FINAL REPORT

Data Synthesis and Analysis
Nitrogen Processes Study (NIPS)
Nutrient Distributions and Dynamics in Lavaca, San Antonio and Nueces/Corpus Christi Bays in Relation to Freshwater Inflow

Part I: Results and Discussion

by

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In response to House Bill 2 (1985) and Senate Bill 683(1987), as enacted by the Texas Legislature, the Texas Parks and Wildlife Department and the texas Water Development Board must maintain a continuous data collection and analytical study program on the effects of and needs for freshwater inflow to the State's bays and estuaries. As part of the mandated study program. This research project was funded through the Board's Water Research and Planning Fund, authorized under Texas Water Code Sections 15.402 and 16.058(e), and administered by the Department under interagency cooperative contract No. 9-483-705, 9-483-706, 8-483-607.

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CHAPTER I - SAN ANTONIO BAY (NIPS-I)

INTRODUCTION

The Nitrogen Processes Study (NIPS) was undertaken under contract from the Texas Water Development Board in order to better understand the relationship of freshwater inflow into South Texas estuaries and the biological productivity that occurs in them. It is important to study the characteristics of the inflow especially the nitrogen components because nitrogen is generally regarded as the "essential" nutrient whose abundance controls the amount of biological production of an ecosystem (Ryther and Dunston, 1972; Thayer, 1974; Boynton *et al.*, 1982).

The extent that an estuary provides habitat for organisms is mainly related to food availability and/or protective cover. The difference that creates the protective cover or food availability is the freshwater inflow into the estuary. The quantity of freshwater into an estuary can be quite variable on all time scales but without that inflow the estuaries would merely be like the rest of the marine coastline. The freshwater provides habitat for brackish plants and animals by reducing the salinity and by carrying dissolved nutrients, particulate organic matter, and sediment, while the seawater itself is not a very large source of these materials. The riverine organic matter is often largely composed of carbonaceous material with a low food quality in such materials as leaves, stems and wood fiber while the dissolved nutrients entering the estuary can be utilized for plant growth and provide food for the animal populations. So the nutrient content of the freshwater along with salinity reduction effects provide critical aspects that important animal populations require, especially in the larval and juvenile stages.

The Program

The NIPS program was organized around a conceptual model of nitrogen utilization in San Antonio and Nueces/Corpus Christi Bays (Fig. 1). Each of the boxes represent a biomass or standing stock for ecosystem components while arrows represent fluxes or transfer rates between the components. The utility of such a model is to help organize and coordinate field measurements so that all of the most important organisms and processes are included in the study. In a practical sense, only a finite amount of organisms and processes can be investigated at one time therefore the most important ecosystem components were chosen for the study in the NIPS program and these are depicted by boxes with solid lines. Likewise only the flux rates with solid lines were chosen for measurement while the dashed line boxes and arrows were not included in this study. The subject of this component report is nutrients and their importance in the San Antonio Bay ecosystem. Several of the measurements made by the nutrient component were in collaboration with other components like - phytoplankton, zooplankton, benthic meiofauna and isotopic studies.

The Products

The ultimate product of the NIPS program is a more comprehensive set of simultaneous measurements collected synoptically and analyzed in unison to create a new and better characterization of process rates and biomasses in the San Antonio, Nueces/Corpus Christi and Lavaca Bay ecosystems and to determine the influence that freshwater inflow has in maintaining the bays and estuaries as they exist today.

