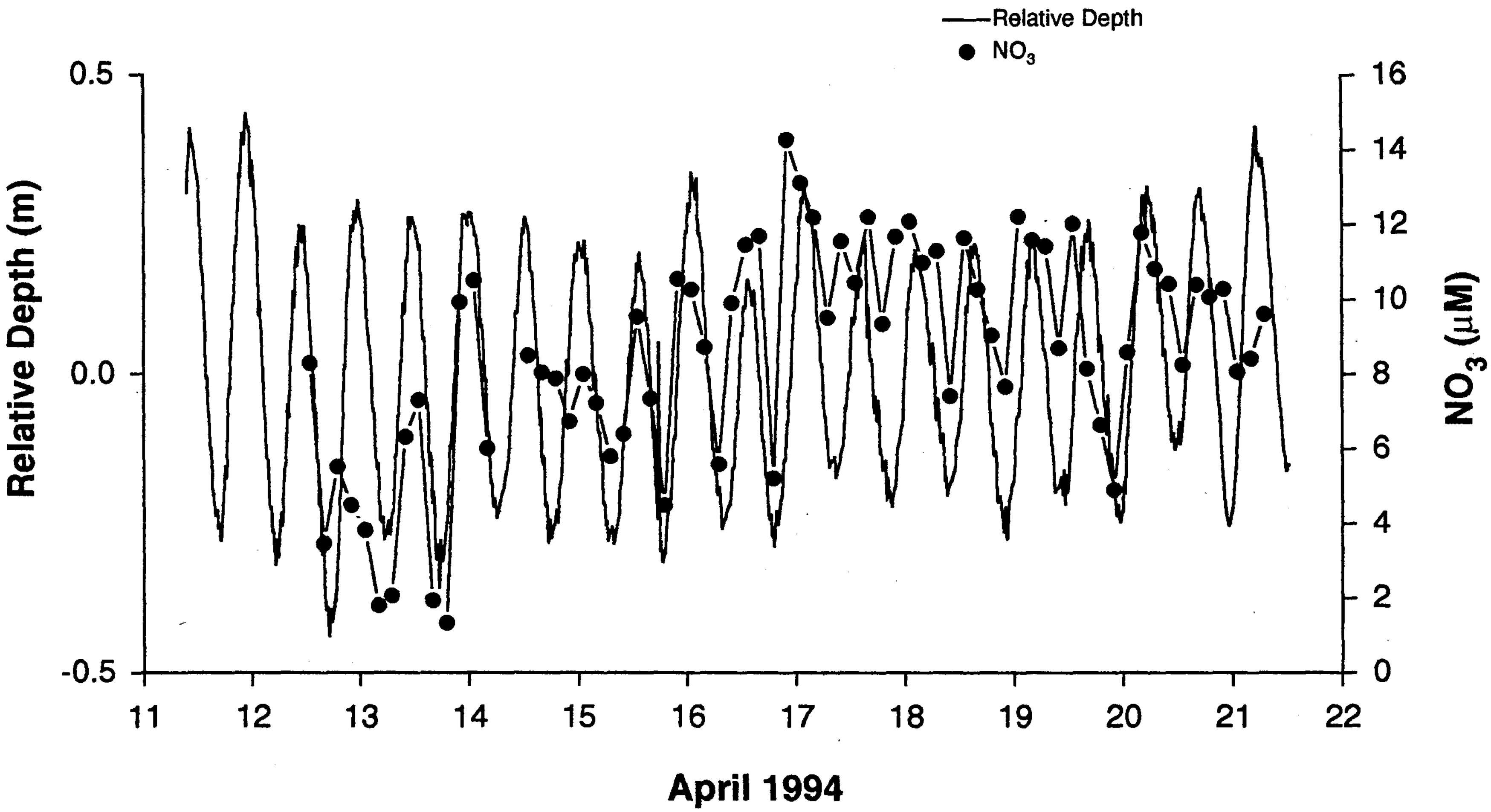
A66 : 3-hour nitrate (NO_3) and 15-minute relative tidal depth. Station 2. Goodwin Island, VA. April 1994.



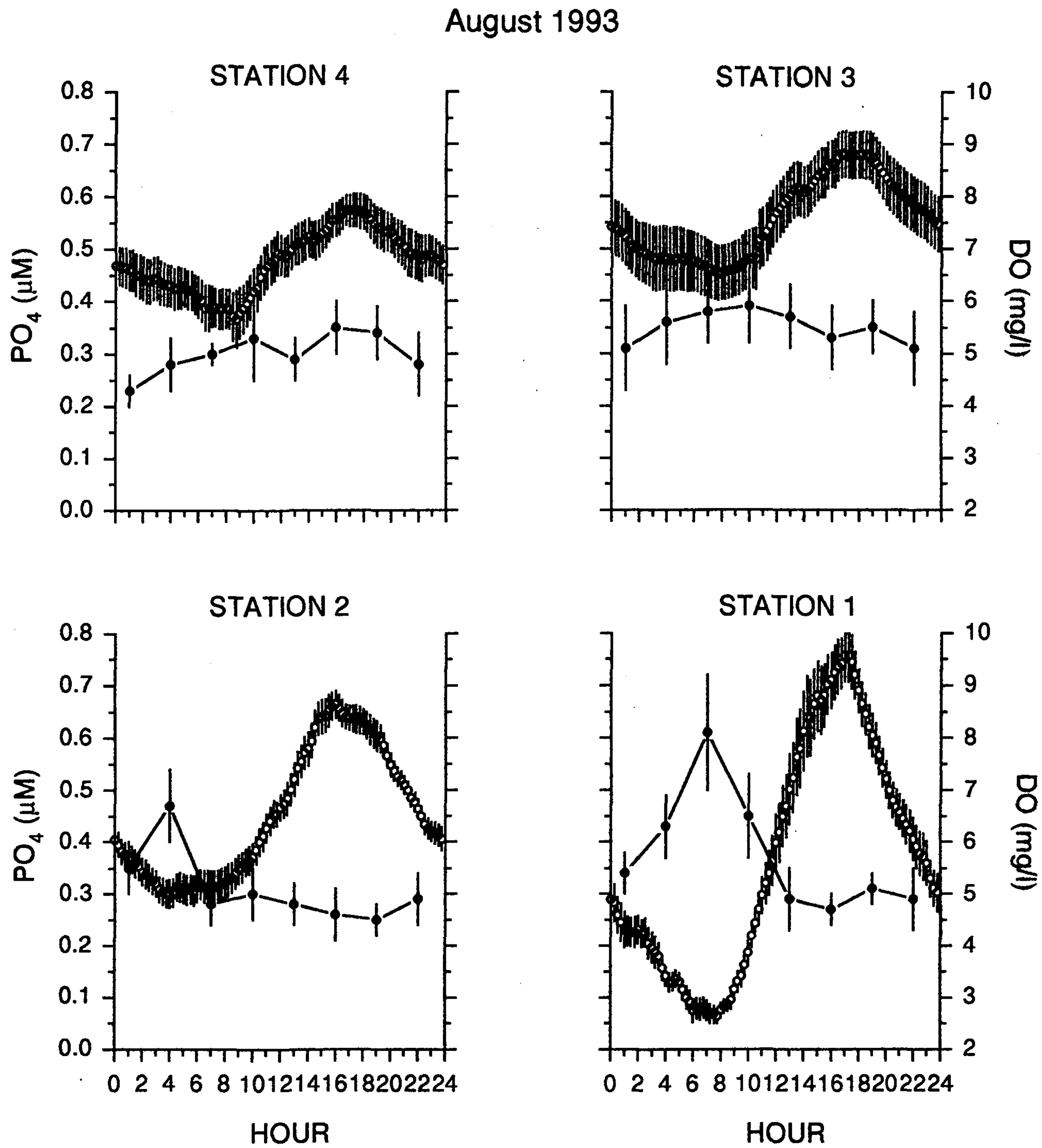
A67 : 3-hour nitrate (NO_3) and 15-minute relative tidal depth. Station 3. Goodwin Island, VA. April 1994.



A68 : 3-hour nitrate(NO_3) and 15-minute relative tidal depth. Station 4. Goodwin Island, VA. April 1994.

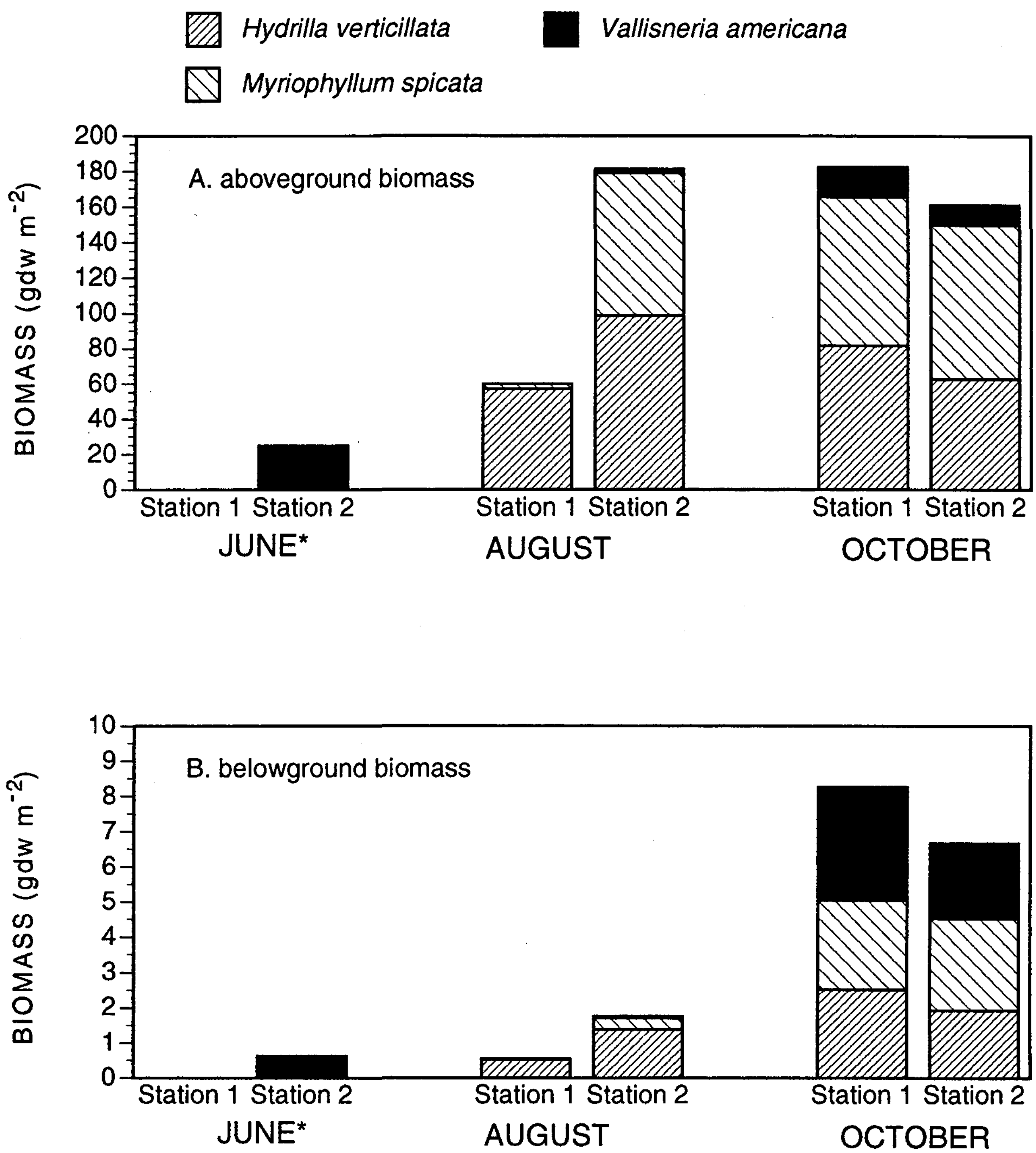


A69: Mean dissolved oxygen (DO) and orthophosphate (PO_4) concentrations aggregated over a diel cycle for stations 1 through 4 in August 1993.



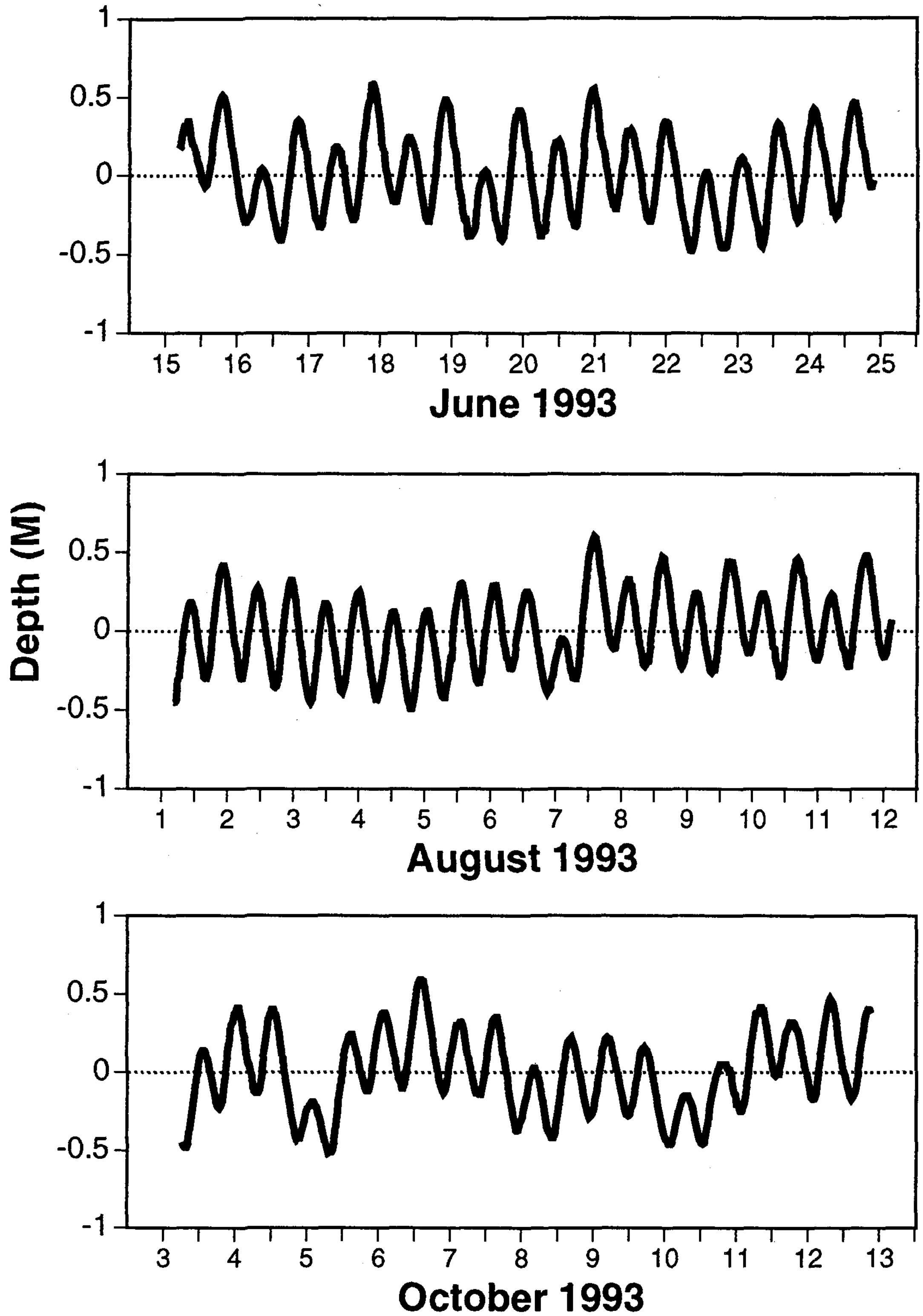
Appendix B

Appendix B1. Biomass at Havre de Grace monitoring stations, 1993.