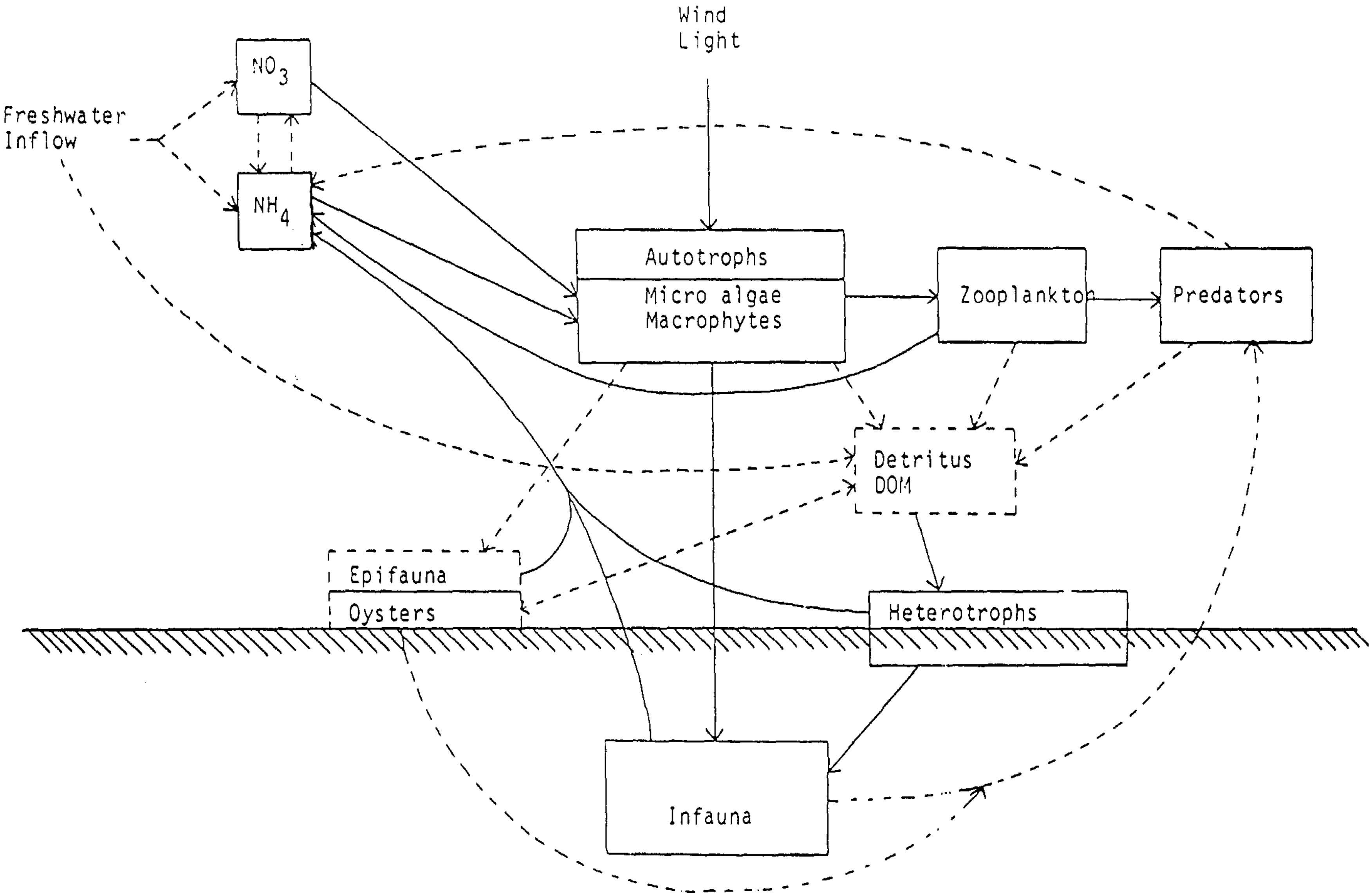


Figure 1. Conceptual model of nitrogen cycle in San Antonio Bay, with boxes representing biomass and arrows representing fluxes. Solid lines represent proposed measurements and dashed lines represent data not being collected.

Specifically, the nutrient component will discuss the following topics:

1. How does the river inflow interact with bay water to produce nutrient distributions in the bay over space and time?
2. How and where are the nutrients used in the bay? Is nitrogen more important than phosphorus and silicate?
3. Do primary production processes utilize any particular form of nitrogen in preference over another especially when the waters are turbid from river sediment or resuspended by the winds?
4. What is the relationship of nutrients to conservative properties like salinity or other tracers?
5. What qualitative evidence is available to relate resuspension of sediments to increased nutrients concentration on the water column?
6. What physical transport processes can be deduced from the distribution of parameters measured at each of the stations?
7. What approximate direct quantitative effects did increased freshwater inflow have on nutrient concentrations in the bays?
8. What long term effects, if any, did the increased freshwater inflow have on nutrient properties in the bay?
9. How does the physical characteristics of a bay affect circulation and distributions of properties within the bay?

The Study Area

The NIPS-I program was carried out in San Antonio Bay from November 1986 through July 1987 with a later followup trip in July 1988. Thirty hydrographic sampling sites were occupied within San Antonio Bay for distribution of properties (Fig. 2). Process rates measurements were collected at four of the stations (A,B,C and D) that were aligned along a salinity gradient. Six sampling trips were undertaken during the regular study plus additional follow up for a total of seven. Process rate measurements were collected on five trips.

METHODS

Sample Collection

The areal distribution of temperature, salinity, nutrients (nitrate, nitrite, ammonium, o-phosphate and dissolved silicon), chlorophyll a, water transparency (Secchi disk and profiling quantum meter), and dissolved oxygen were determined throughout San Antonio Bay estuary (includes Ayres and Mesquite Bays) at 38 sampling sites (Fig. 2) on six occasions from late 1986 through summer 1987 and a followup sampling in July 1988. The surveys were conducted in San Antonio Bay during a single day starting at the headwaters. Polyvinylchloride pipes were used to mark the station locations in areas of open bay if landmarks or structures were absent. Water samples were collected from the surface by hand immediately below the surface film. In shallow water (< 2m) near bottom water samples were collected with a horizontal water sampling bottle (Kahl model #CEPWASO 2). All water samples were collected from the same sampling bottle. In deeper water, a

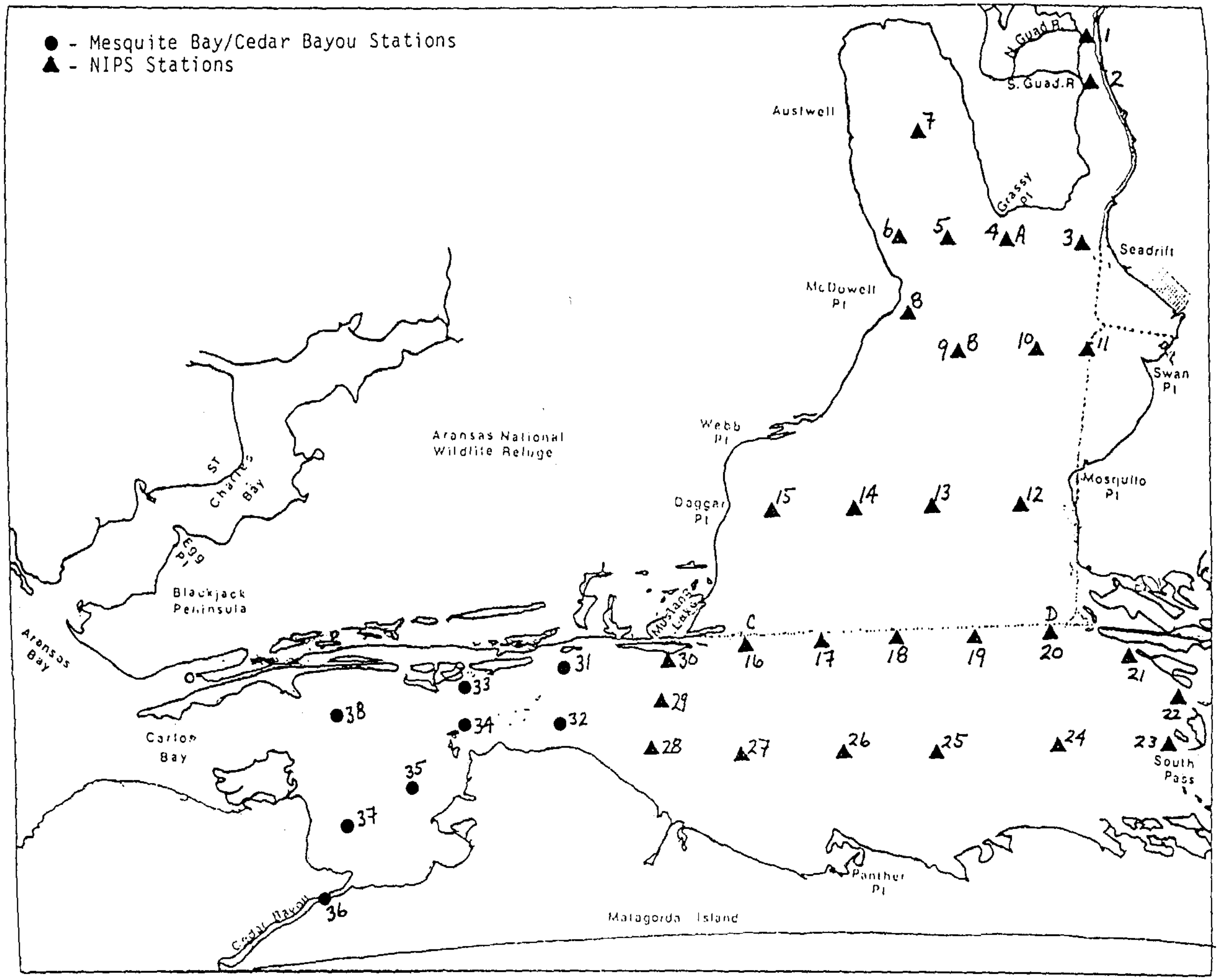


Figure 2. Survey and experimental station locations in San Antonio Bay.

5 liter Niskin bottle was adapted to automatically trip 10-15 cm above the bottom. If bottom disturbance was apparent, the samples were retaken.

Nutrients

The 60 ml subsamples were immediately drawn from the sampling bottle and cooled by ice in the dark. Within three hours, the samples were transported to the shipboard laboratory and analyzed for phosphate, silicate, nitrate plus nitrite, nitrite and ammonium using automated, continuous-flow colorimeters. Data acquisition and control were managed by a Hewlett-Packard 9845A computer. The procedures of Whitledge *et al.* (1981) were utilized as they apply to a Technicon AutoAnalyzer II which had been modified with small-volume glassware to optimize stability and sensitivity. The analytical methods of Murphy and Riley (1962) were followed for reactive phosphorous, and Armstrong *et al.* (1967) for silicate and nitrate. Ammonium was measured by the phenolhypochlorite method of Koroleff (1970) as adapted to the AutoAnalyzer by Slawyk and MacIsaac (1972) and modified by Patton and Crouch (1977).

The analytical accuracy was determined by measuring the absorbances of five known concentrations of each analyte (standards) at least once every 12 hrs. These were regressed upon concentrations using a least squares method, from which updated chemical factors were derived. The standards of highest concentration were also included among each set of station samples to monitor analytical stability (Whitledge *et al.* 1981).

Time

Time was recorded as local to the nearest minute using a digital watch that was recently checked and set.

Temperature

Temperature was determined at each station at the surface and near bottom to the nearest tenth of a degree (0.1°C) Celcius using a model 4000 Hydrolab. Surface readings were collected first and then near bottom. If large variations between surface and bottom values were noted, additional determinations were made. The last sampling in July 1988 utilized a Seabird model SeaCat high precision CTD to accurately profile temperature on each station with a resolution of 0.01°C.

Salinity (Conductivity; Refractivity)

Salinity was determined at each station using conductance measurements from a model 4000 Hydrolab that were automatically corrected to 25°C. In addition, a direct estimation of salinity was determined by a hand refractometer for comparison purposes. The estimated accuracy of the Hydrolab was quoted to be 0.1‰ while the refractometer has been shown to be ± 1‰ when calibrated (Behrens, 1965). The last sampling in July 1988 utilized a Seabird model Seacat high precision CTD to accurately profile salinity at 2-3 cm intervals on each station with a resolution of 0.01 ‰. Conductance measurements from the Hydrolab were converted to salinity units using the practical salinity scale (Lewis and Perkin, 1981) that accounts for temperature and pressure factors. Some calibration samples were also collected in the field, returned to the laboratory, and analyzed for conductivity ratio using the AGE Minisal salinometer which had an accuracy of 0.005 ppt.

Water Transparency

Water transparency was determined with a standard size Secchi disk to the nearest 5 cm. Only one individual collected the measurements on each field trip. An integrating quantum meter (Licor model LI-1905A) was used to calculate extinction of coefficients during the four experimental sampling trips.

Bottom Depth

Bottom depth of less than 3m was determined to the nearest 5 cm with the Secchi disk which was lowered until the line went slack. In deeper water, the depth sounder was read in feet and converted to meters.

Chlorophyll a and Phaeopigments

Samples for chlorophyll a and phaeopigments were collected from the surface and bottom sampling bottle in calibrated syringes. The 10 ml samples were filtered in the field, placed in scintillation vials containing 90% acetone and placed on ice in the dark. The samples were transferred to a shipboard freezer as soon as possible for transportation to the laboratory. The method of Holm-Hansen *et al.* (1965) was used to analyze the samples fluorometrically.

Dissolved Oxygen

Dissolved oxygen was determined at each station using a model 4000 Hydrolab. The estimated accuracy of the oxygen determination is quoted as 0.1 mg/liter.

Latitude and Longitude

Latitude and longitude of the sampling locations was determined with a Furuno loran model LC-90. The position readings for several sampling trips were compared and averaged for each sampling site. Sampling sites near accurately known land marks were checked to assure accuracy.

FRESHWATER INFLOW

The Guadalupe River inflow has previously been estimated to require about two months to fill the entire bay system between Matagorda and Aransas, during high flow periods and as long as six months during low flow periods (Steed, 1972). A 45 day running mean was taken for the Guadalupe River gaged flow to represent the effect of river flow on San Antonio Bay (Fig. 3). This calculated result of the water inflow to San Antonio Bay therefore is an adjustment to increase memory in the system for constituents. The gaged inflow for the 35 year period of 1941 through 1976 was a mean value of 4.96×10^3 acre-ft/day. The year of 1987, however, had a high value of ~ 230×10^3 acre-feet/day and 1988 with a high of about 10×10^3 acre-feet/day. The mean flow over the three year period before the 1987 floods was 2.58×10^3 acre ft/day (range of 1 acre-ft/day to 40×10^3 acre-ft/day) while the mean for 1987 was 10.63×10^3 acre-ft/day. Using this range of river flow and considering the volume of San Antonio Bay (.754 Km^3) (Armstrong, 1987), the