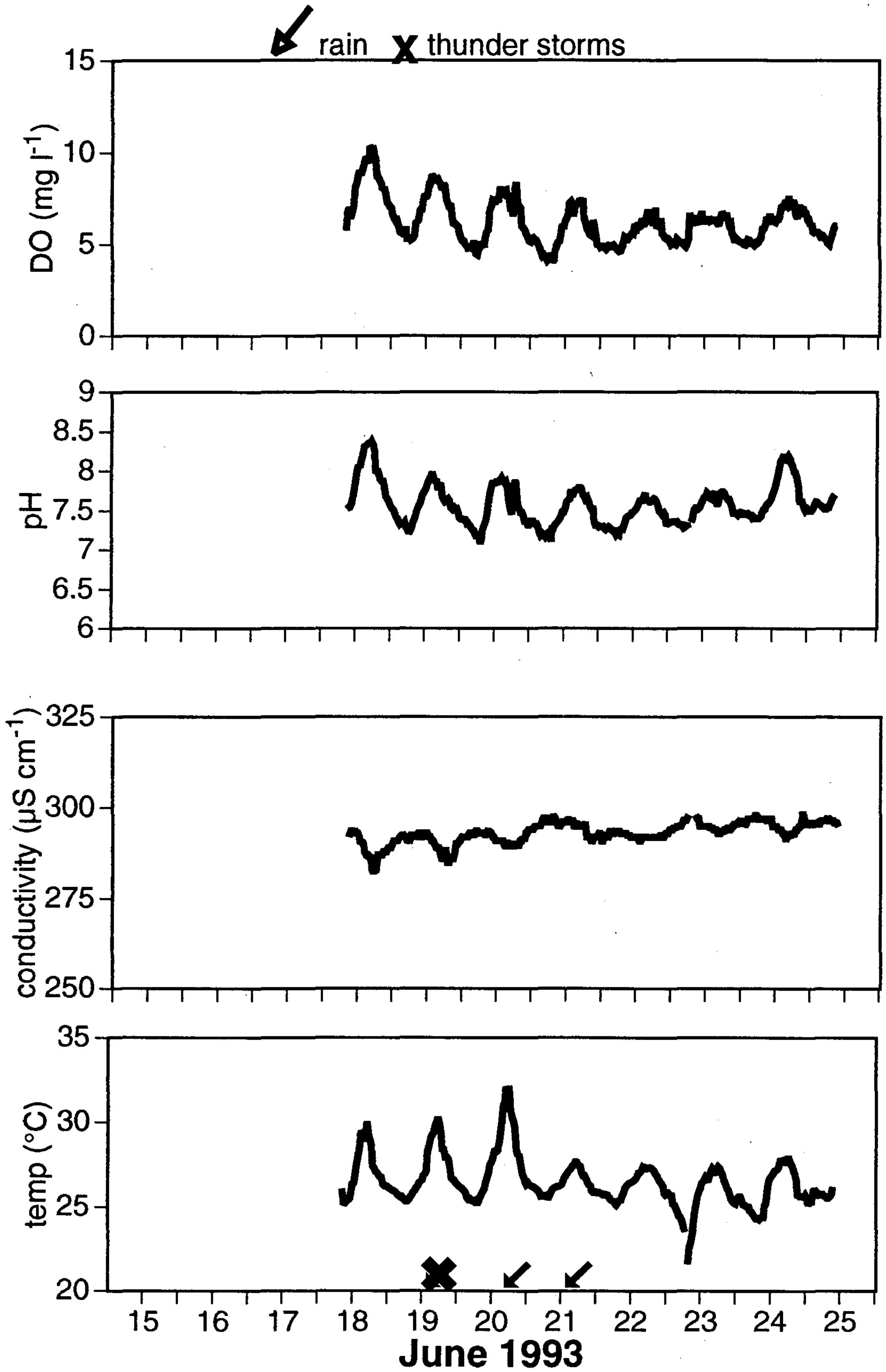


*=estimates only

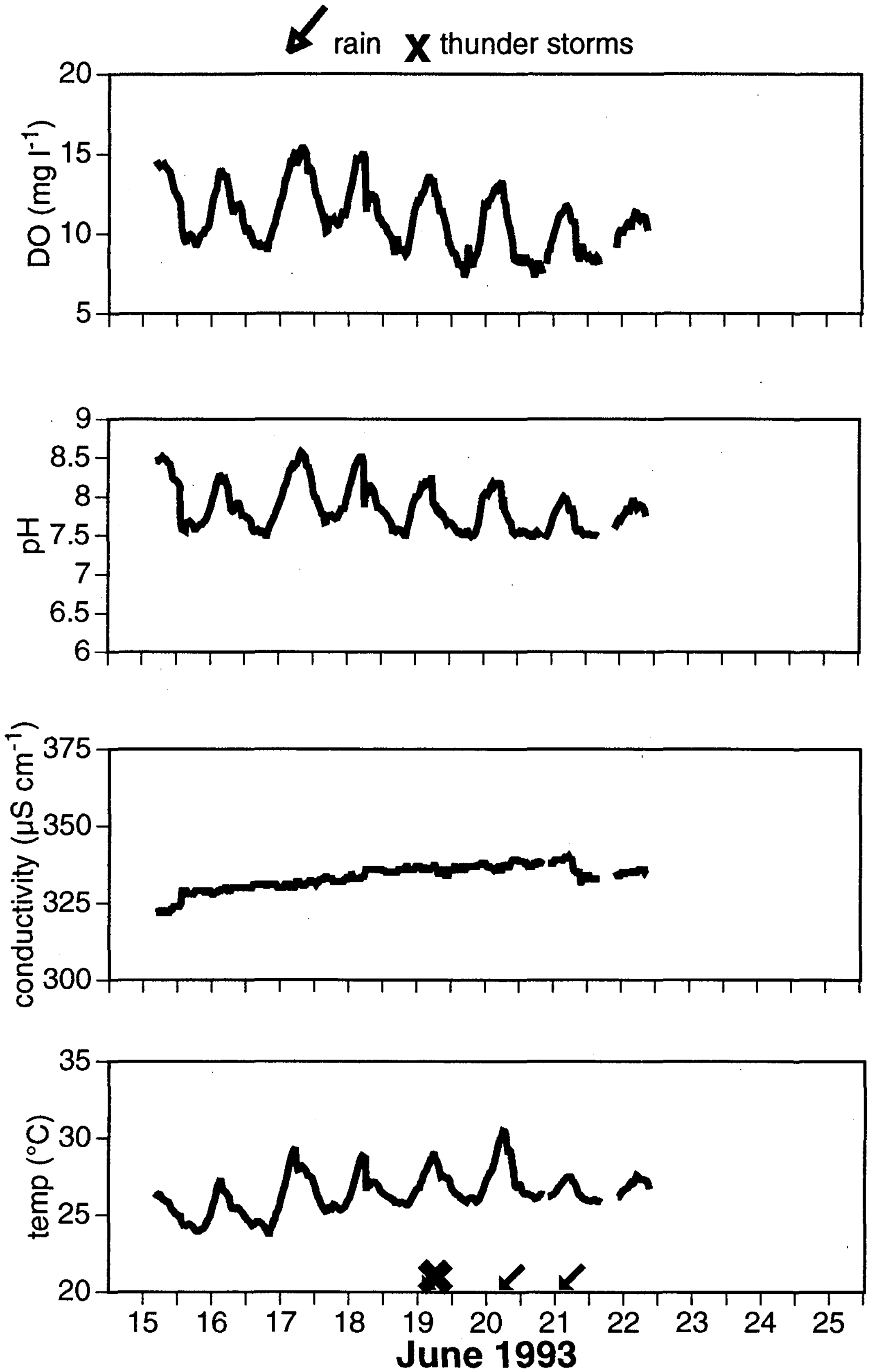
Appendix B2. Tidal variations at Havre de Grace.



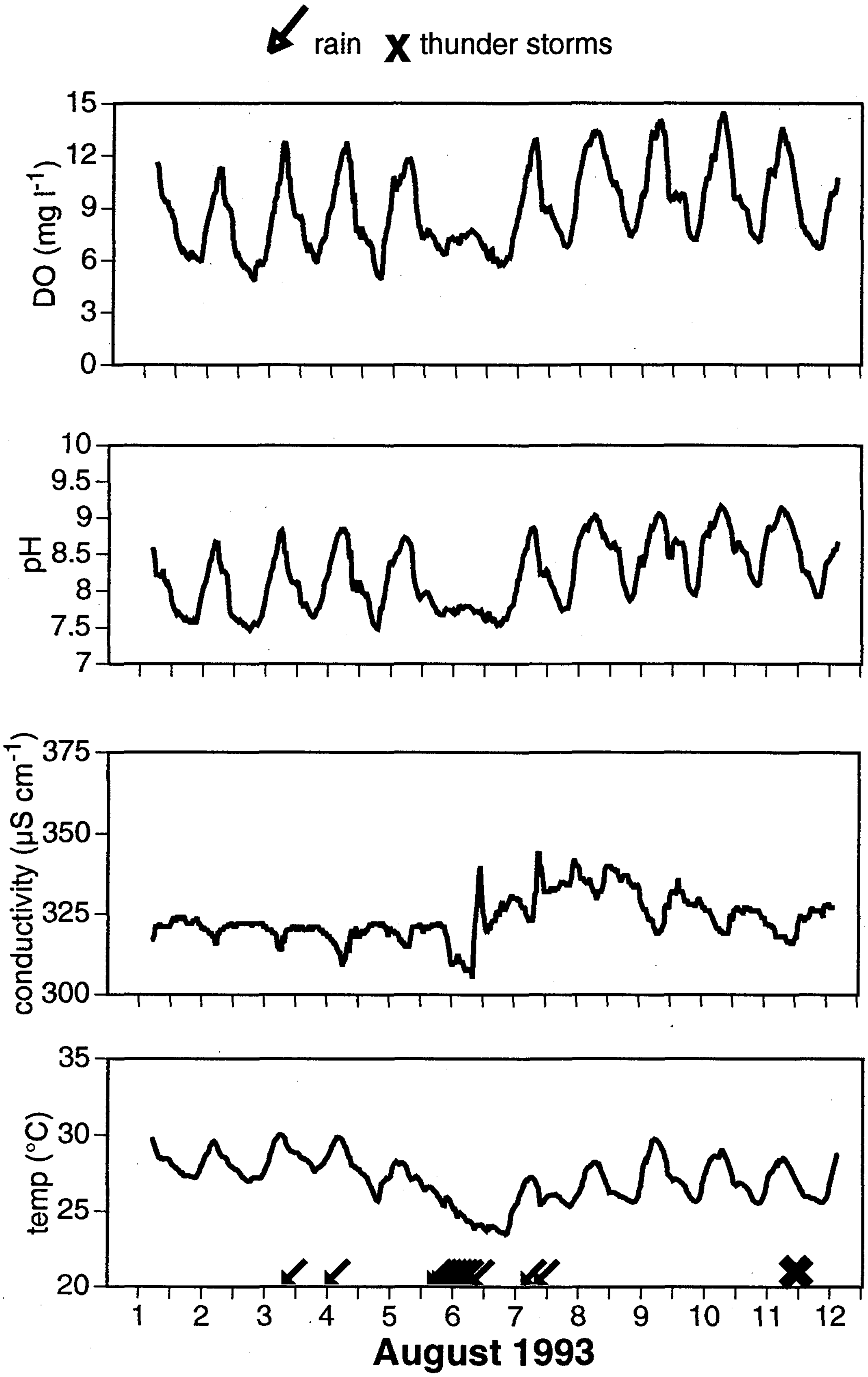
Appendix B3. Physical data from Station 1, Havre de Grace, 1993.



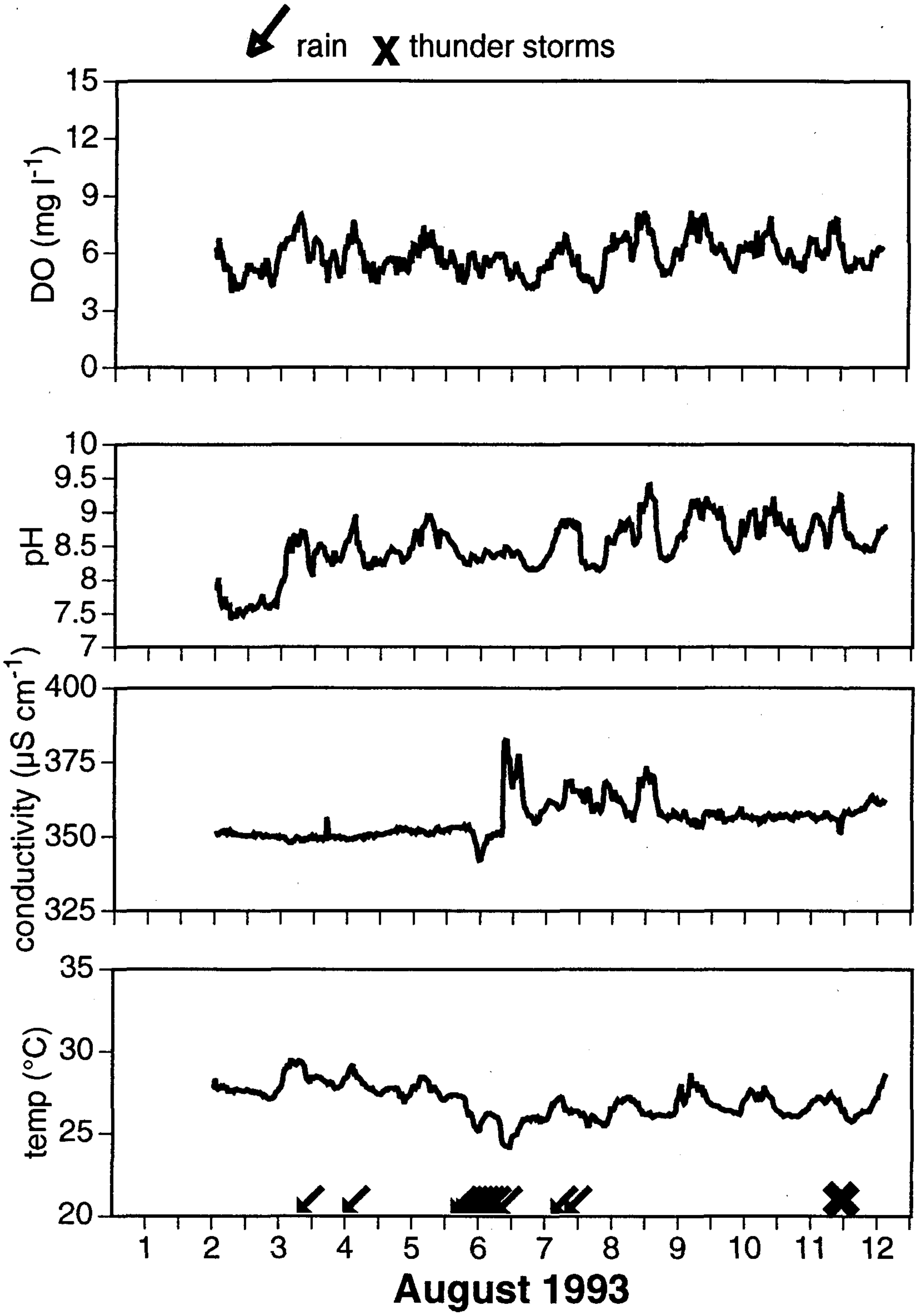
Appendix B4. Physical data from Station 2, Havre de Grace, 1993.



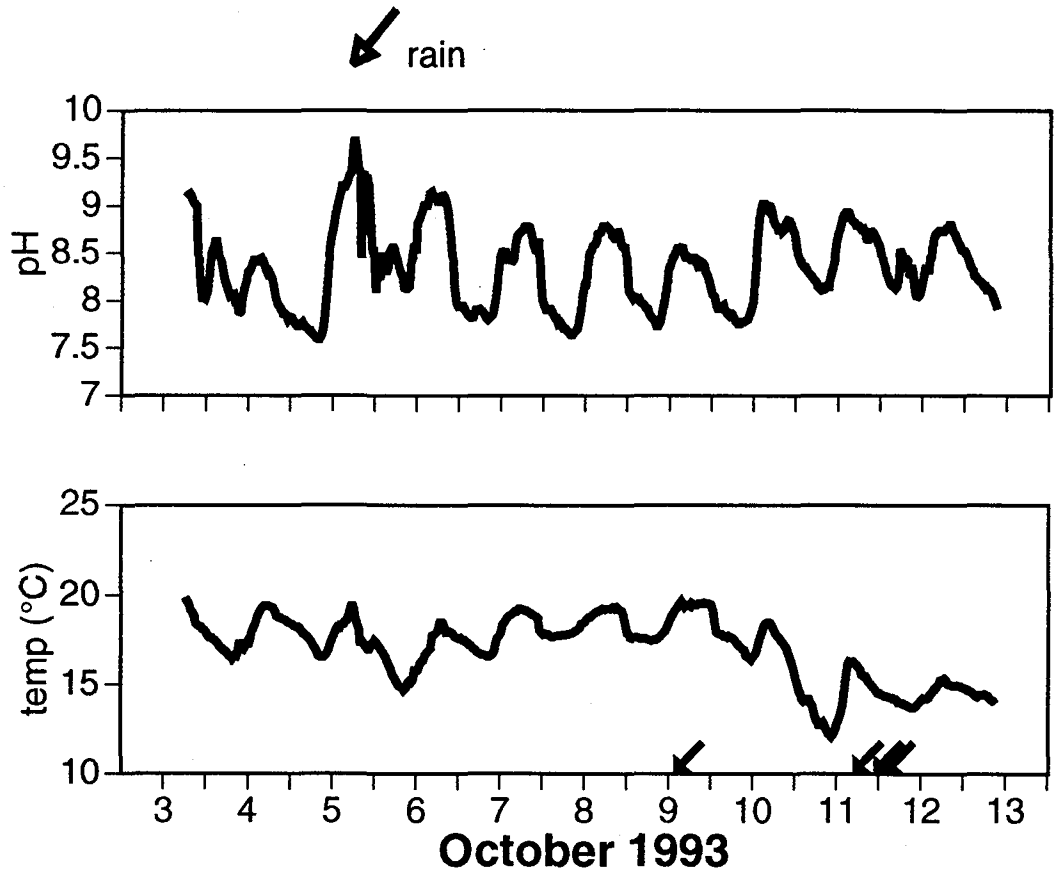
Appendix B5. Physical data fromStation 2, Havre de Grace, 1993.



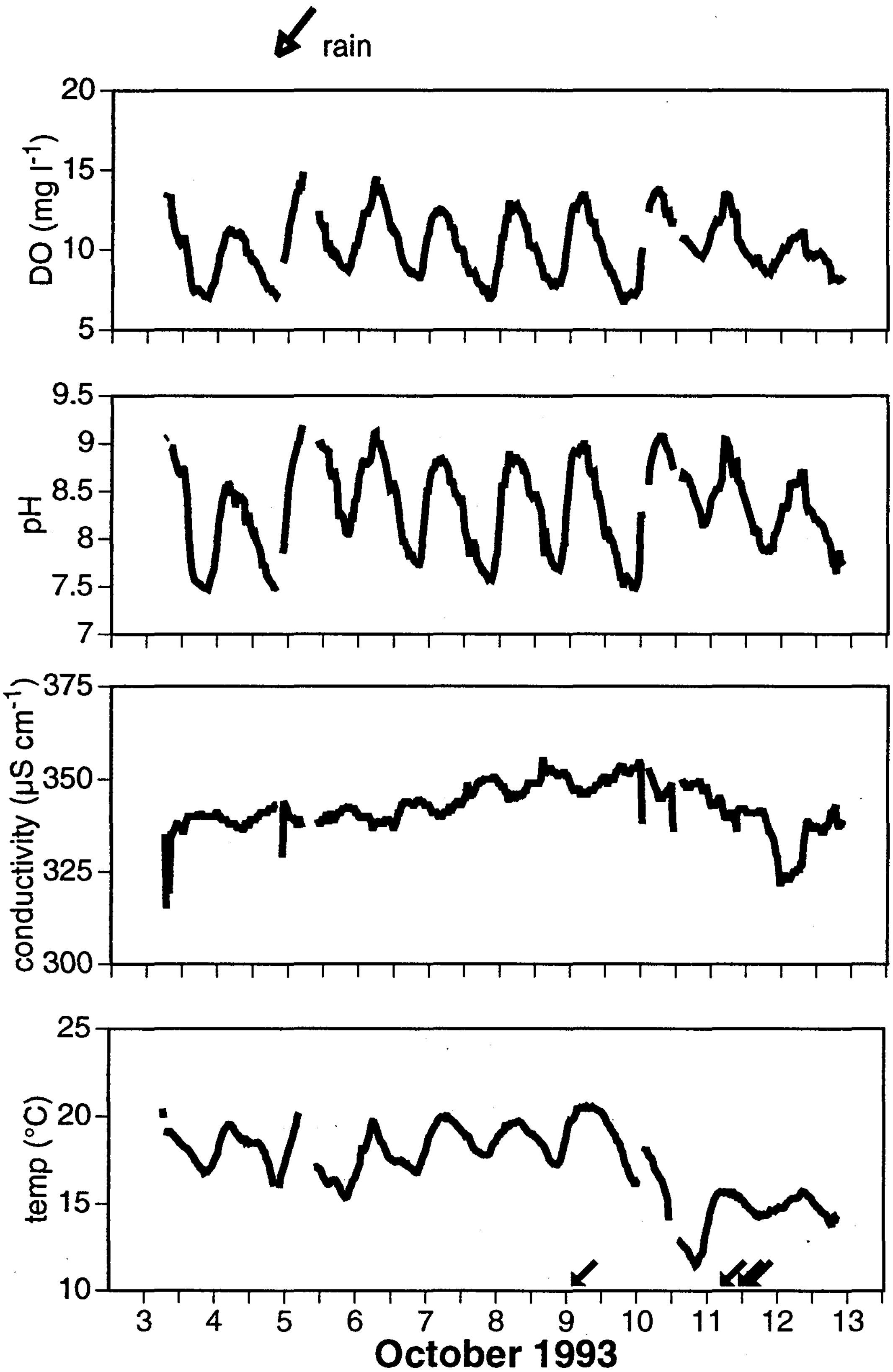
Appendix B6. Physical data fromStation 3, Havre de Grace, 1993.