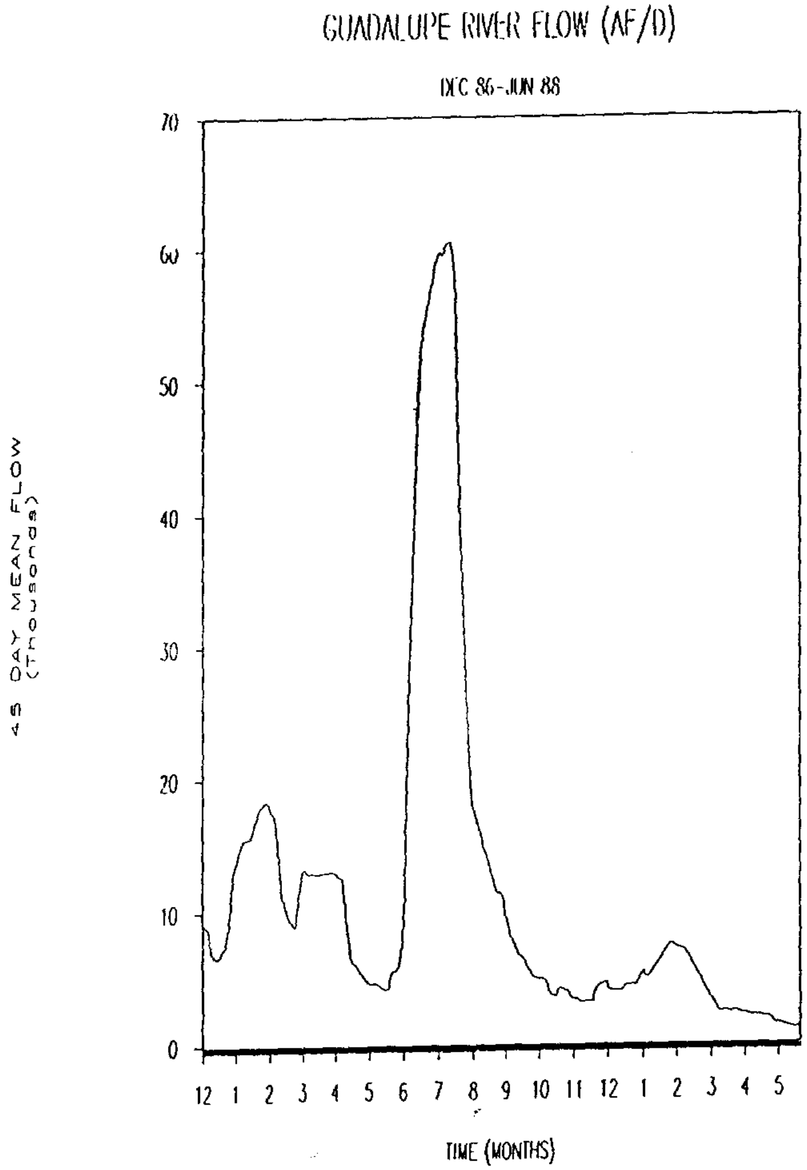


Fig. 3. Gaged Guadalupe River flow which has been smoothed with a 45 day mean for the period December 1986-June 1988

replacement time for water ranges from 2.6 to 613 days in high flow and low flow periods and a long term mean value of 123 days.

DISTRIBUTIONS

Salinity

The distribution of surface salinity revealed the dynamic nature of the freshwater input during the winter of 1986 and the spring of 1987. The largest change in the surface salinity occurred between November 1986 and January 1987 (Fig. 4). Subsequent samplings showed the large continued input of freshwater into the upper bay. The horizontal distributions of salinity indicate that freshwater enters San Antonio Bay and transits down the west side of the bay in many instances. The location of minimum salinity values whether on the west side or in the central bay is probably determined by wind speed and direction. The salinities at the river mouth were always less than 1 ‰ in the seven sampling times. The highest salinity water located in the southeast corner of the bay ranged from 1 to 32 ‰ at the surface and 5 to 32 ‰ in bottom waters. The extremely low salinity in July 1987 represented the maximum extent of freshwater influx in the lower bay area with approximately 80% of the bay water less than 1 ‰. This period corresponds to the low salinity observed in the hydrosonde data at Seadrift (Fig. 24).

Bottom salinity values were significantly higher (Fig. 5) especially in November, March and April in middle bay areas where higher salinity water from the Victoria Barge Canal may enter the bay through old oyster shell dredge channels (Texas A&M Research Foundation, 1973). These differences in salinity between surface and bottom over the 1-

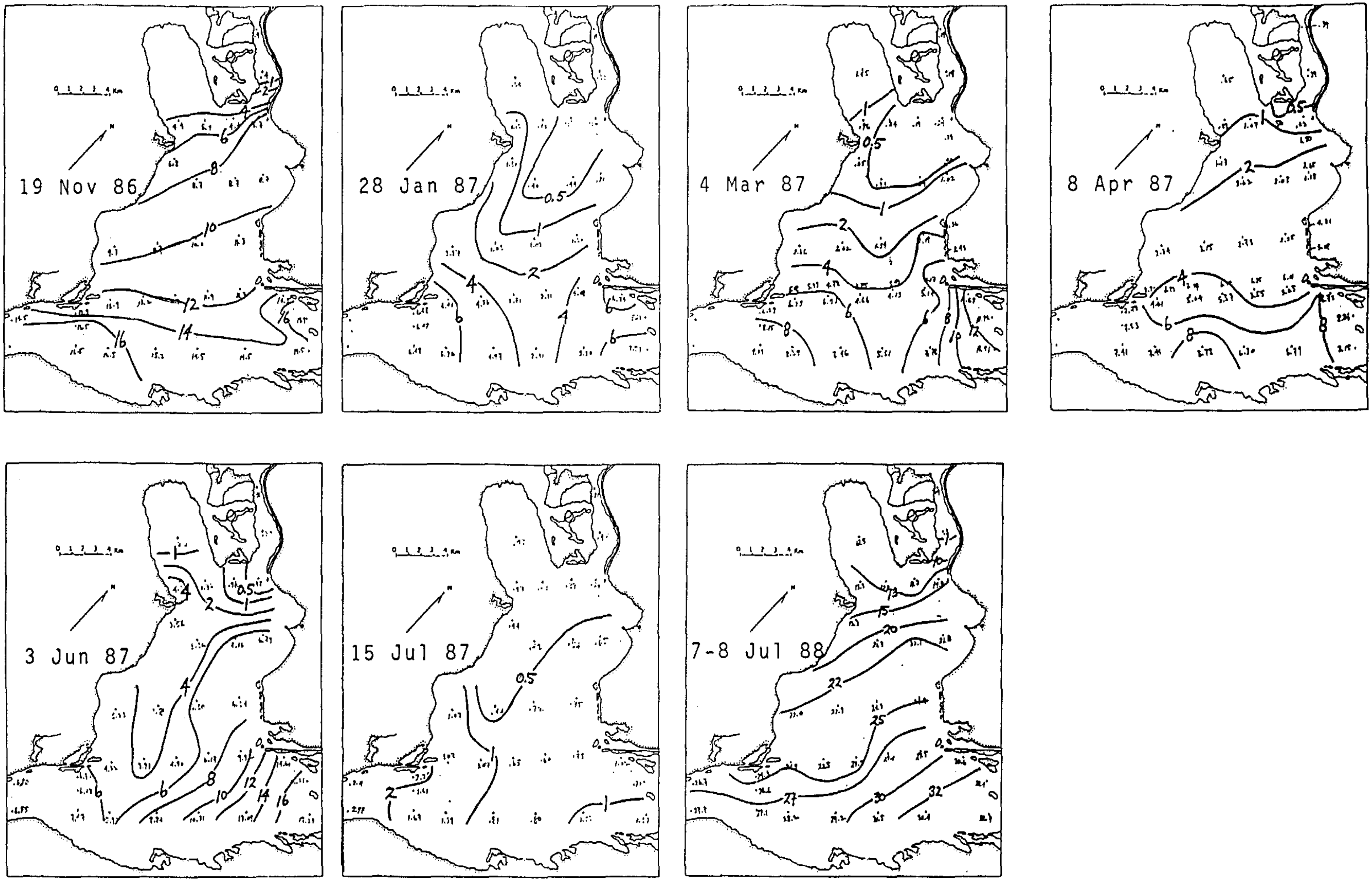


Figure 4. Surface salinity (o/oo) in San Antonio bay.

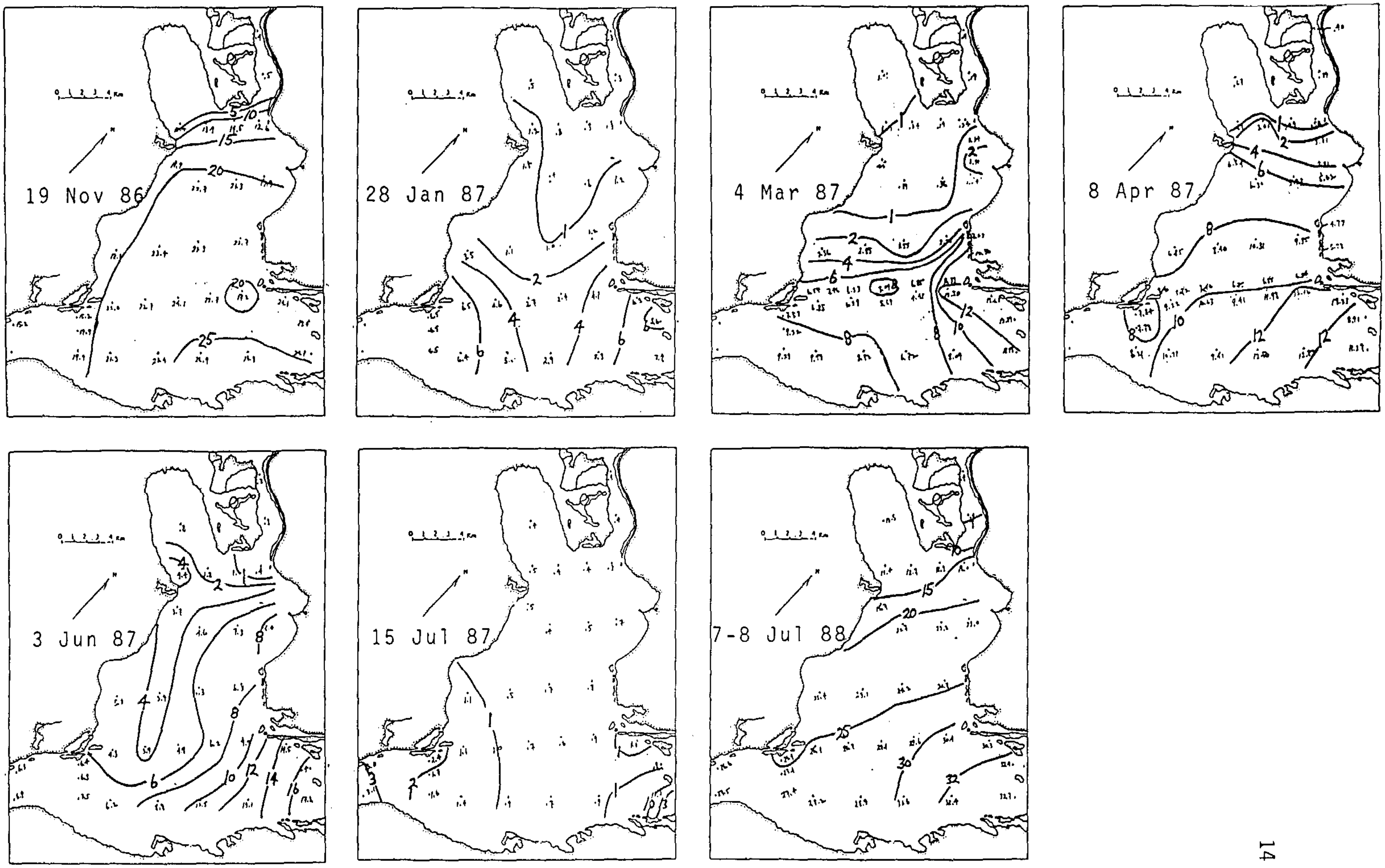


Figure 5. Bottom salinity (o/oo) in San Antonio bay.

2 meter water column established a vertical density gradient that apparently was not destroyed by wind mixing.

Nitrate

Freshwater inflow into San Antonio Bay introduced nitrate concentrations of 68-120 ug-at/liter into the upper bay ecosystem with the highest concentration in November and the lowest in July 1987 (Fig. 6). Increased river flow rates have been observed to lower nutrient concentrations in other rivers as flow increases. The total flux (conc x flow) increases during high flow conditions by about a factor of two. The range of observed nitrate concentrations in San Antonio Bay surface waters was 0.1 to 120 ug-at/liter. In all samplings the surface nitrate was reduced to less than 1.0 μmole/liter in lower San Antonio Bay and a few samples from Ayres and Mesquite Bays were as low as 0.03 ug-at/liter. This suggests that nitrogen uptake processes are occurring at significant rates to deplete the water of nitrogen as it transits from the upper bay.

No external source of nitrate other than river input was evident during this period of high inflow. Near bottom concentrations were enhanced during July 1987 especially in the middle bay areas where nitrification may be occurring (Fig. 7). The horizontal distributions of nitrate actively follow the pattern of deduced freshwater flow in San Antonio Bay. The direct correlation of salinity and nitrate is not very good because of the non-conservative nature of nitrate, nevertheless the west side of the bay contains much larger concentrations of nitrate than the east. The range of river input of inorganic nitrogen into San Antonio Bay is 2.2×10^3 to 3.1×10^5 kg N/day (Table 3).