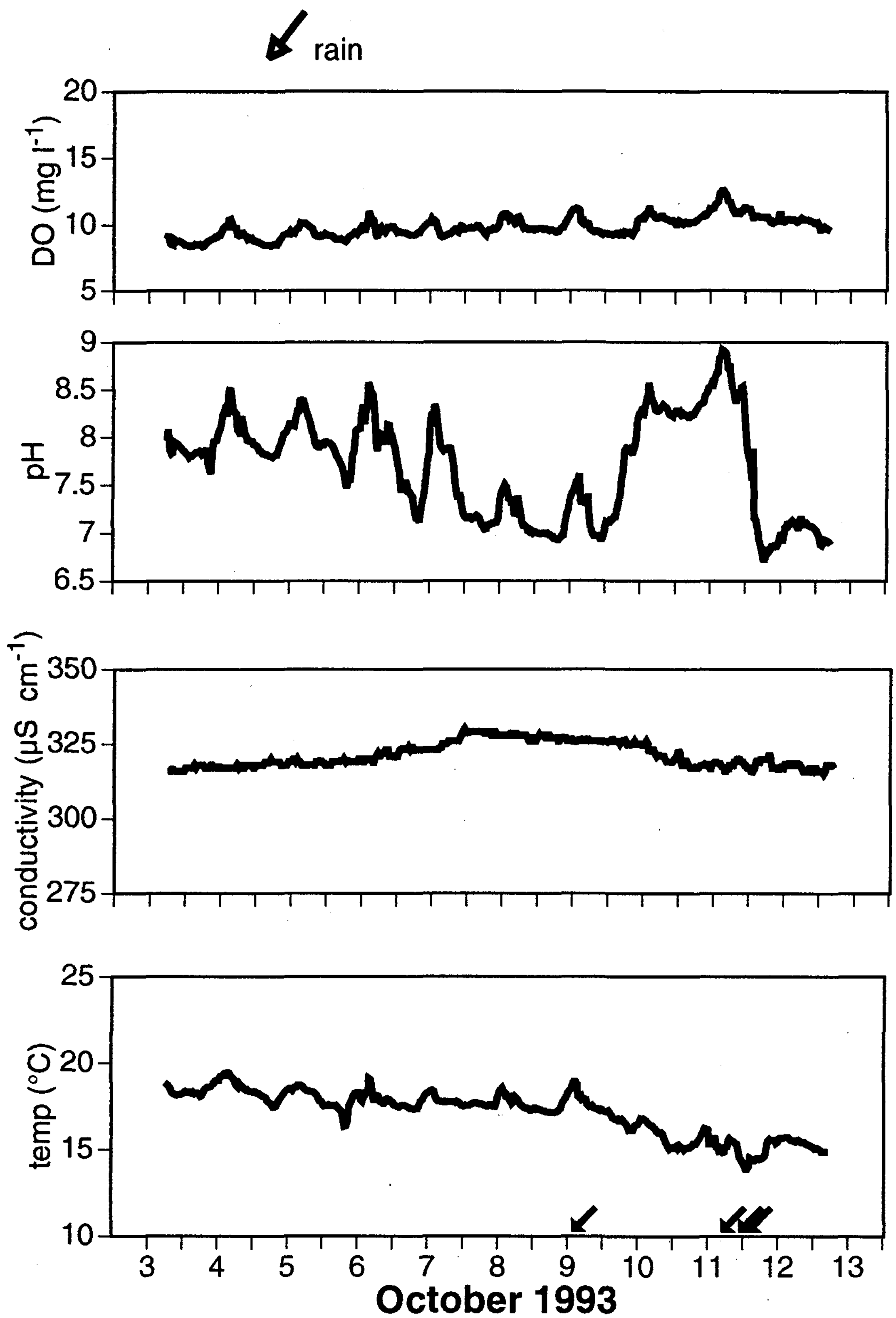
Appendix B7. Physical data fromStation 1, Havre de Grace, 1993.



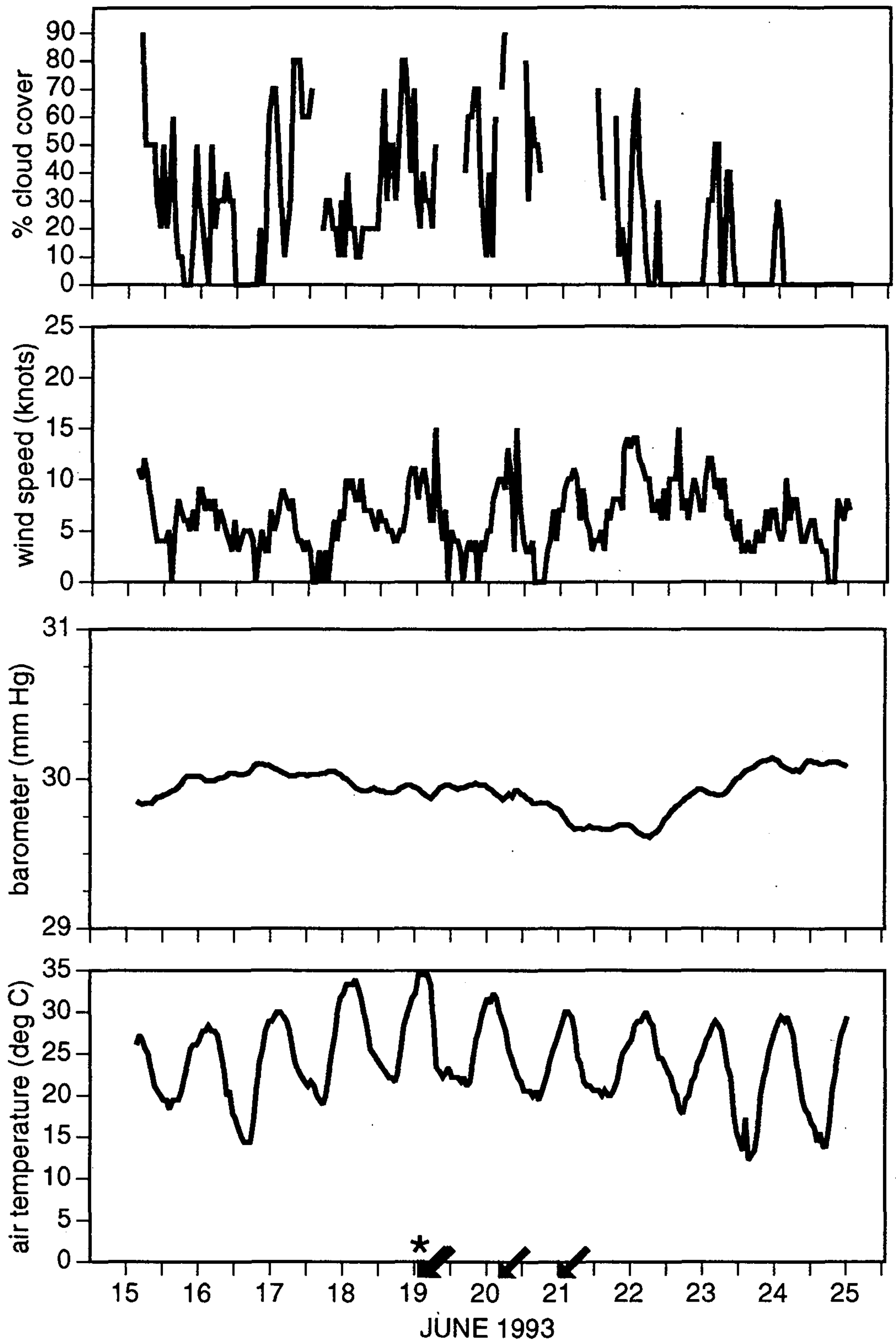
Appendix B8. Physical data fromStation 2, Havre de Grace, 1993.



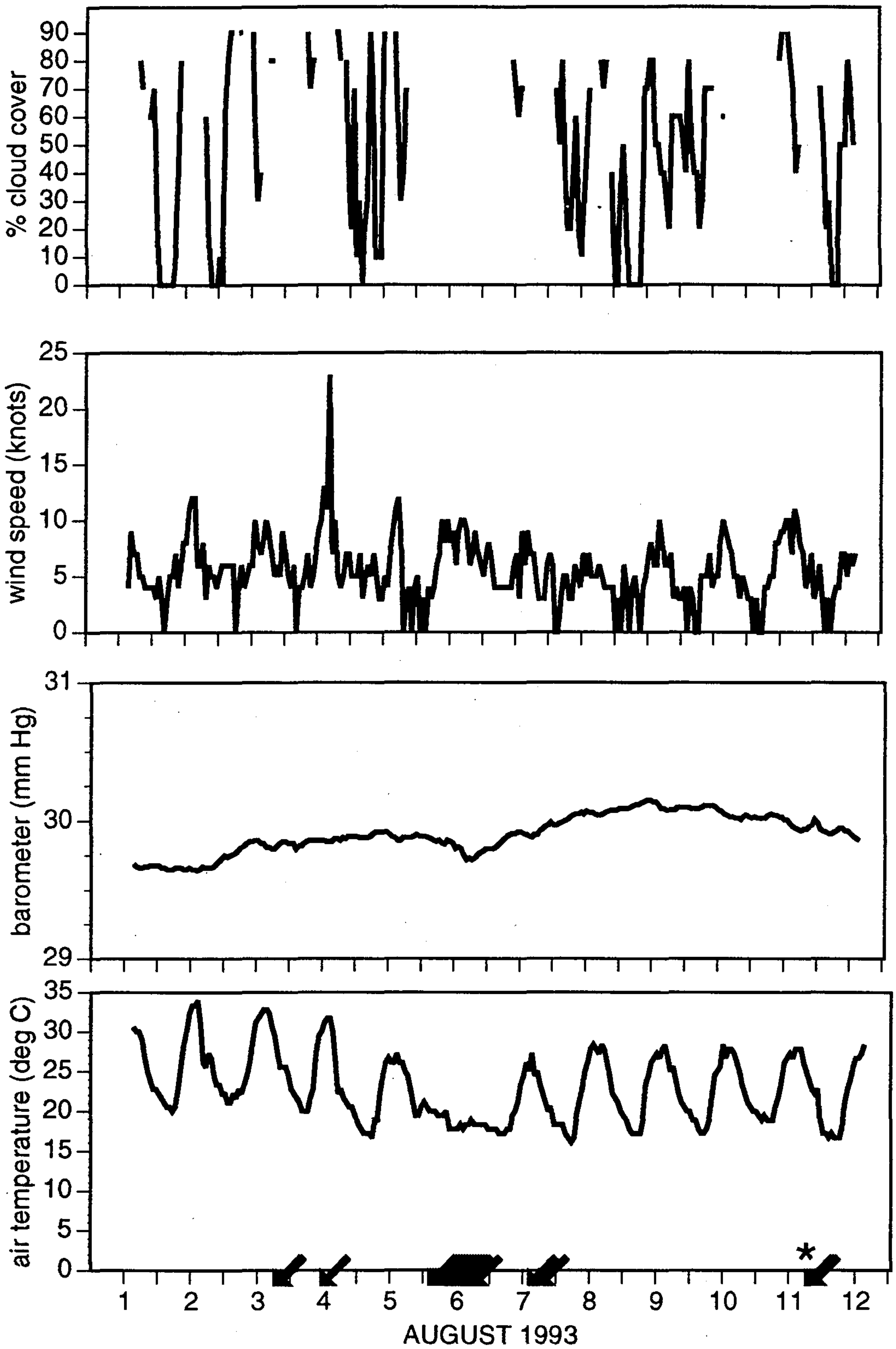
Appendix B9. Physical data fromStation 3, Havre de Grace, 1993.



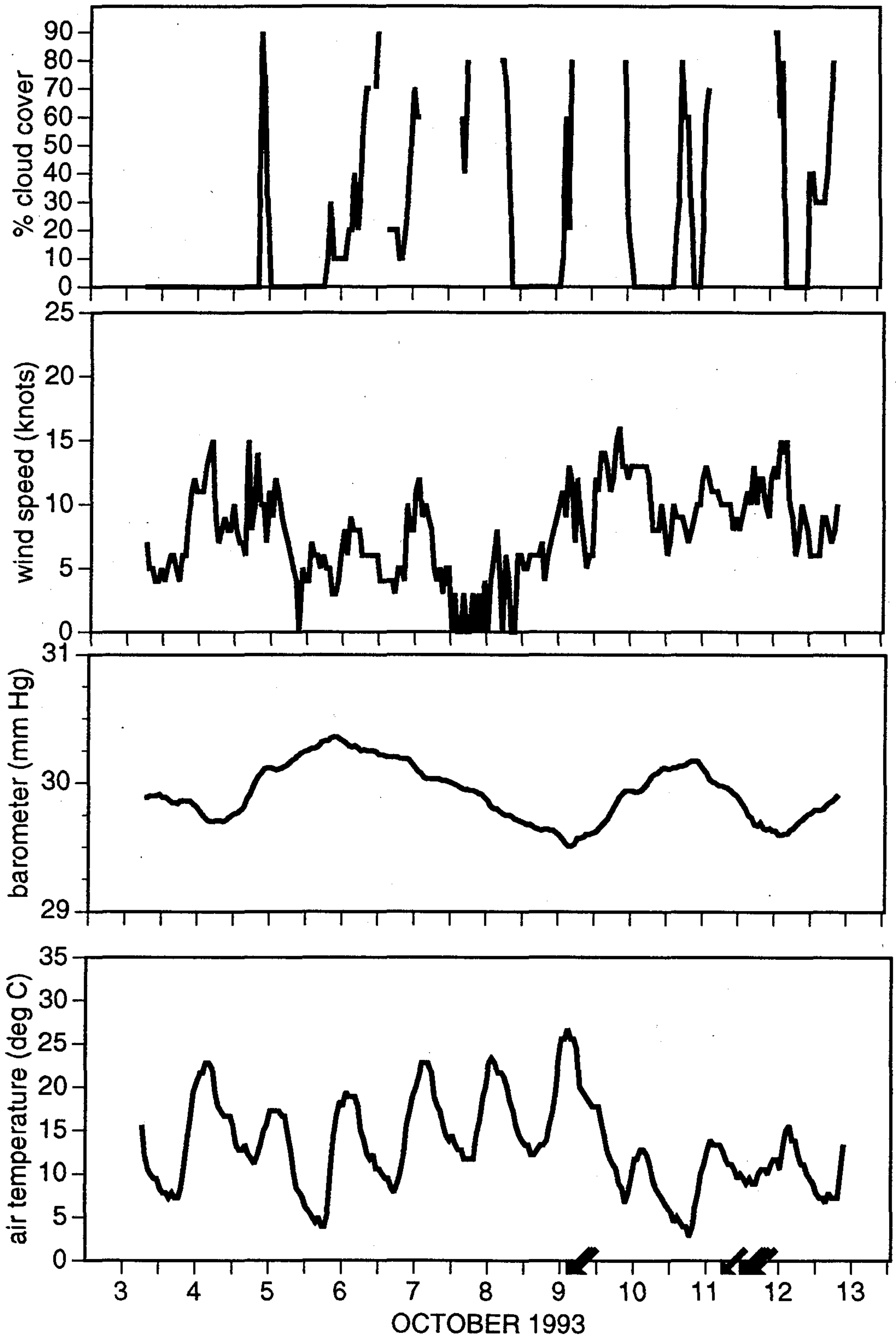
Appendix B10. Weather Observations at BWI Airport. Arrows indicate rain, * indicates thunderstorms.



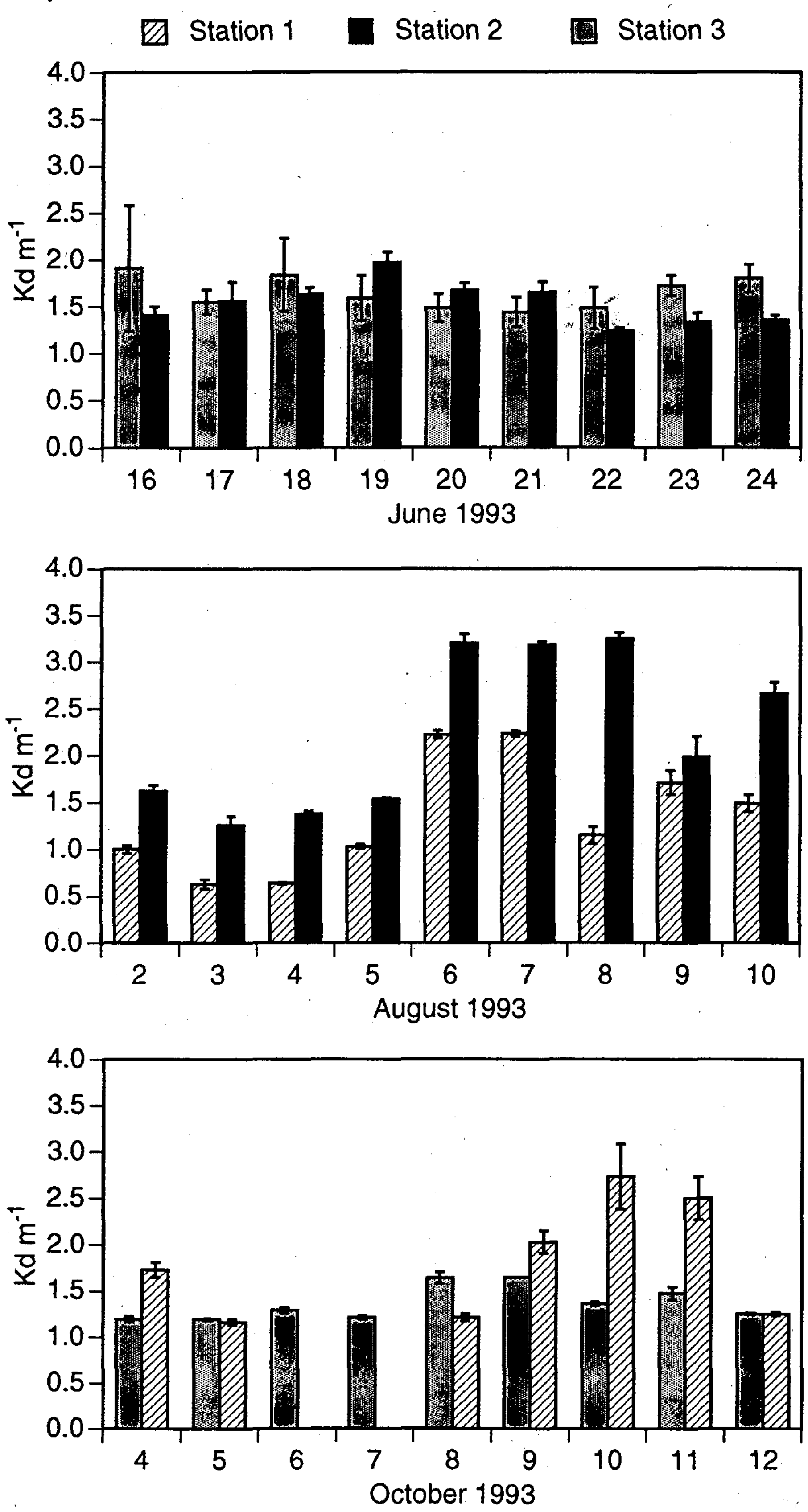
Appendix B11. Weather Observations at BWI Airport. Arrows indicate rain, * indicates thunderstorms.



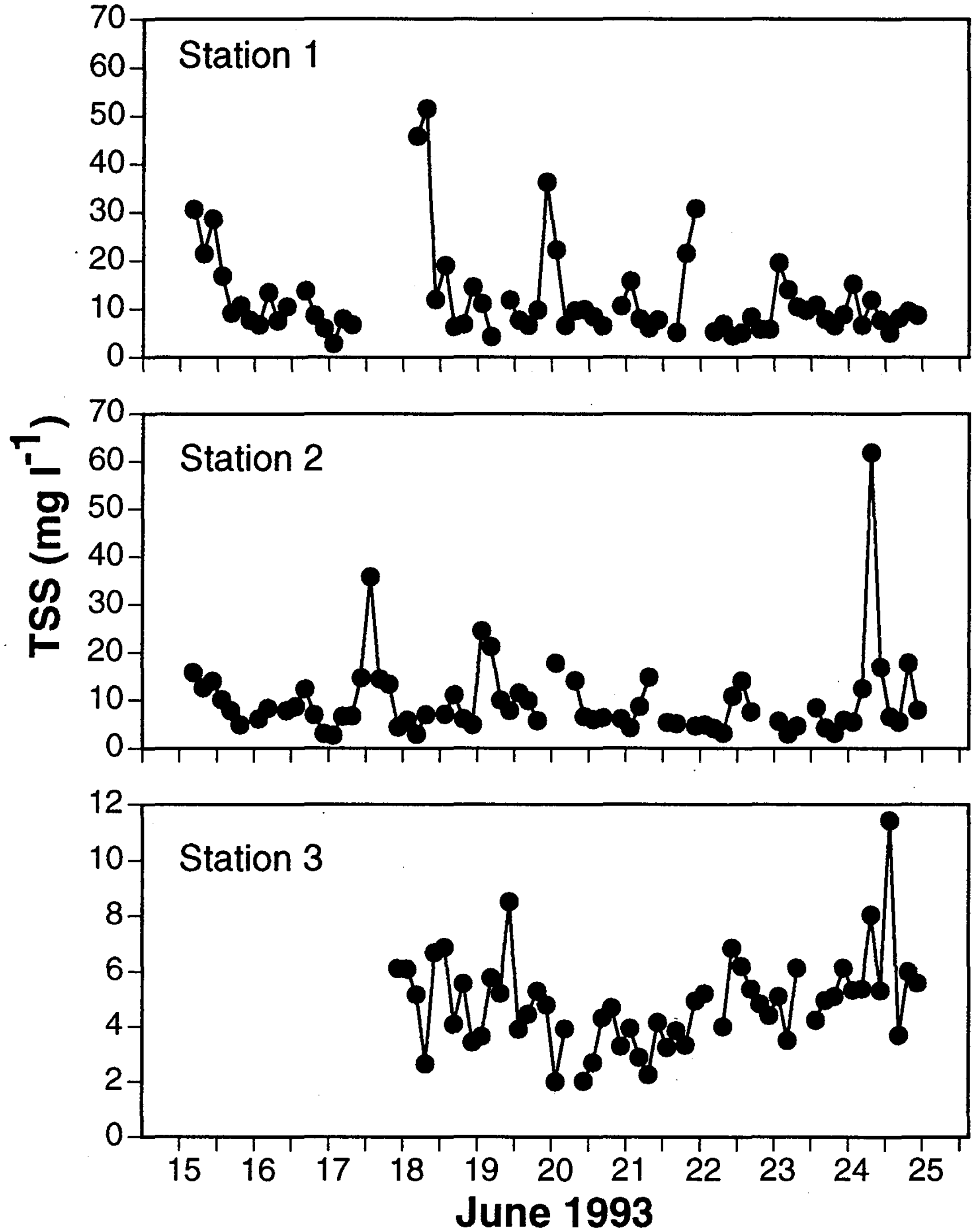
Appendix B12. Weather Observations at BWI Airport. Arrows indicate rain.