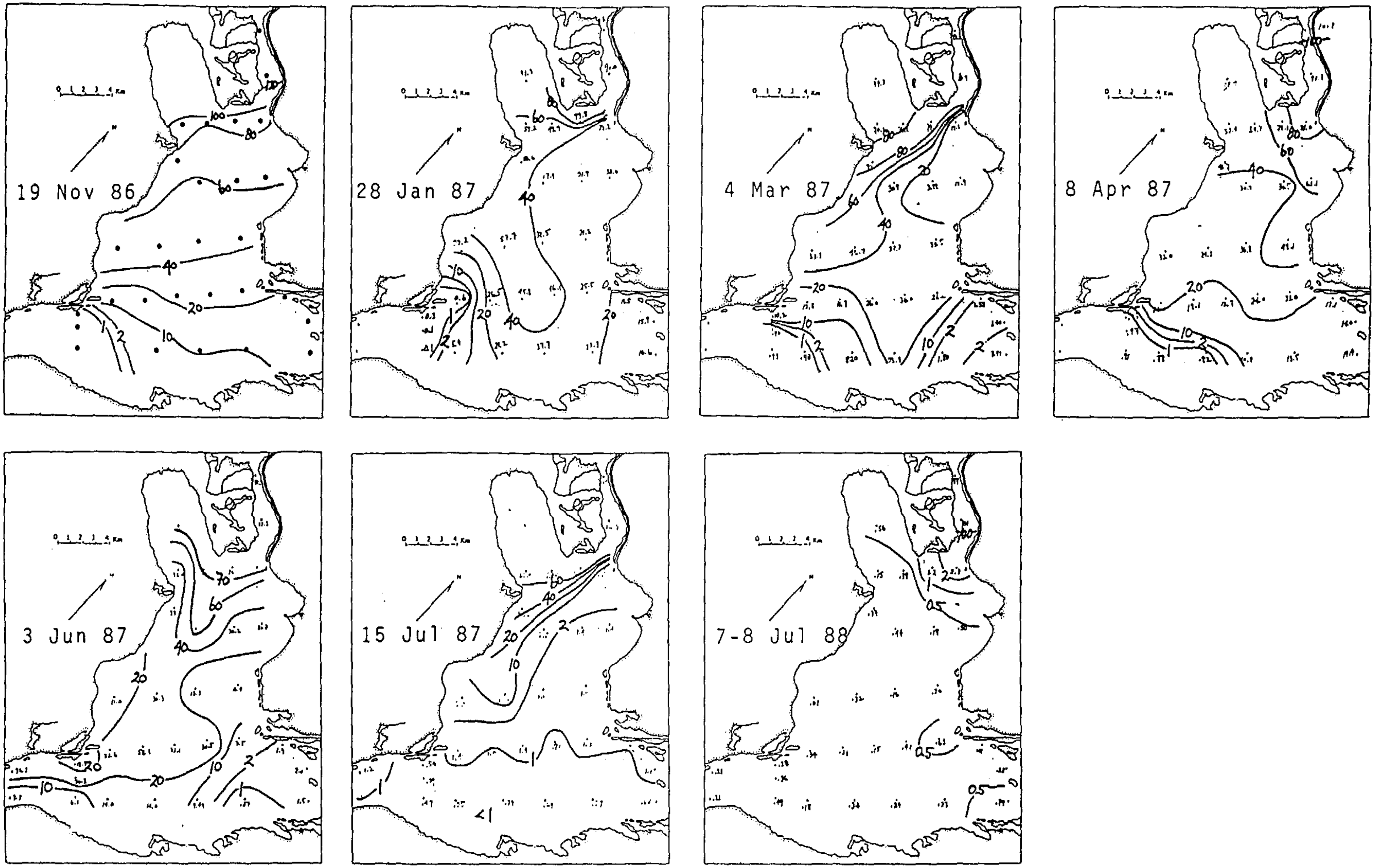
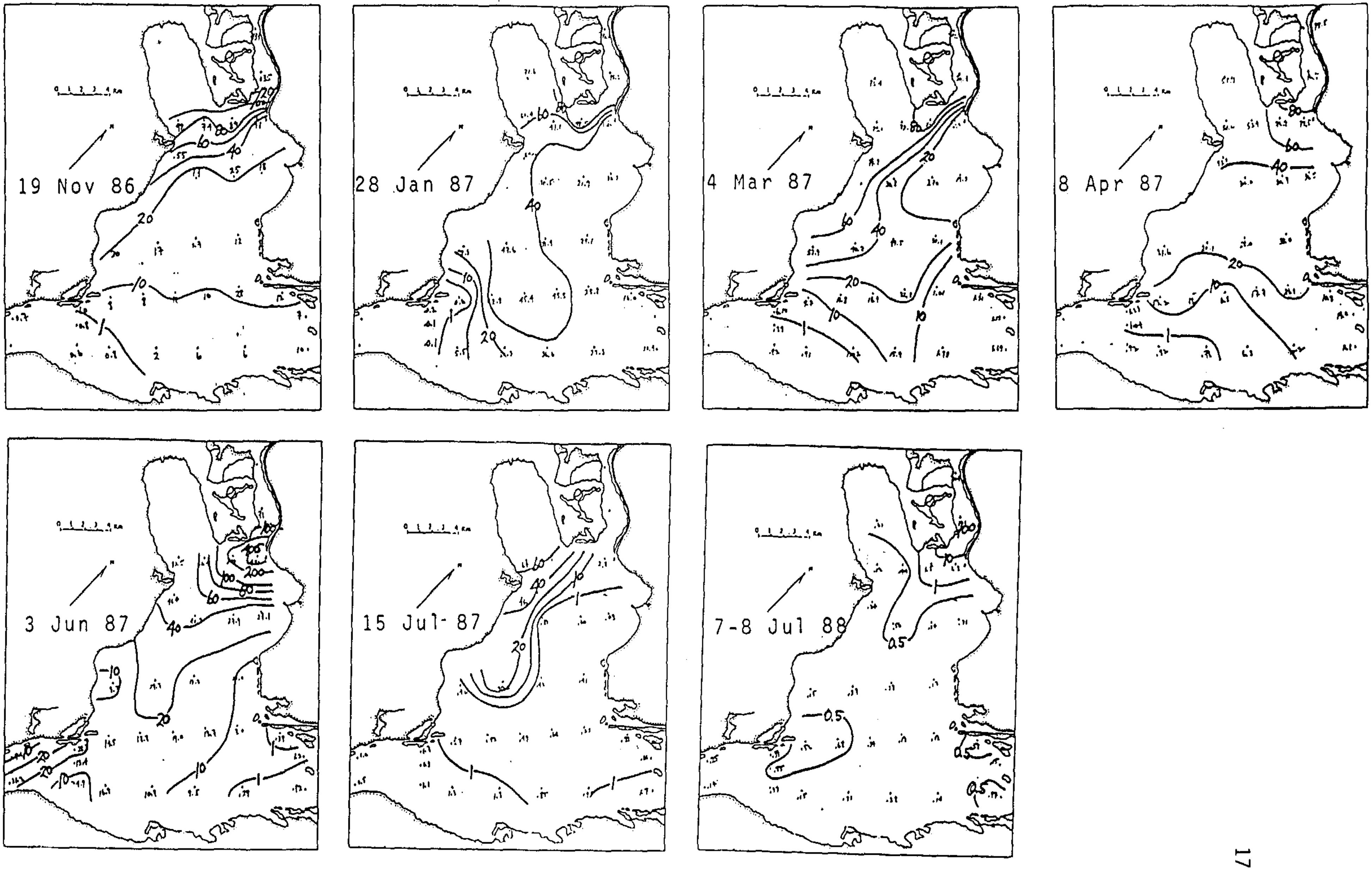


Figure 6. Surface nitrate (umole/l) in San Antonio bay.


19 Nov 86

28 Jan 87

4 Mar 87

8 Apr 87

3 Jun 87

15 Jul 87

7-8 Jul 88

Figure 7. Bottom nitrate (umole/l) in San Antonio bay.

Turbidity of San Antonio Bay waters is derived from river inflow, resuspension of bottom sediments by wind and phytoplankton growth processes. The lack of light penetration can inhibit phytoplankton growth so freshwater inflow and intense winds can reduce primary production rates during these events. The lack of high wind conditions can produce high light transparency even though freshwater inflow is larger than normal as in the period of 8 April 1987 (Fig. 8). The wind effects are observed throughout the entire region while freshwater turbidity is more localized to the river mouth.

Surface chlorophyll a distributions throughout the sampling period had maximum concentrations in the middle or lower bay regions. The combination of rather large nutrient concentrations and increased *in situ* light penetration permits the largest accumulations of chlorophyll in the middle bay (Fig. 9). The chlorophyll probably is advected to the lower bay where reduced currents may allow an accumulation in the water column. Nevertheless appreciable quantities of chlorophyll were also observed in the sediments either intact or in the degraded form of phaeopigment. The concentration of chlorophyll a in the river source water ranged from 0.6 to 13.5 μg/liter while the chlorophyll concentrations in the open bay water column were as high as 50 μg/liter.

Bottom chlorophyll concentrations were very similar in distribution to surface quantities but many values were somewhat larger, probably as the result of sinking (Fig. 10). The collection of near bottom samples did not disturb the sediments (this can be observed by high phaeopigment/chlorophyll ratios) so the pigments measured near the bottom are suspended. Maximum chlorophyll concentrations often occurred in the Gulf Intracoastal Waterway especially in near bottom samples which is surprising because of the repeated disturbance by boat traffic.

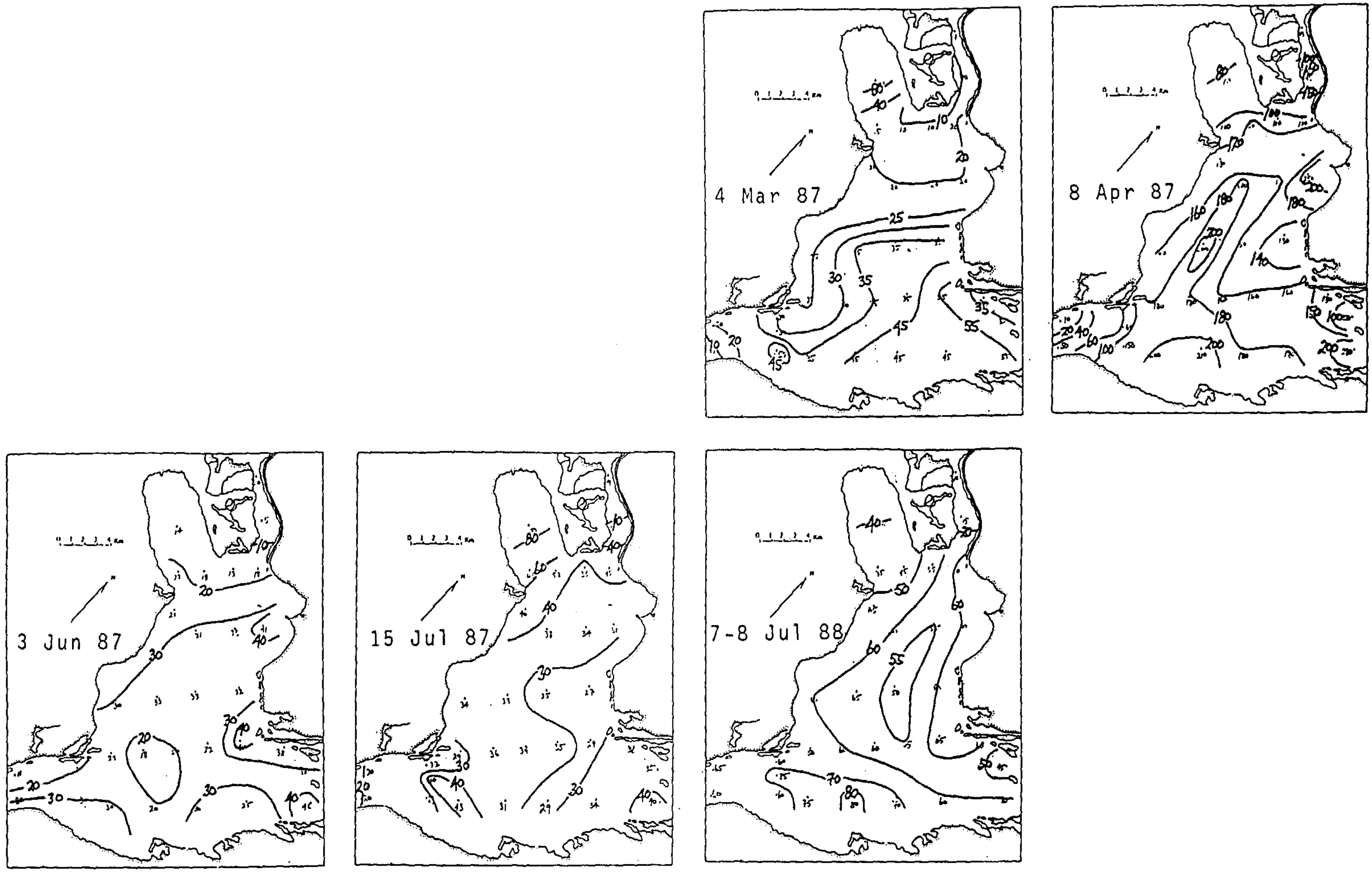


Figure 8. Secchi depth (cm) in San Antonio bay.