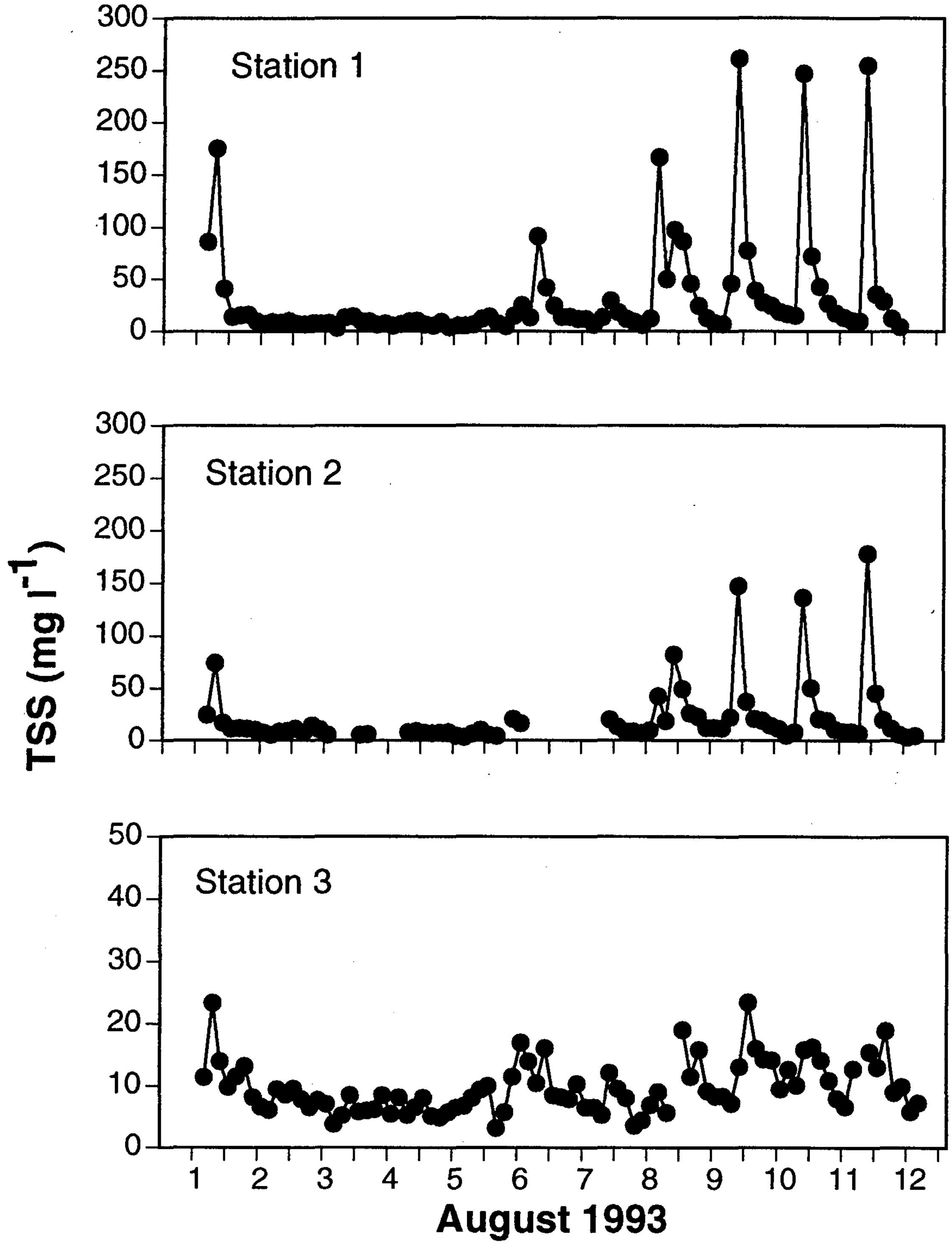
Appendix B13. Daily average light attenuation and standard error at Havre de Grace monitoring stations, 1993.



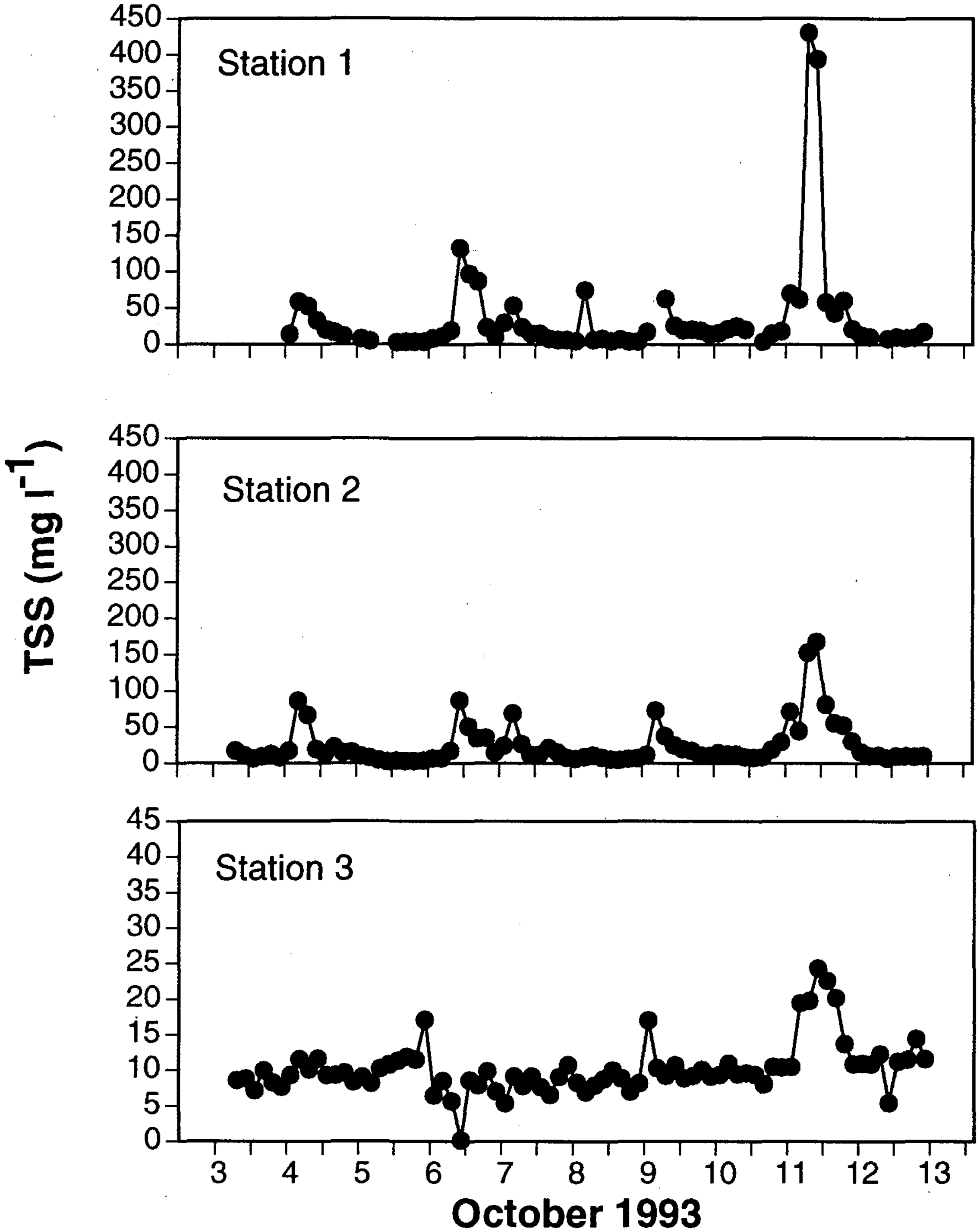
Appendix B14. Total suspended solids at Havre de Grace monitoring stations, June 1993.



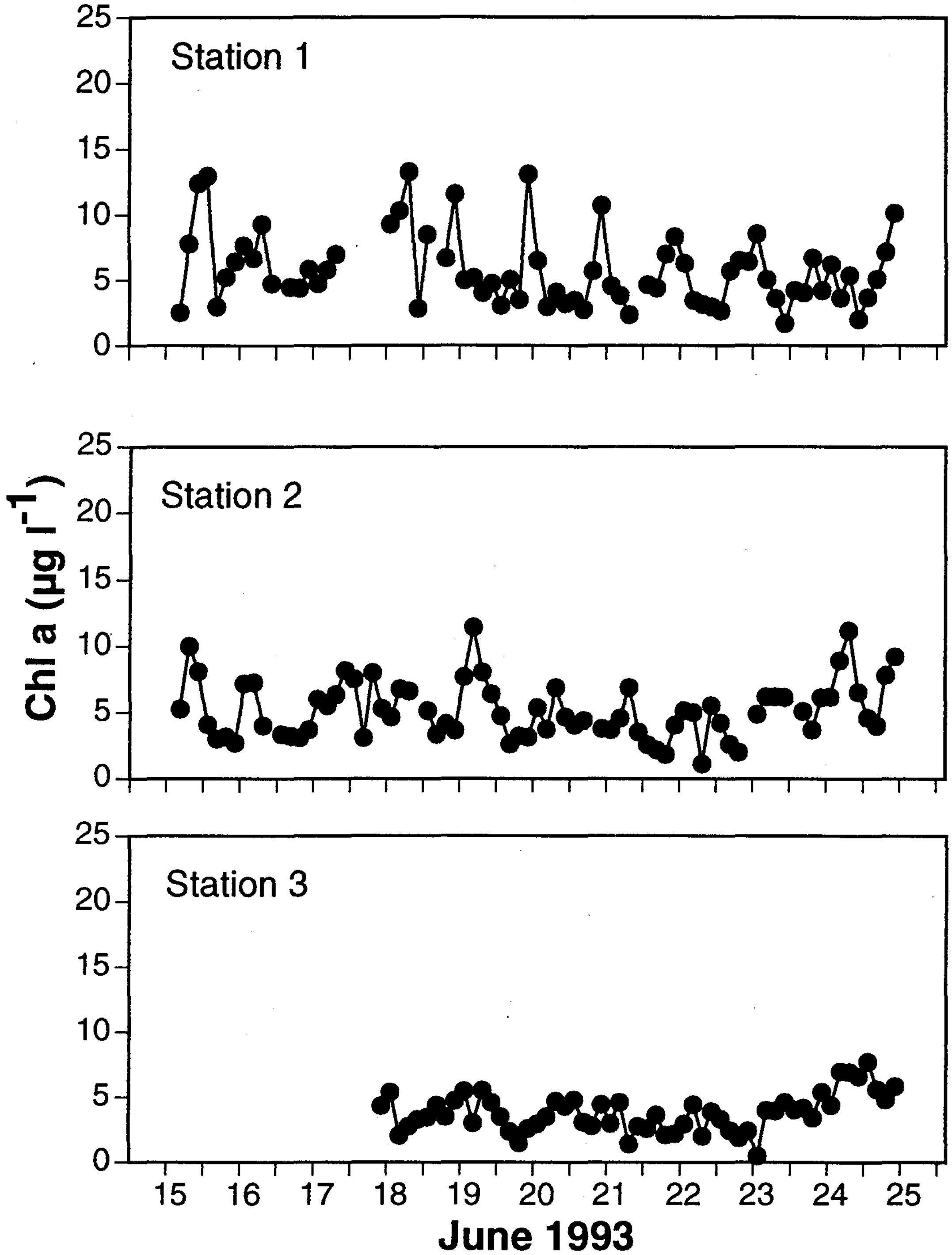
Appendix B15. Total suspended solids at Havre de Grace monitoring stations, August 1993.



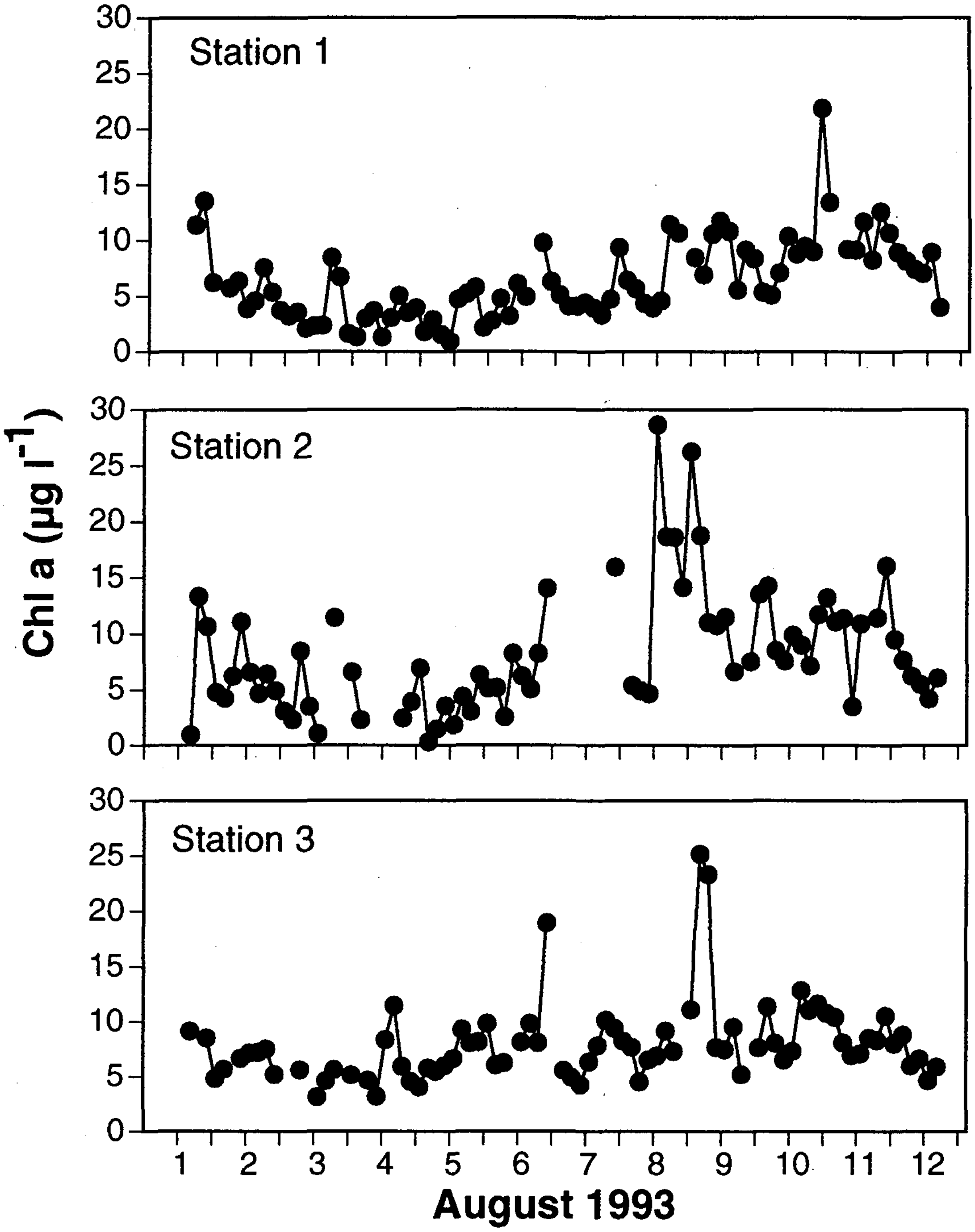
Appendix B16. Total suspended solids at Havre de Grace monitoring stations, October 1993.



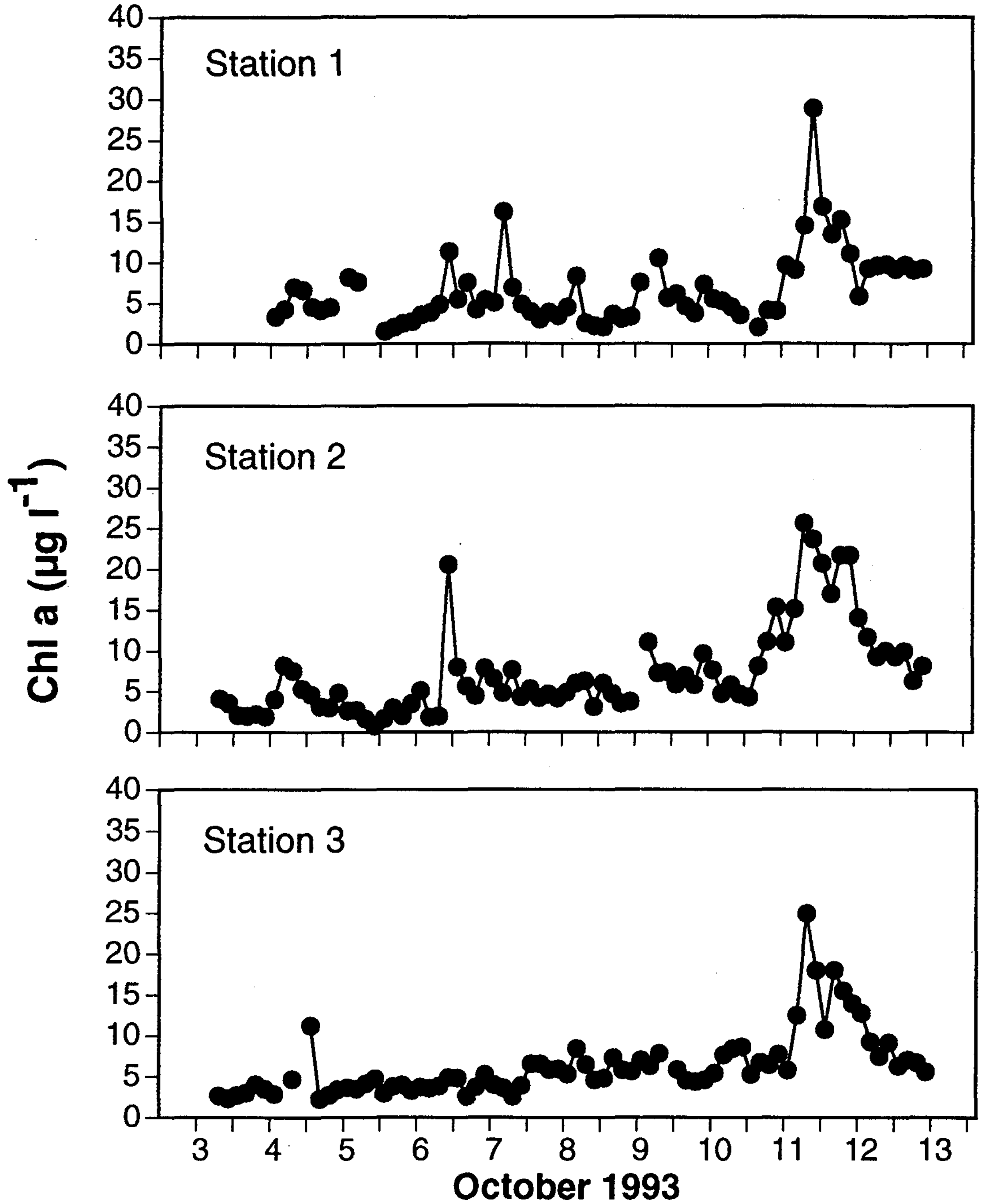
Appendix B17. Chlorophyll a concentrations at Havre de Grace monitoring stations, June 1993.



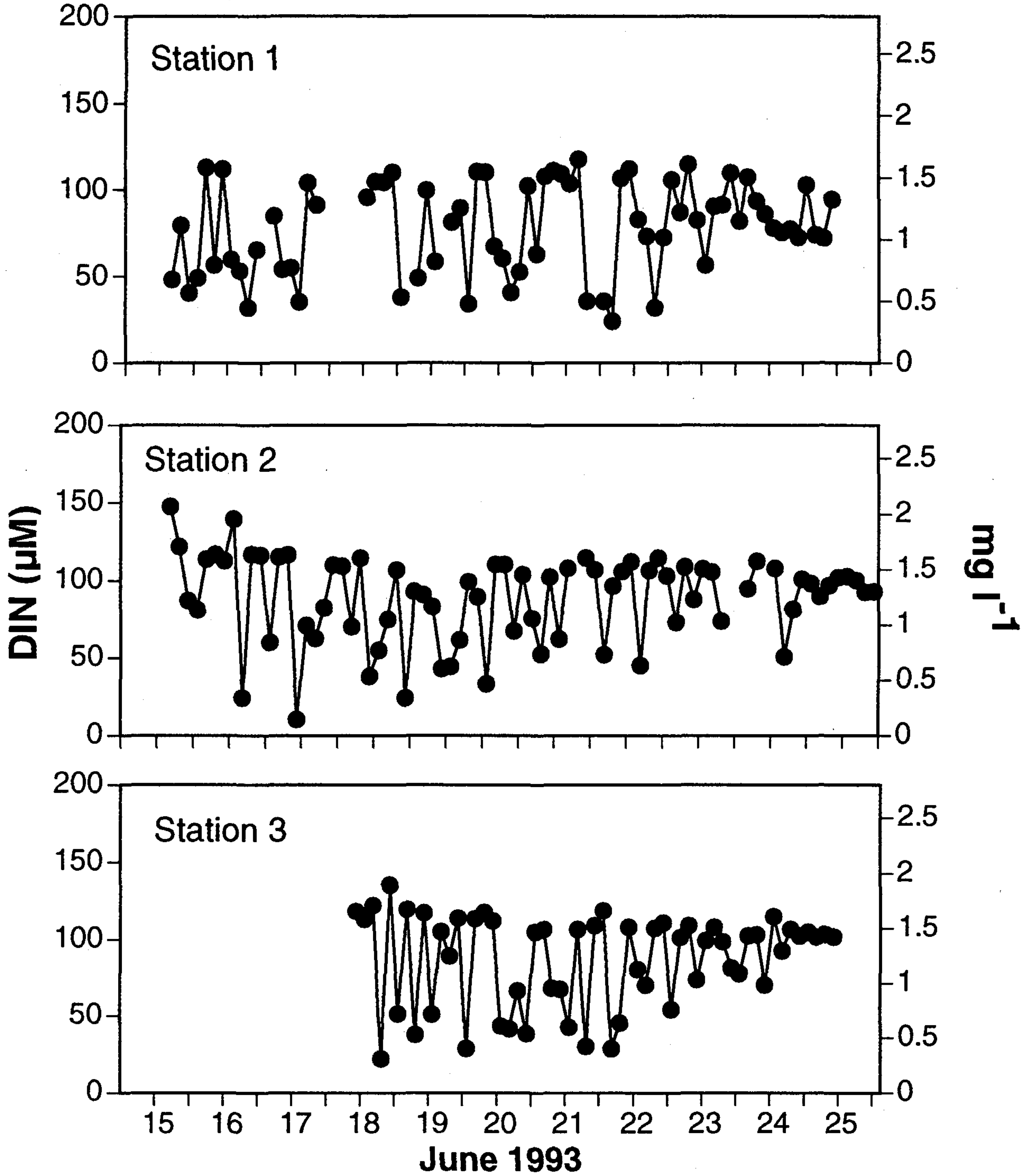
Appendix B18. Chlorophyll a concentrations at Havre de Grace monitoring stations, August 1993.



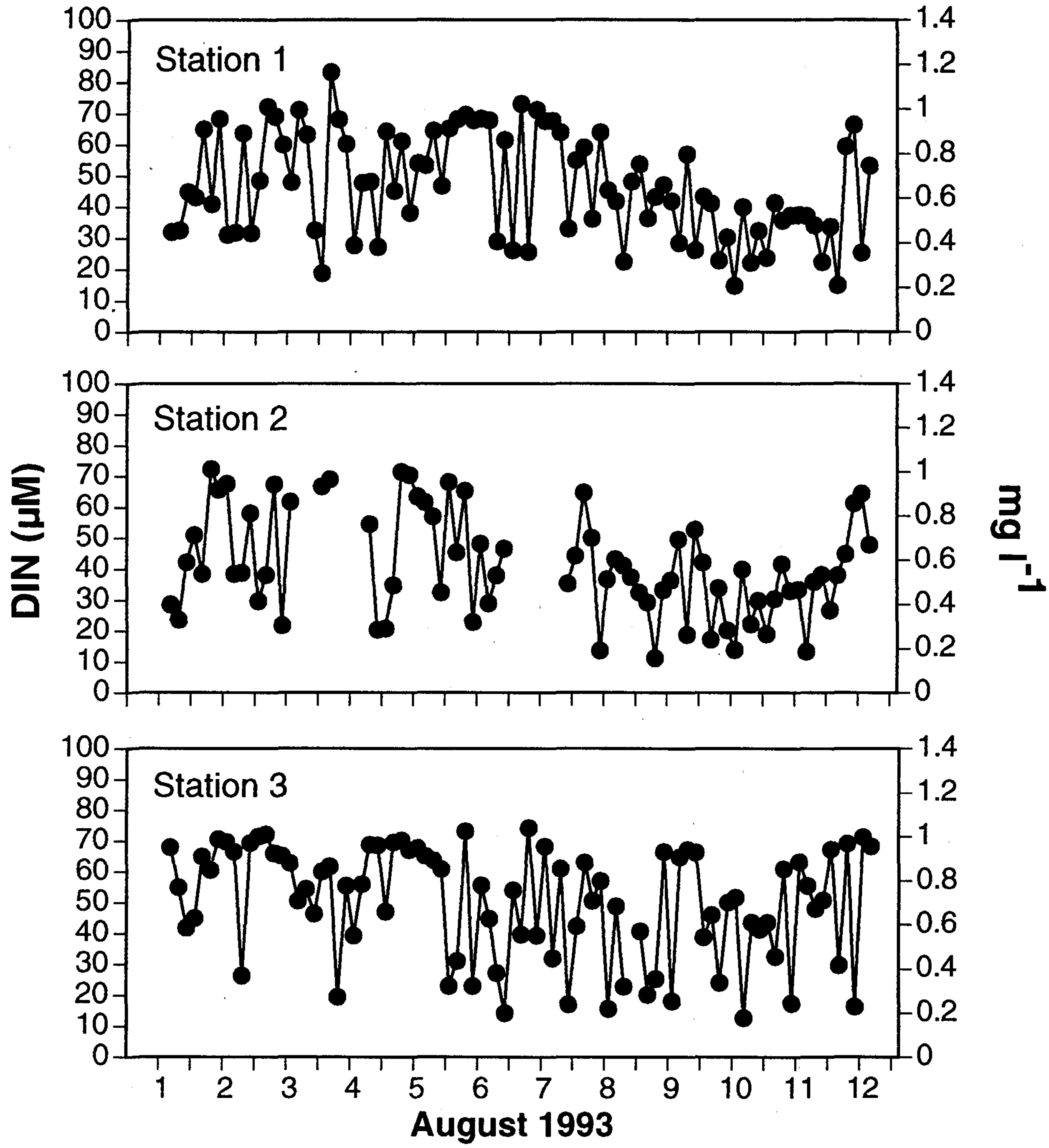
Appendix B19. Chlorophyll a concentrations at Havre de Grace monitoring stations, October 1993.



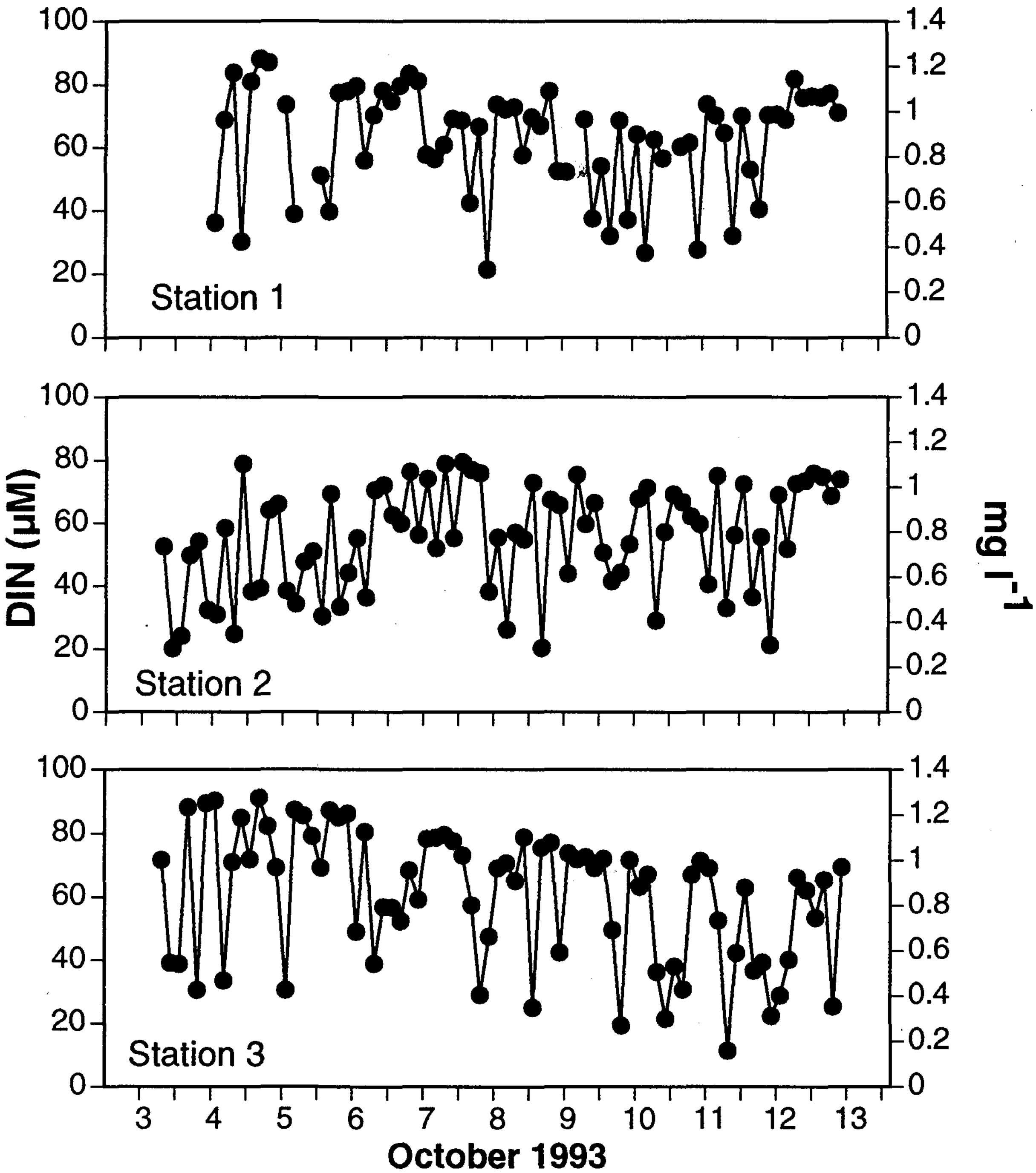
Appendix B20. Dissolved inorganic nitrogen concentrations at Havre de Grace monitoring stations, June 1993.



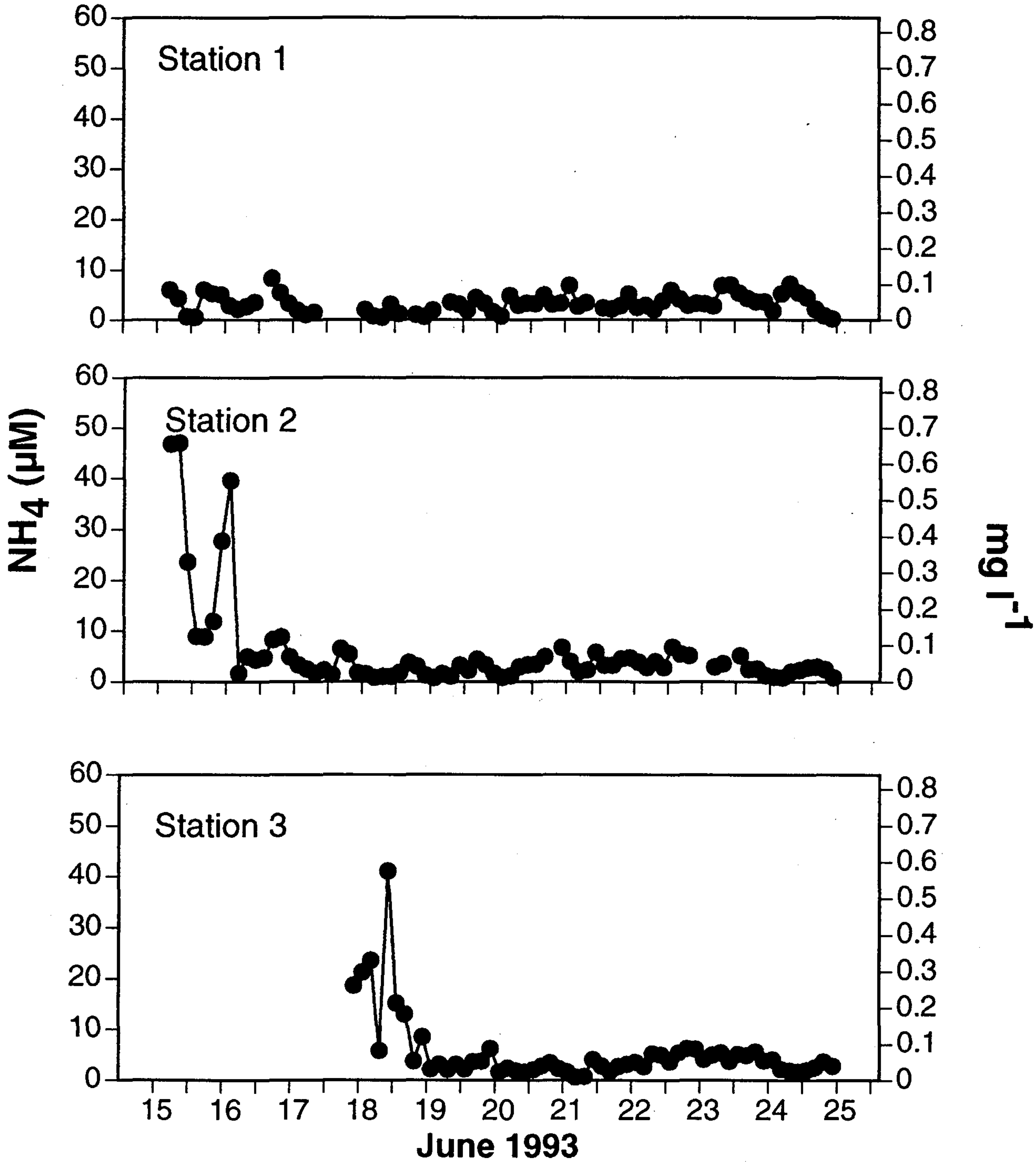
Appendix B21. Dissolved inorganic nitrogen concentrations at Havre de Grace monitoring stations, August 1993.



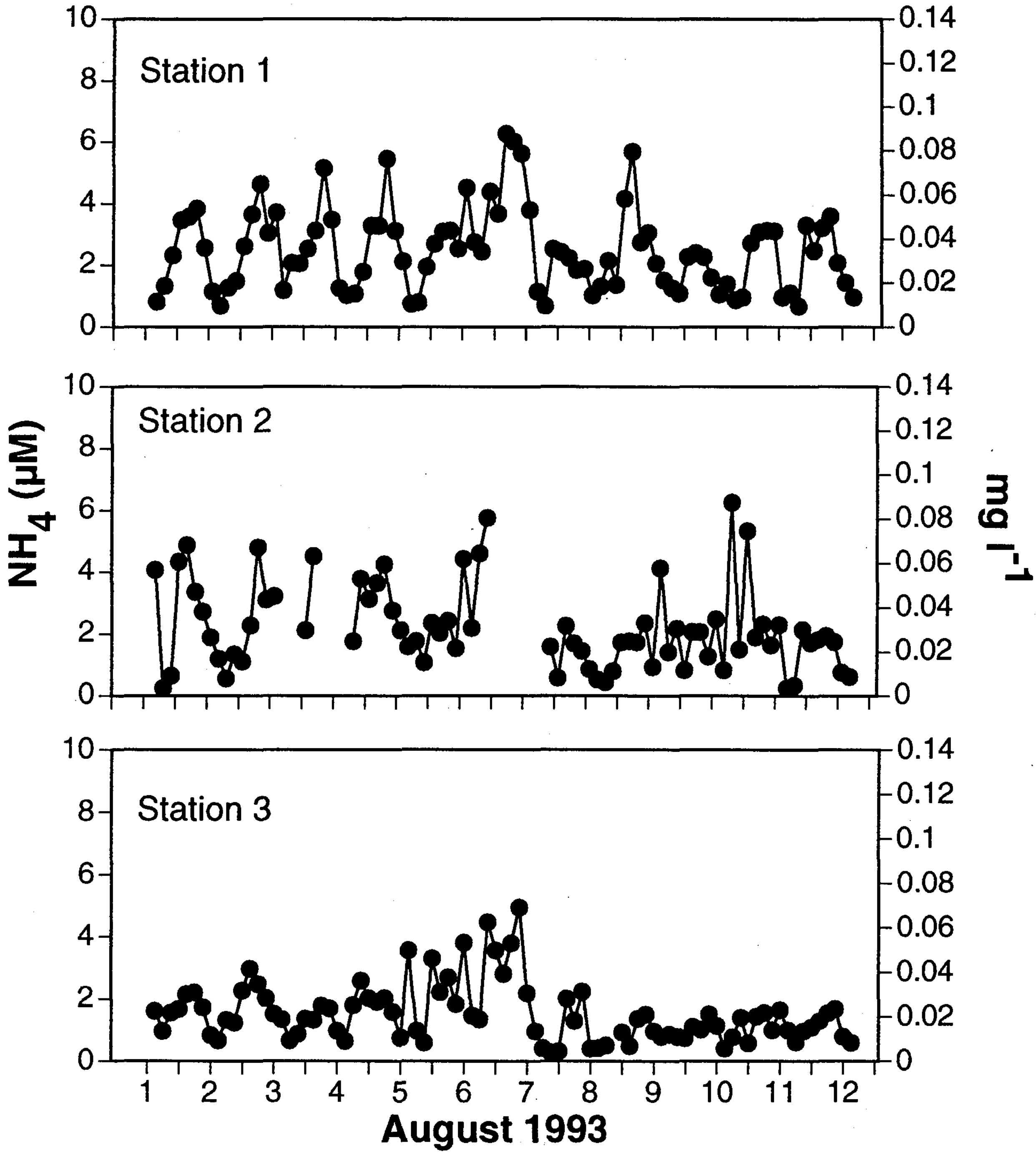
Appendix B22. Dissolved inorganic nitrogen concentrations at Havre de Grace monitoring stations, October 1993.



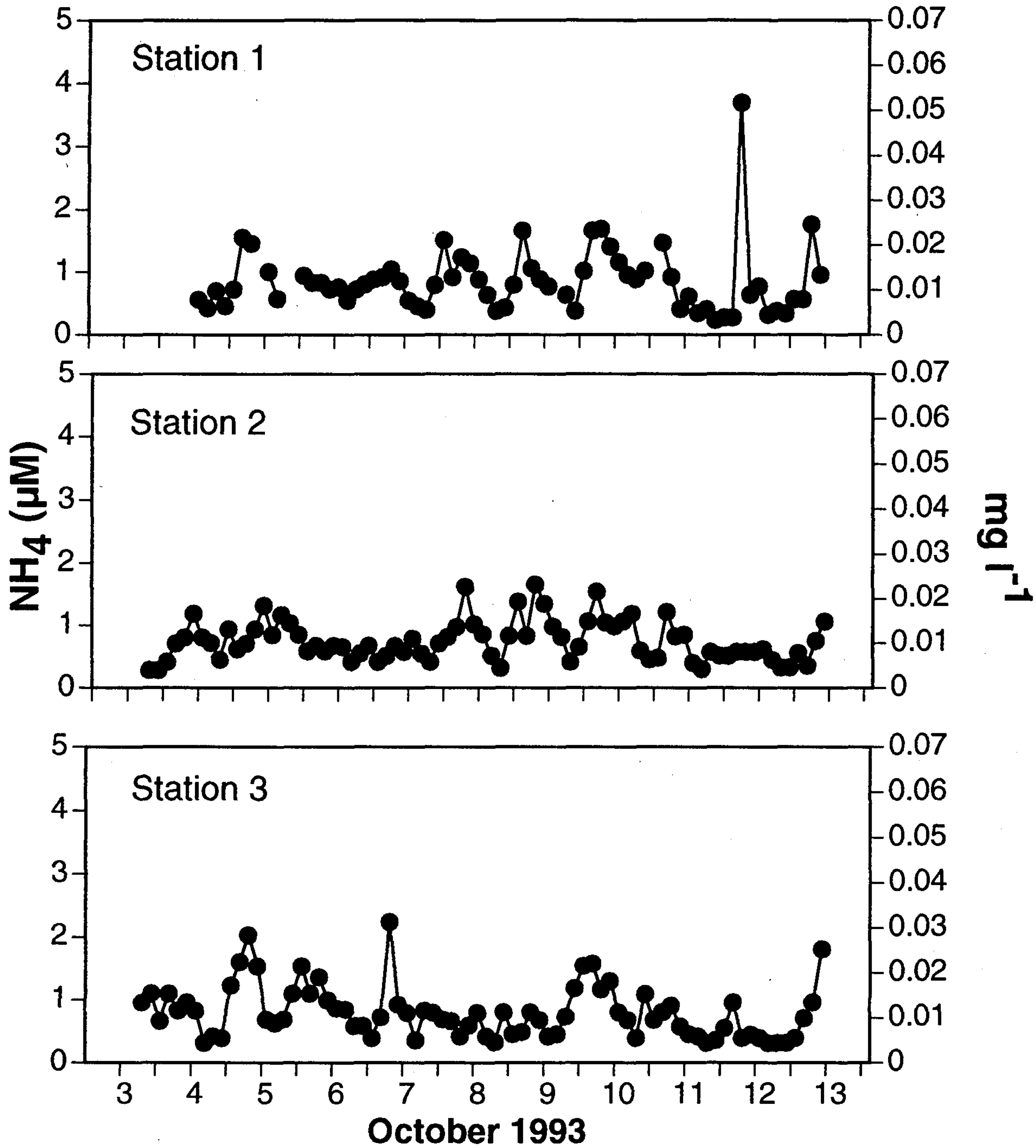
Appendix B23. Ammonium concentrations at Havre de Grace monitoring stations, June 1993.



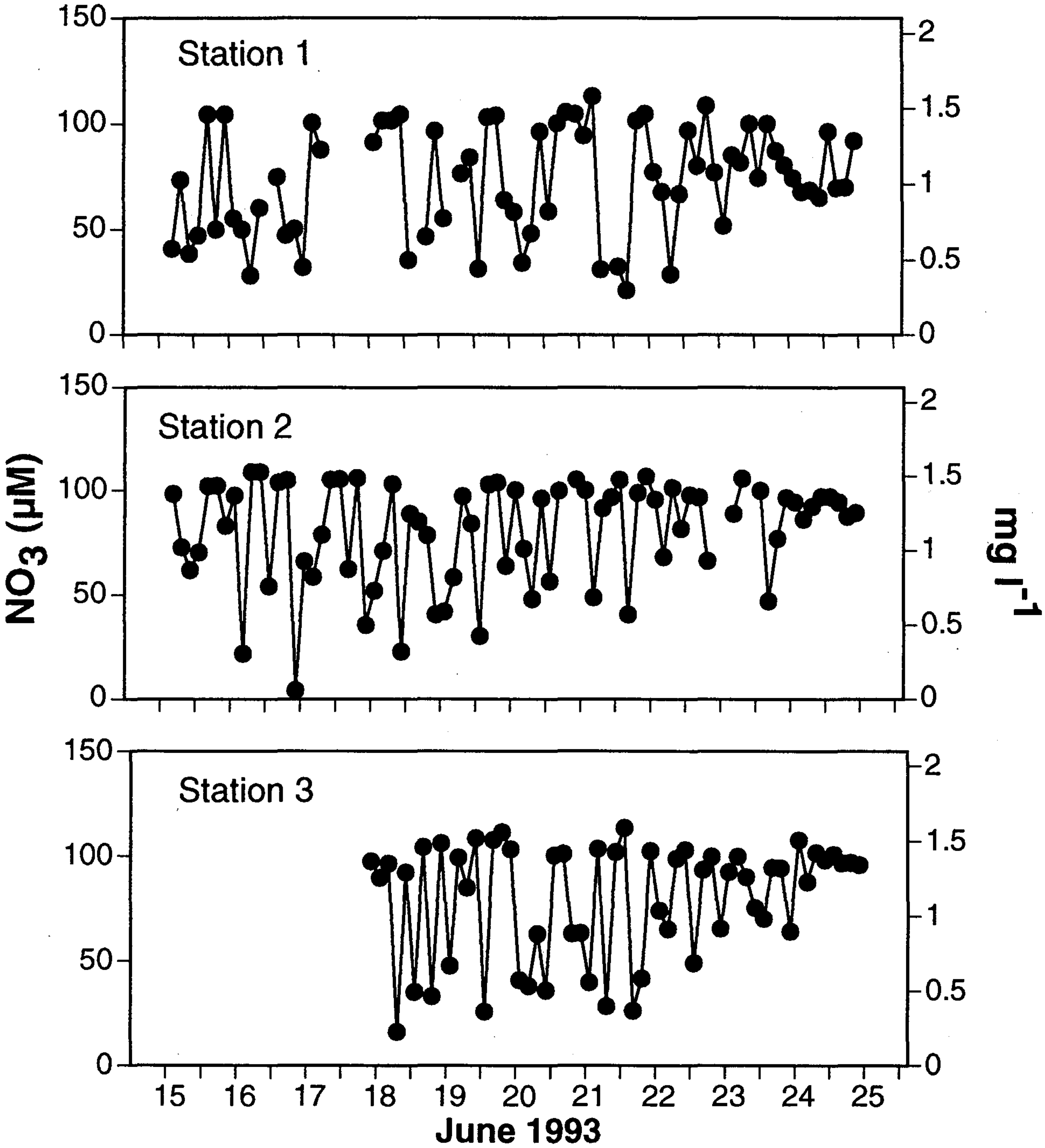
Appendix B24. Ammonium concentrations at Havre de Grace monitoring stations, August 1993.



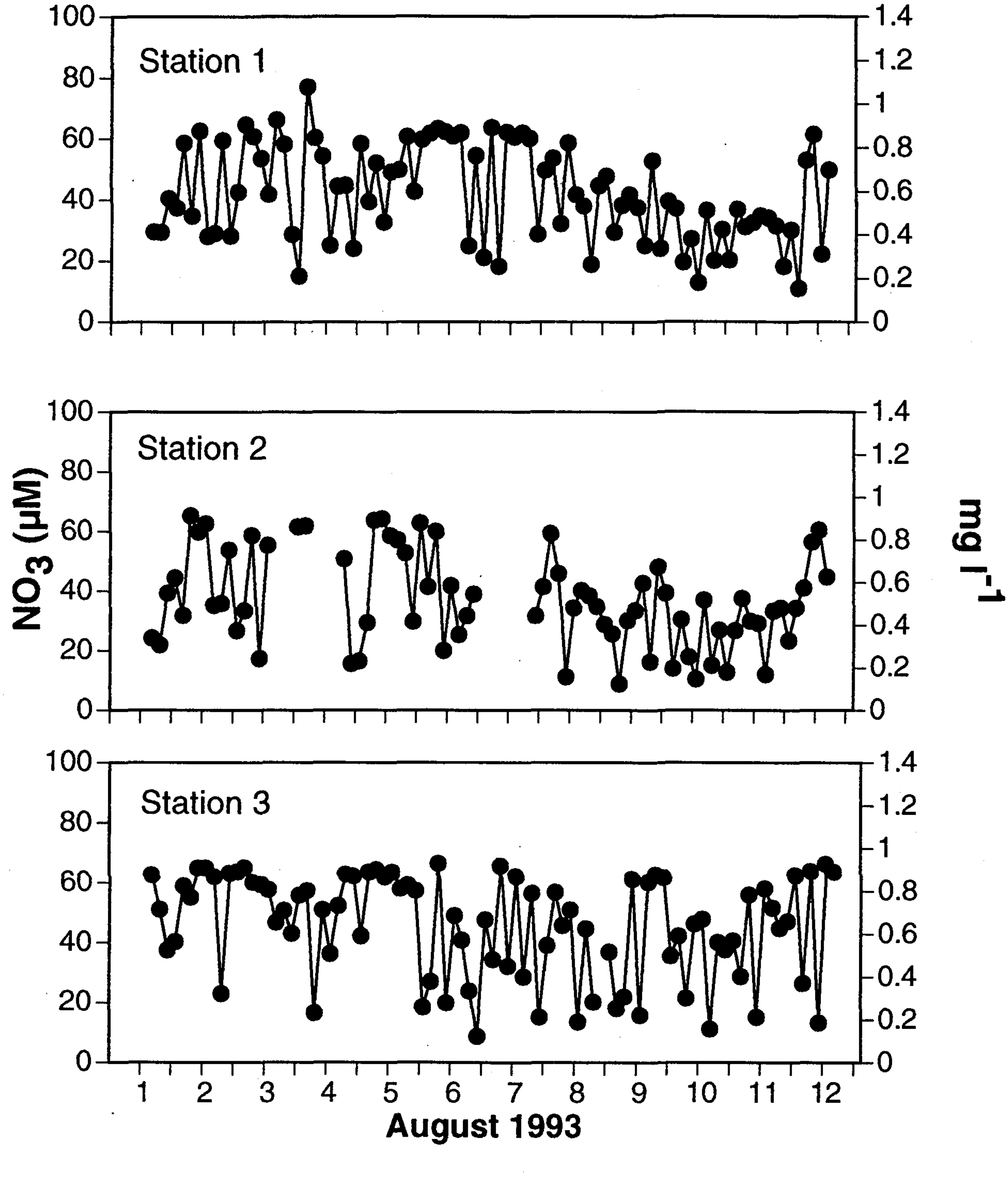
Appendix B25. Ammonium concentrations at Havre de Grace monitoring stations, October 1993.



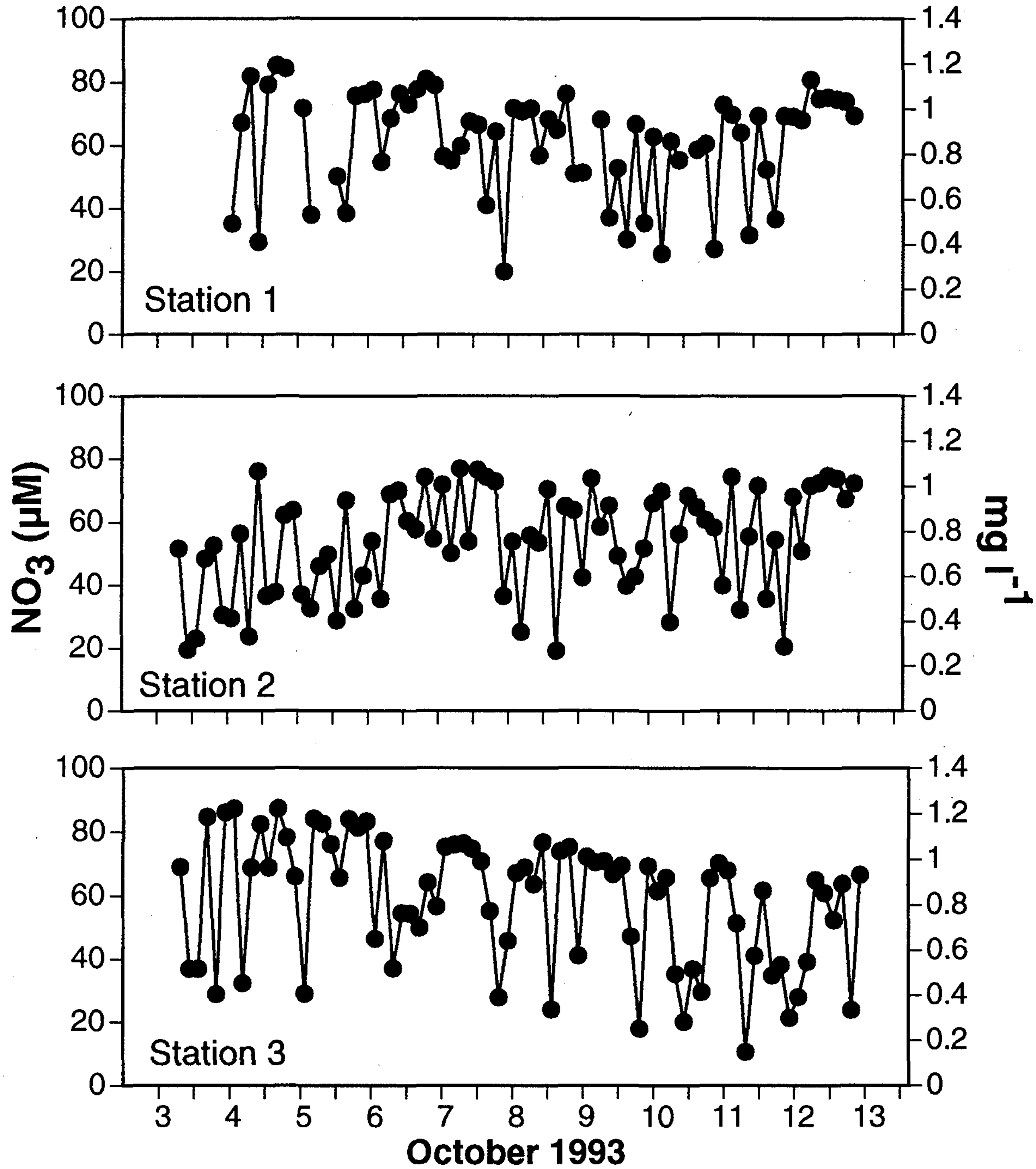
Appendix B26. Nitrate concentrations at Havre de Grace monitoring stations, June 1993.



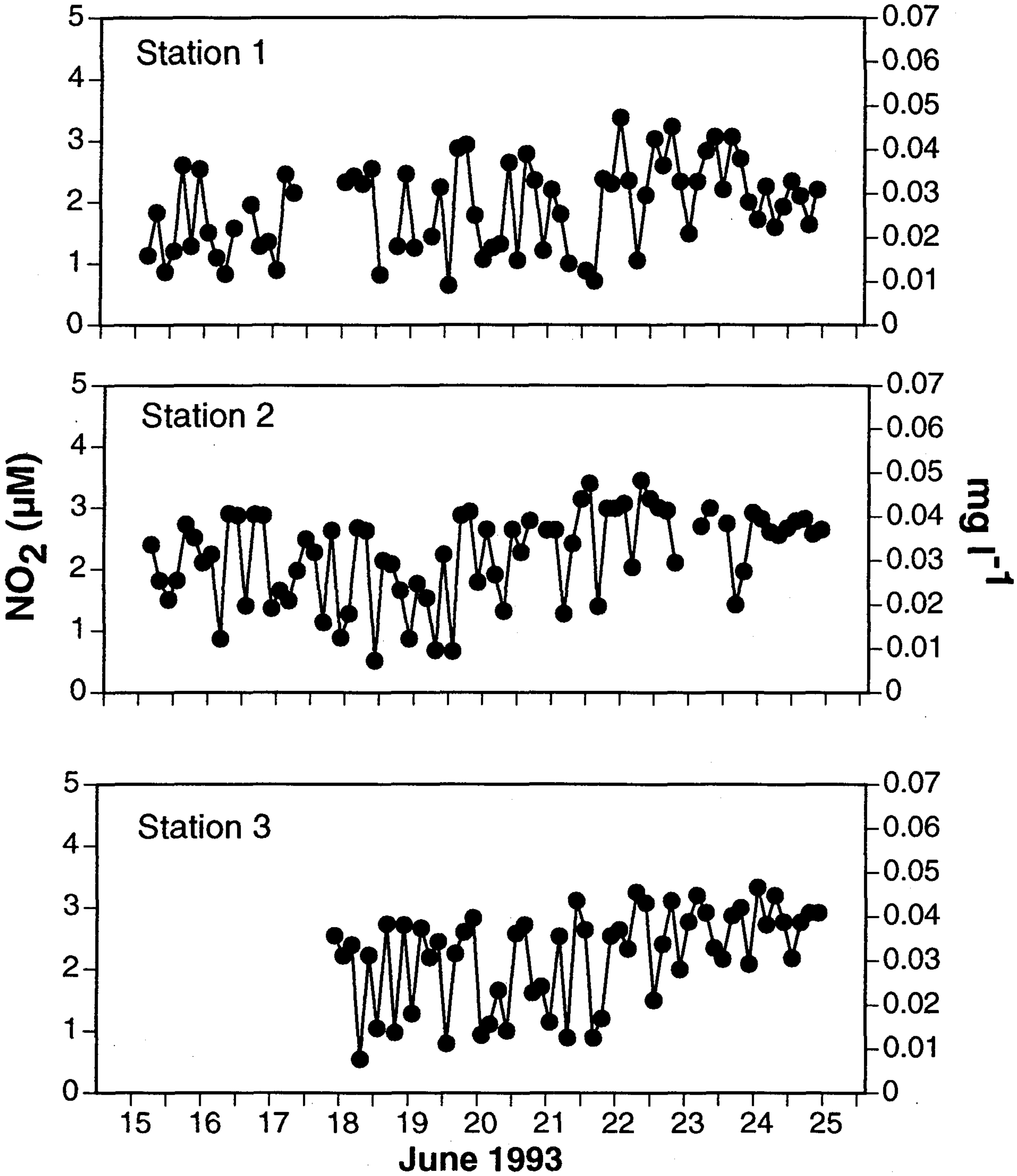
Appendix B27. Nitrate concentrations at Havre de Grace monitoring stations, August 1993.



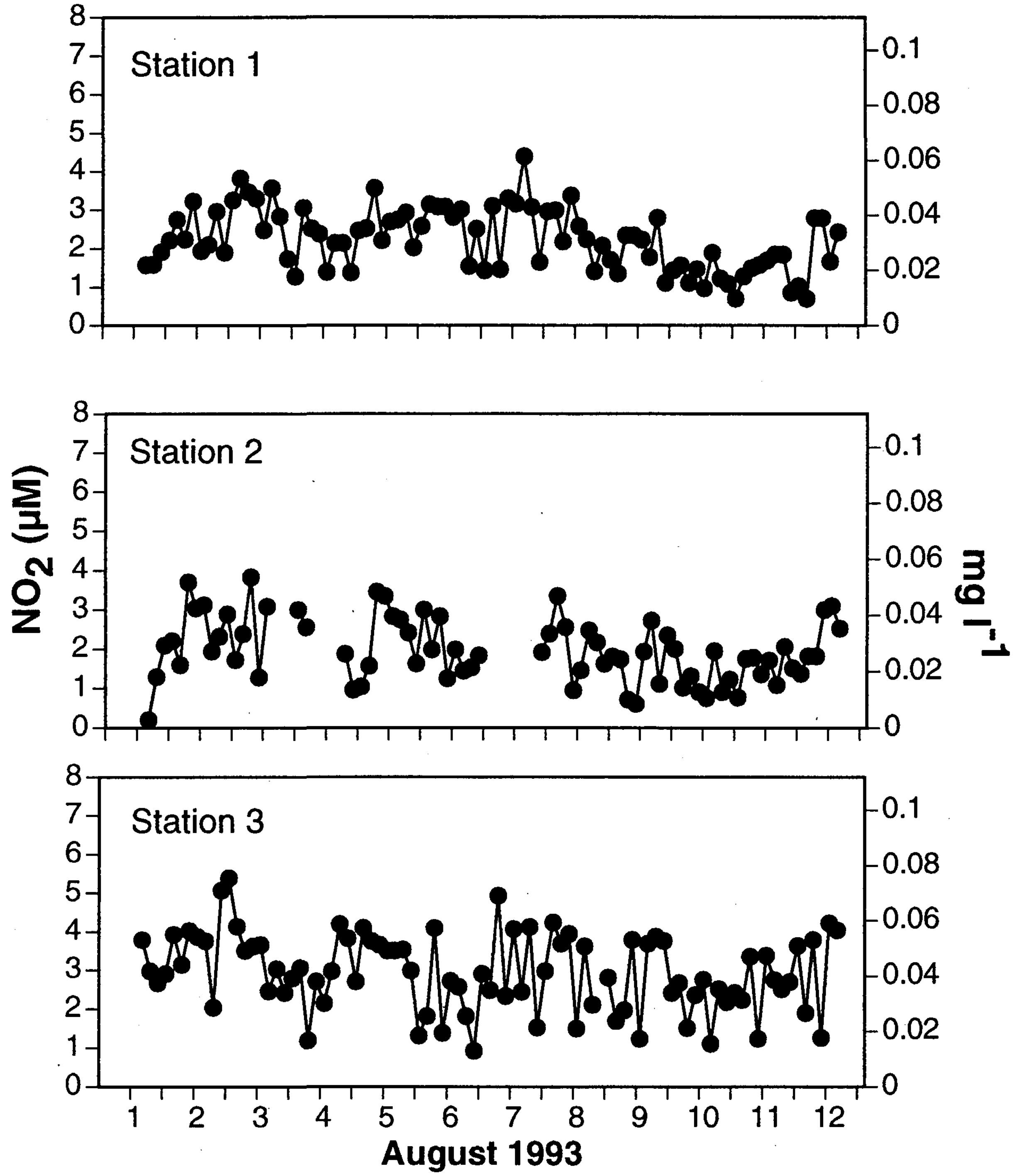
Appendix B28. Nitrate concentrations at Havre de Grace monitoring stations, October 1993.



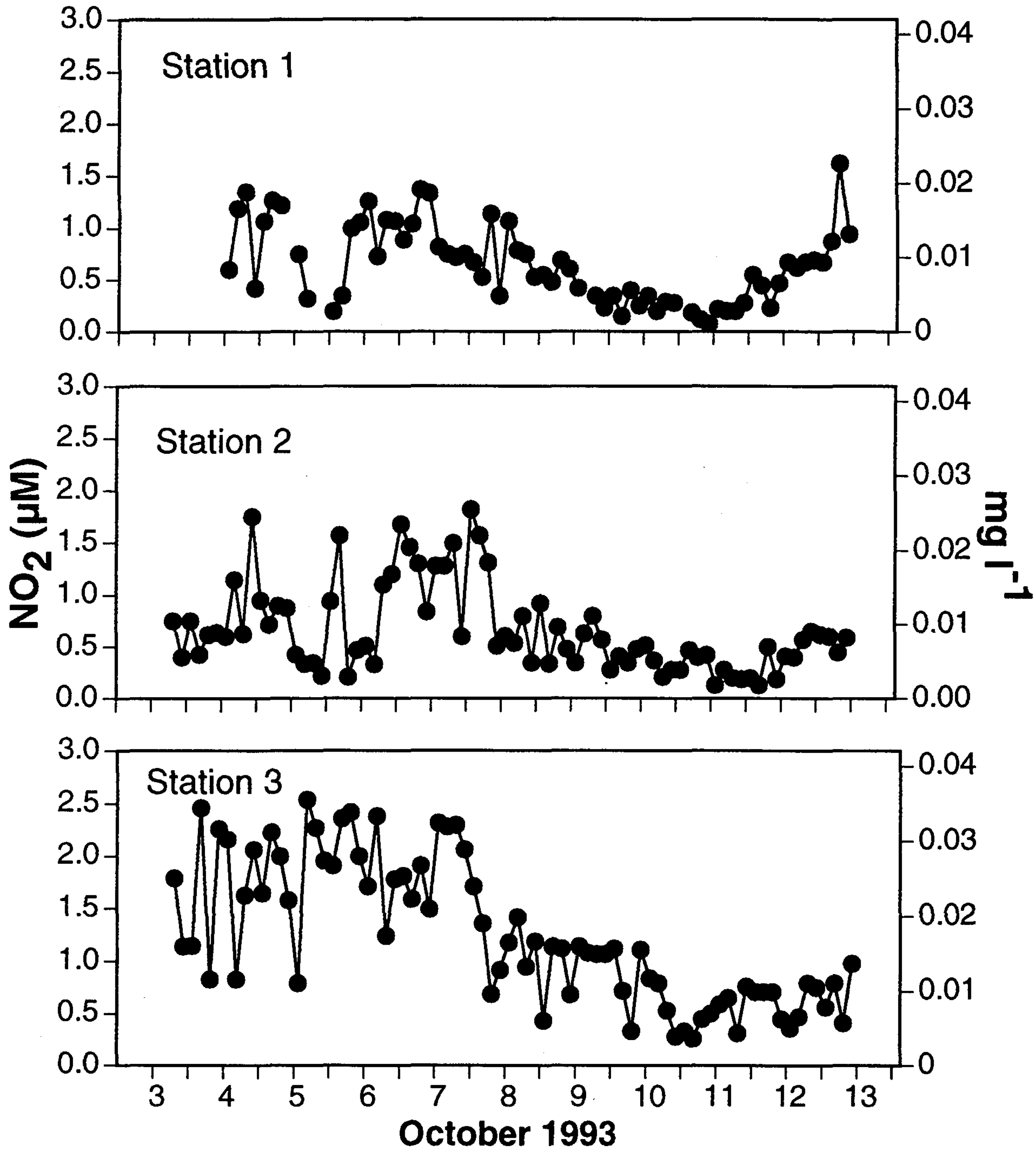
Appendix B29. Nitrite concentrations at Havre de Grace monitoring stations, June 1993.



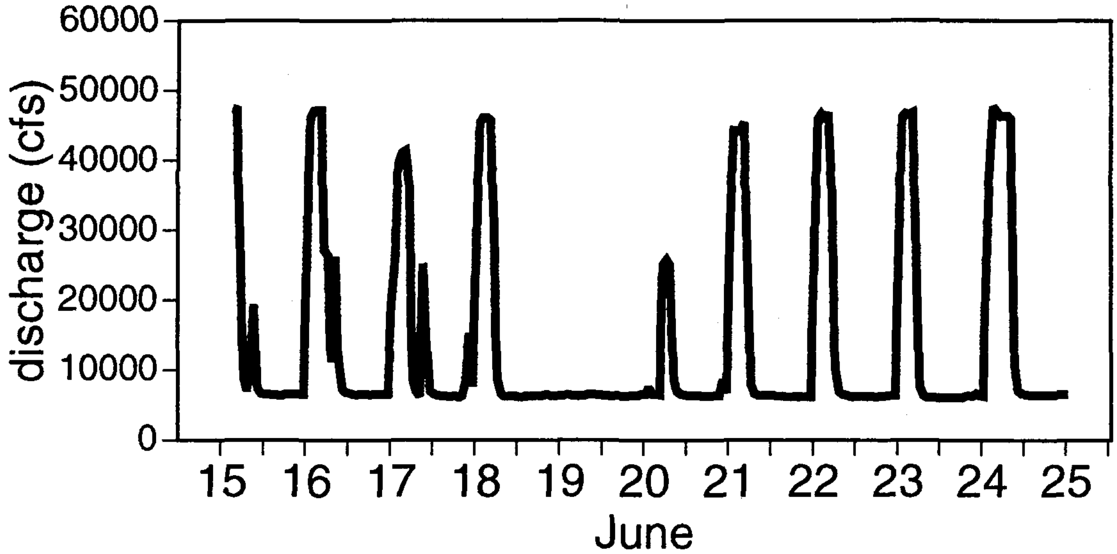
Appendix B30. Nitrite concentrations at Havre de Grace monitoring stations, August 1993.

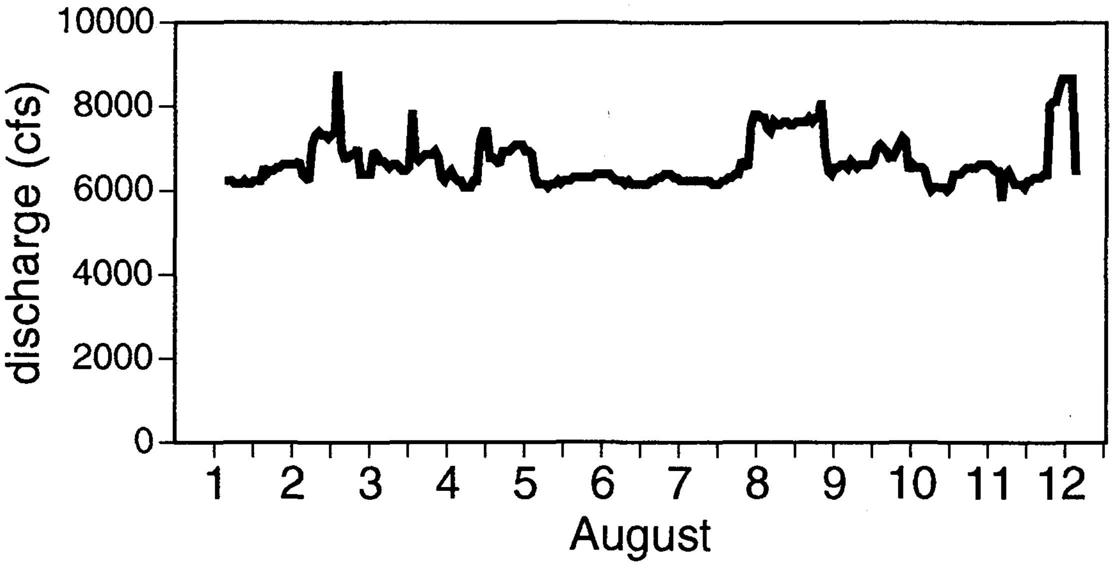


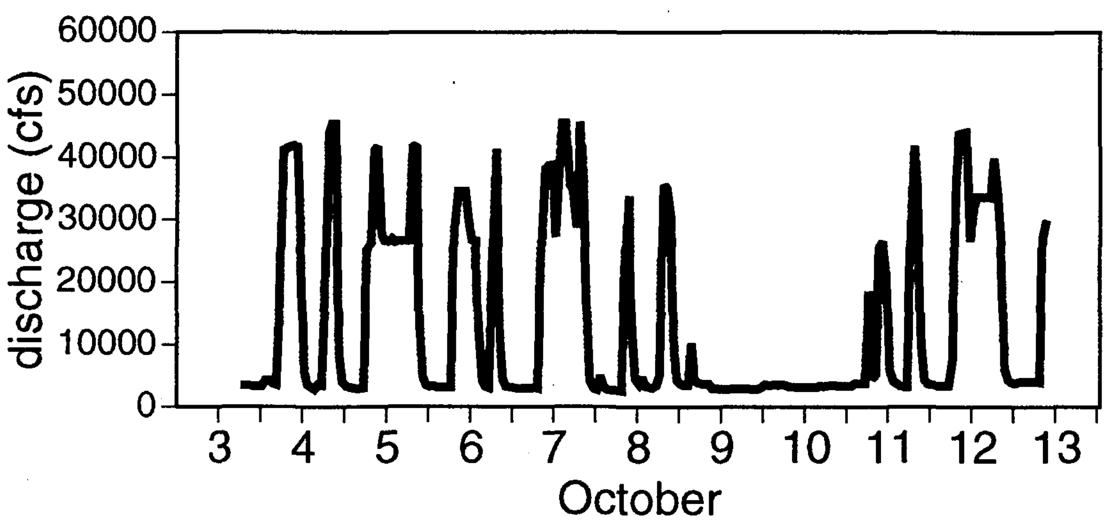
Appendix B31. Nitrite concentrations at Havre de Grace monitoring stations, October 1993.



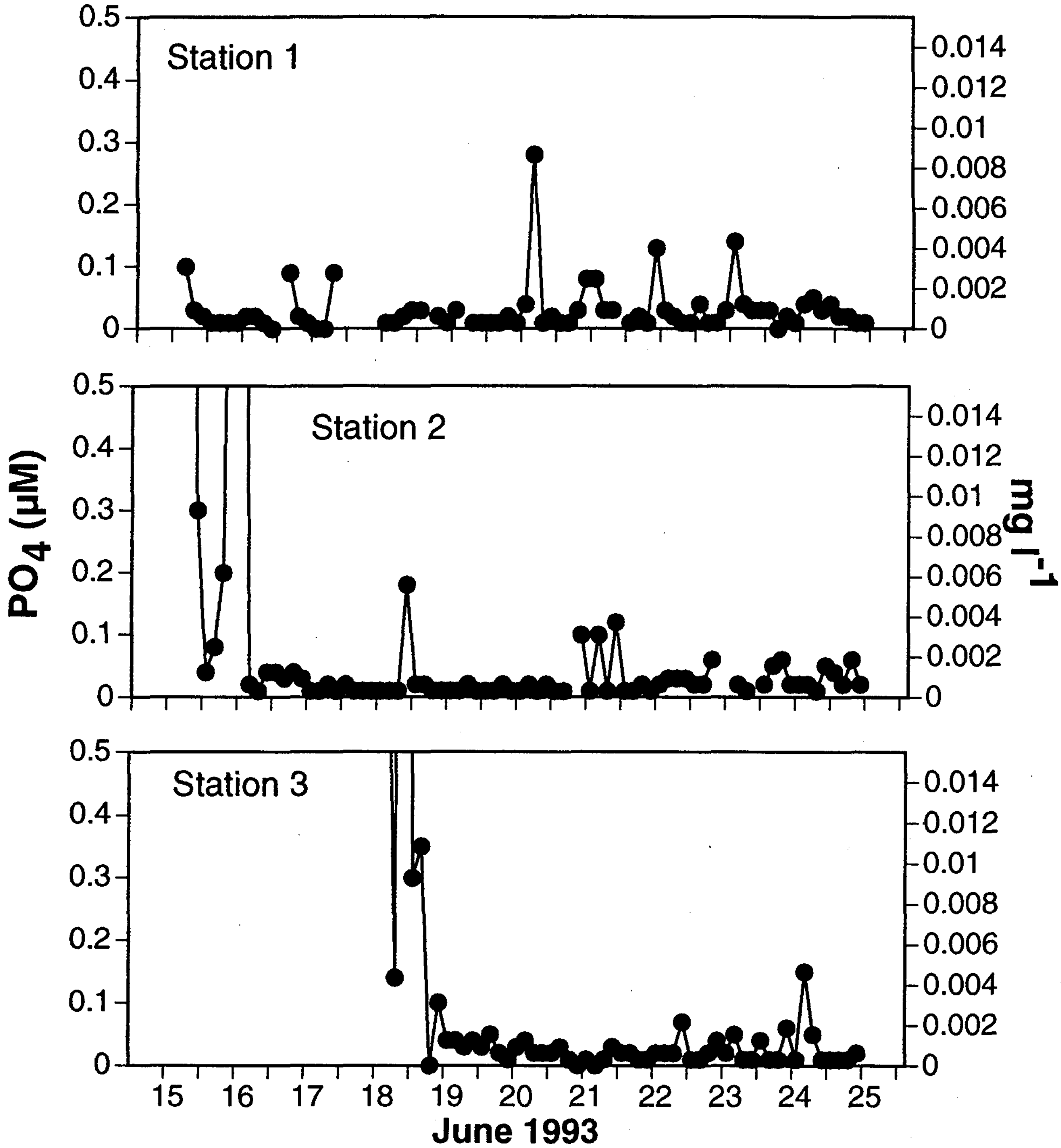
Appendix B32. Discharge at Conowingo Dam, Susquenna River, 1993.



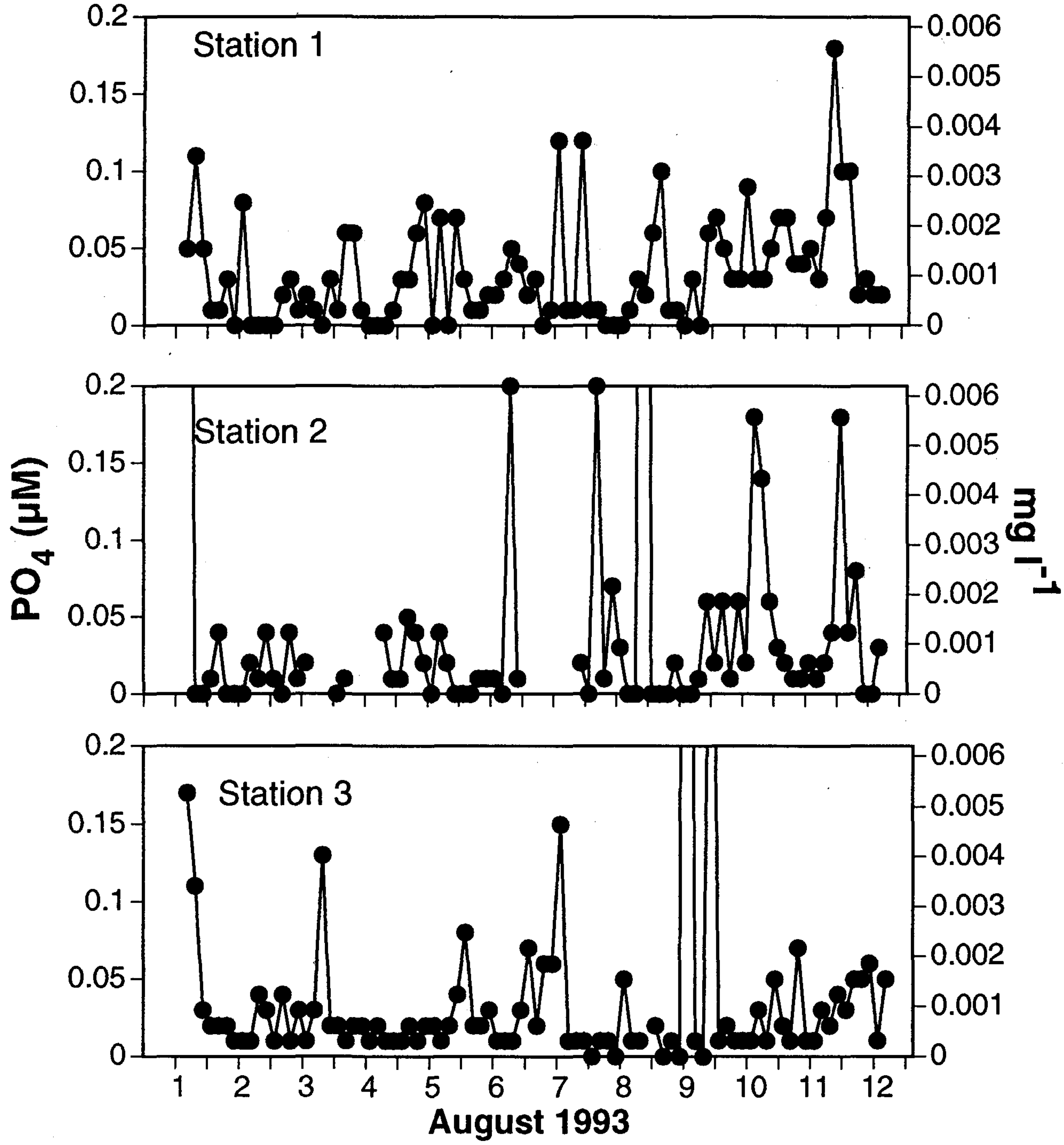




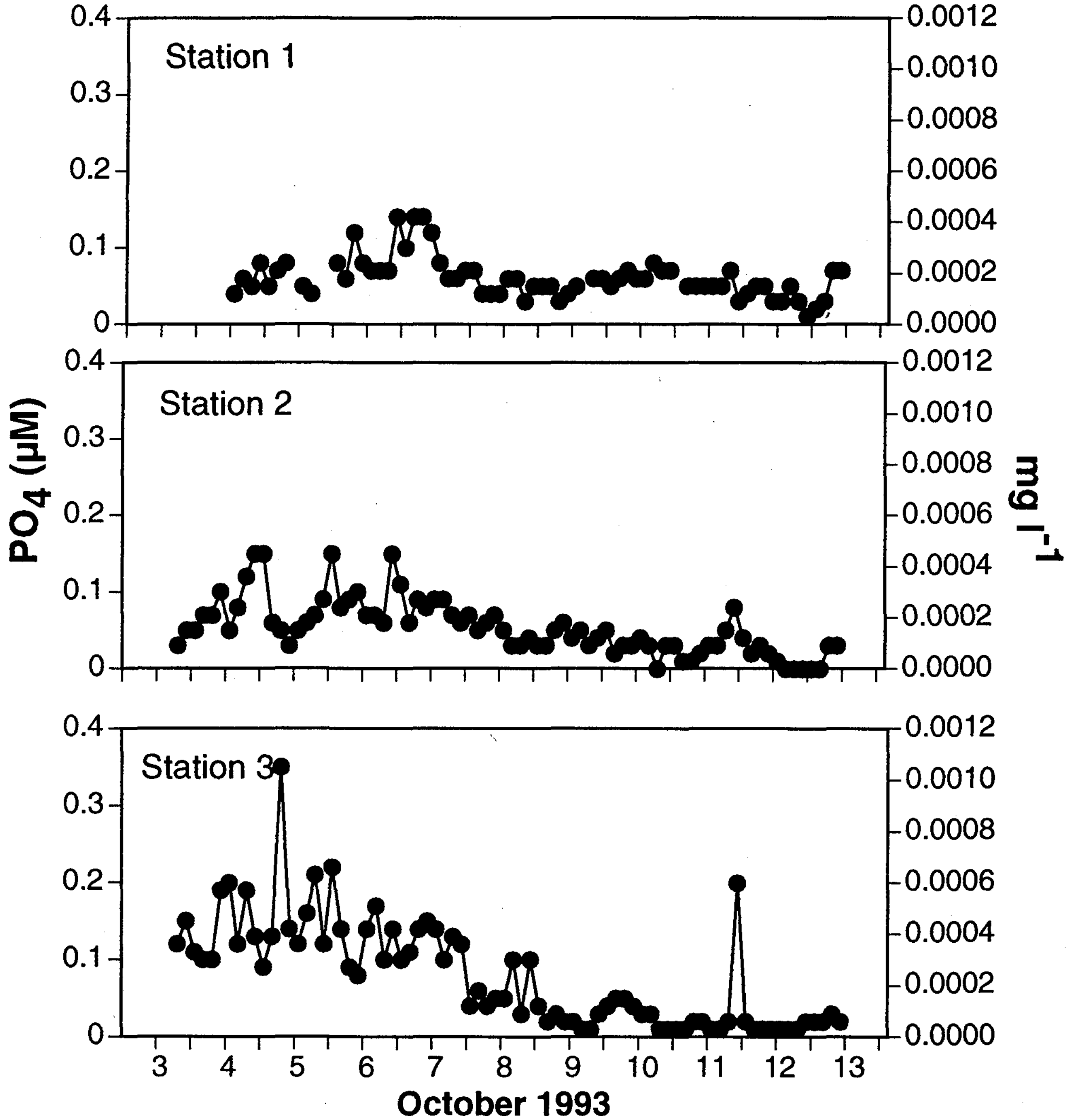
Appendix B33. Phosphate concentrations at Havre de Grace monitoring stations, June 1993.



Appendix B34. Phosphate concentrations at Havre de Grace monitoring stations, August 1993.

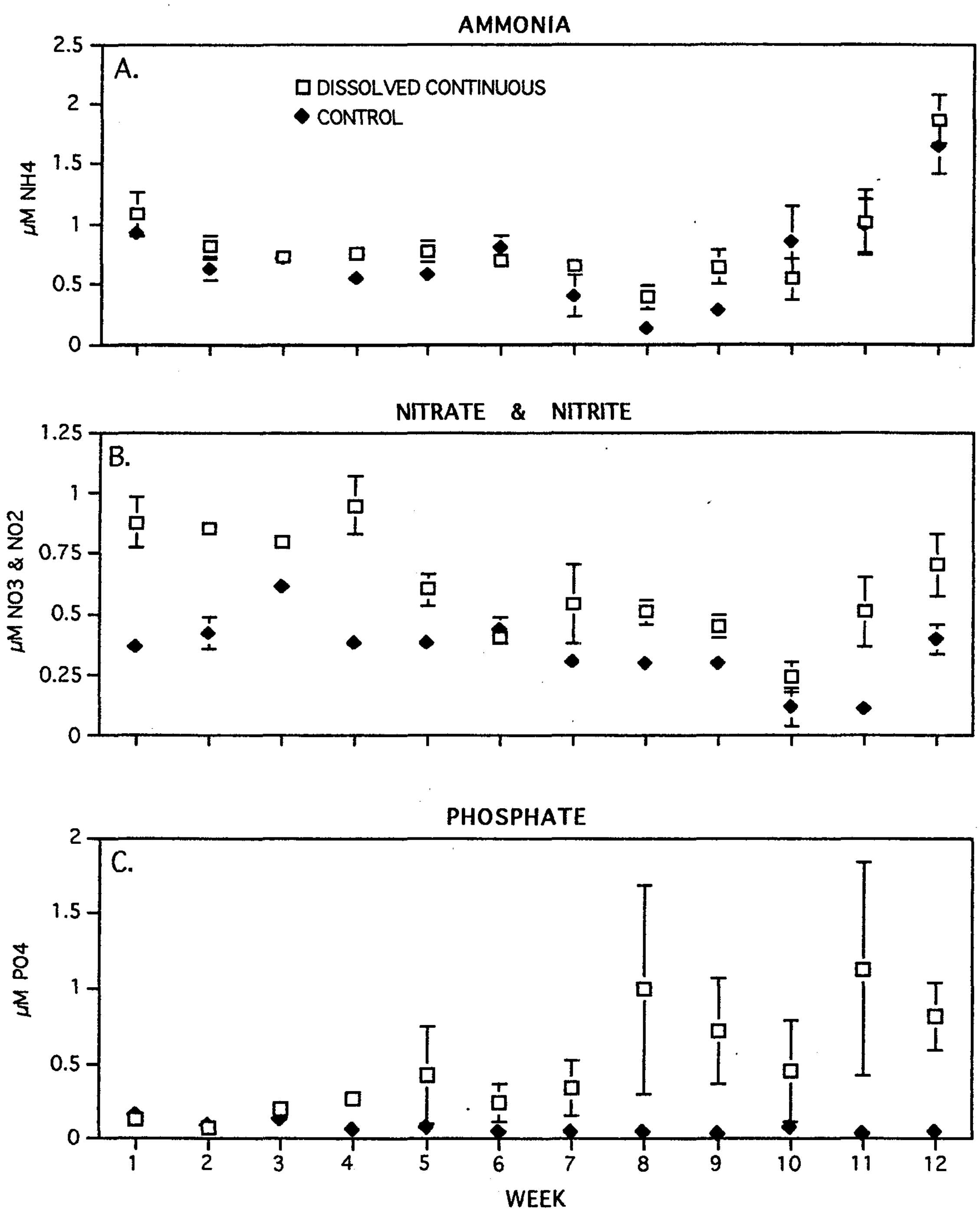


Appendix B35. Phosphate concentrations at Havre de Grace monitoring stations, October 1993.

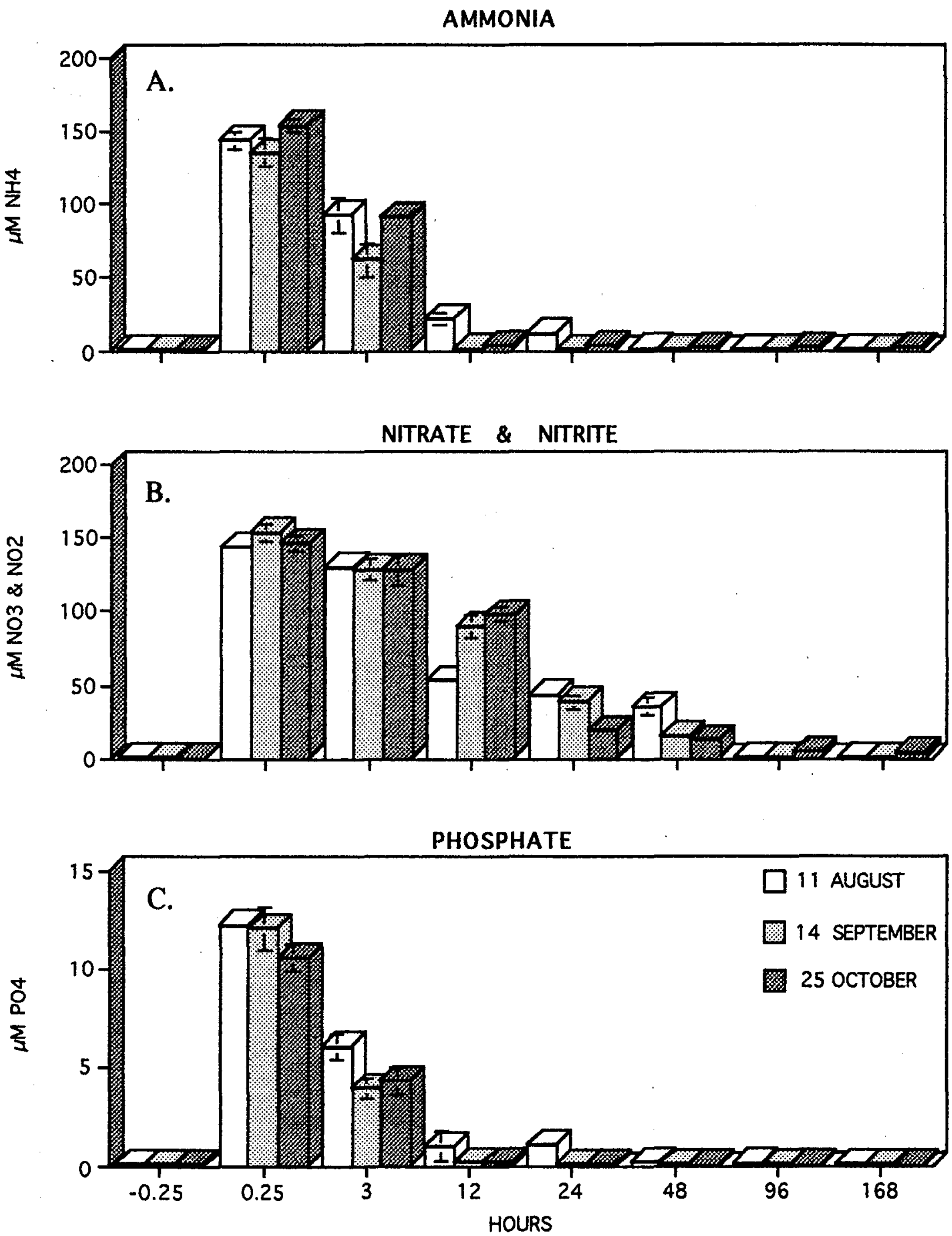


Appendix C

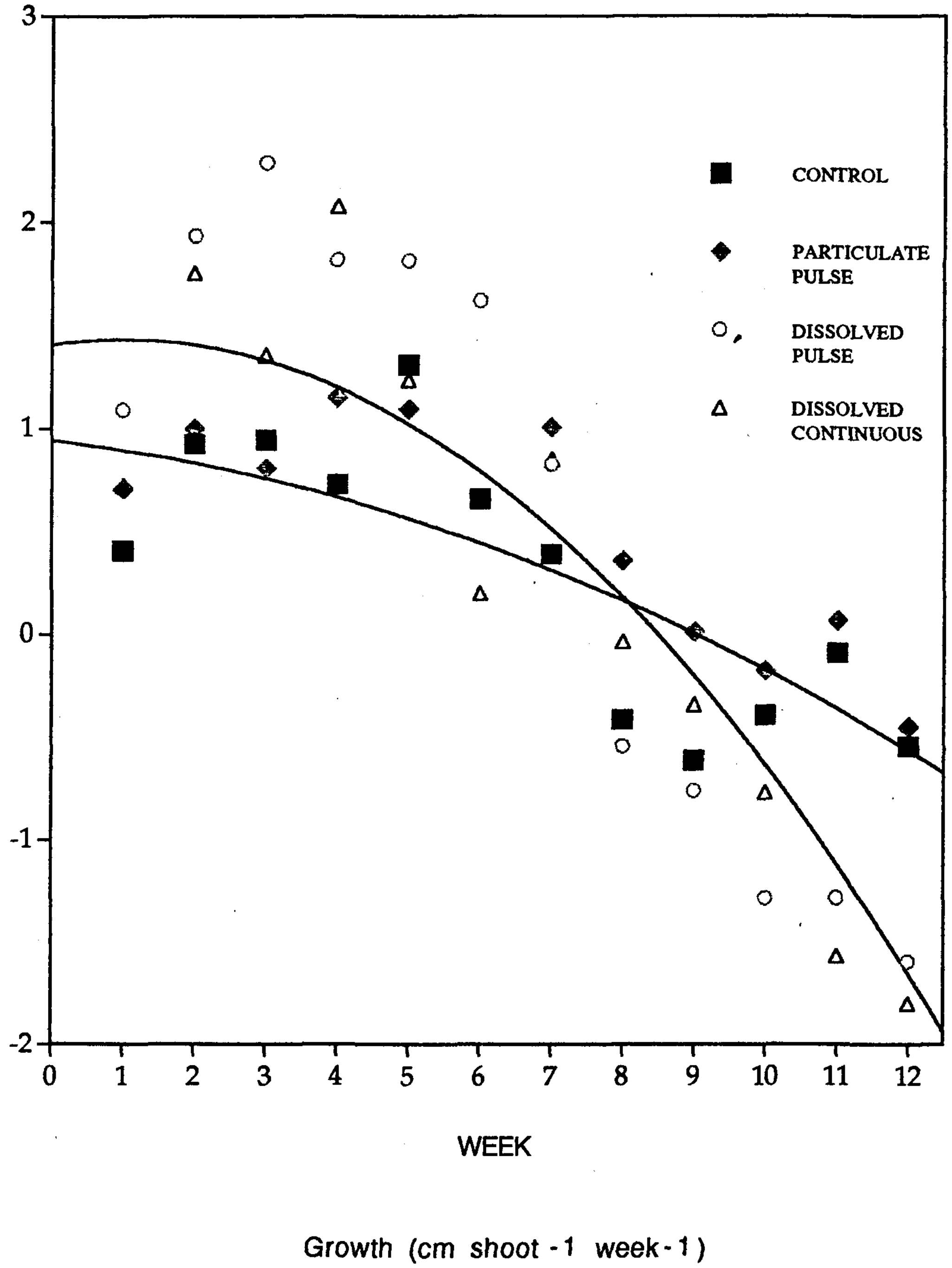
C1: Water column nutrient concentrations for the control and dissolved continuous experimental treatments.



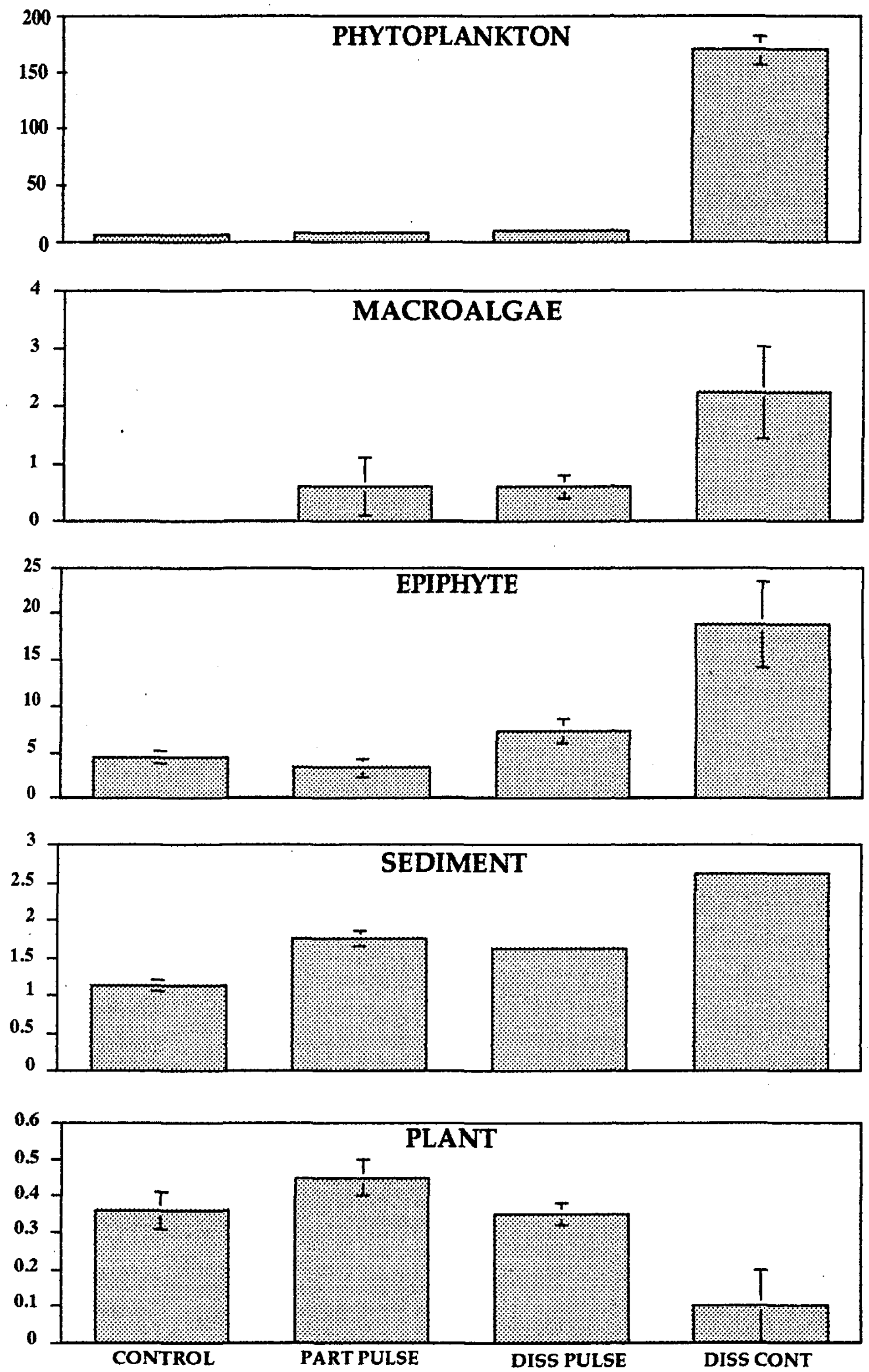
C2: Time series water column nutrient concentrations for the dissolved pulse experimental treatments.



C3: Macrophyte growth rate for control and experimental chambers for the twelve week fall 1993 experiment.



C4: Summary of the autotrophic component biomass at the end of the experiment.



C5: Nitrogen budget for the autotrophic components in the experimental chambers.