Figure 9. Surface chlorophyll a (ug/l) in San Antonio bay.

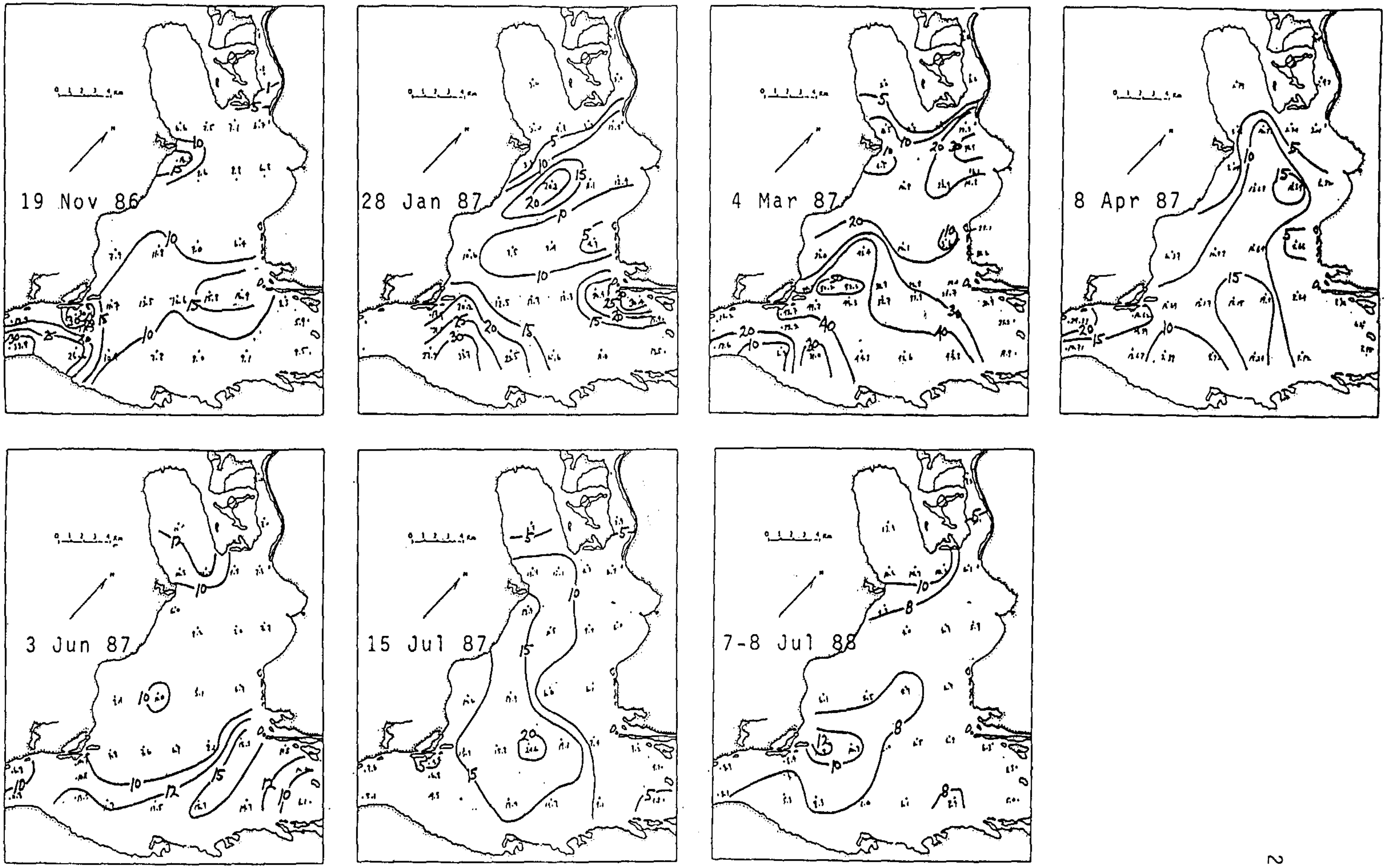


Figure 10. Bottom chlorophyll a (ug/l) in San Antonio bay.

Ammonium distributions in San Antonio Bay displayed a pronounced seasonal pattern. The November sampling found as much as 3 ug-at/liter in the Guadalupe River discharge but much smaller values occurred over the remainder of the bay. Surface and bottom distributions were very similar from November through March but differences were noted in April and remaining sampling periods (Figs. 11 and 12). The enhanced concentrations observed were located in distinct areas with the exception of the July 1987 period when a rather uniform high concentration of 4-6 ug-at/liter was observed over the entire estuary which was both a time of near the maximum freshwater inflow and high water temperatures which tend to elevate organic decomposition rates. In general, the largest concentrations of ammonium were located on the west side of San Antonio Bay so there is an apparent link in space of the inflow of nutrients, production of organic matter, and decomposition into recycled nutrients.

In reference to the question of decomposition of organic matter, depletion of dissolved oxygen in the water column is very indicative of areas where these processes are rapidly occurring. The shallow waters of San Antonio Bay (mean depth of 1.4 m) are often thought to be completely mixed by intense winds. However, depressed concentrations of dissolved oxygen were observed (Fig. 13) in the west and central regions of San Antonio Bay in April 1987 which was during a period of low Guadalupe River inflow although a freshwater accumulation from March was providing conditions for restricted vertical circulation. The surface salinity was between 1 and 2‰ while bottom salinity was greater than 6‰ in the area of oxygen concentrations less than 4 mg/l (2.8 ml/l). The Hydrolab measuring instrument did not present a very accurate depth determination but the higher

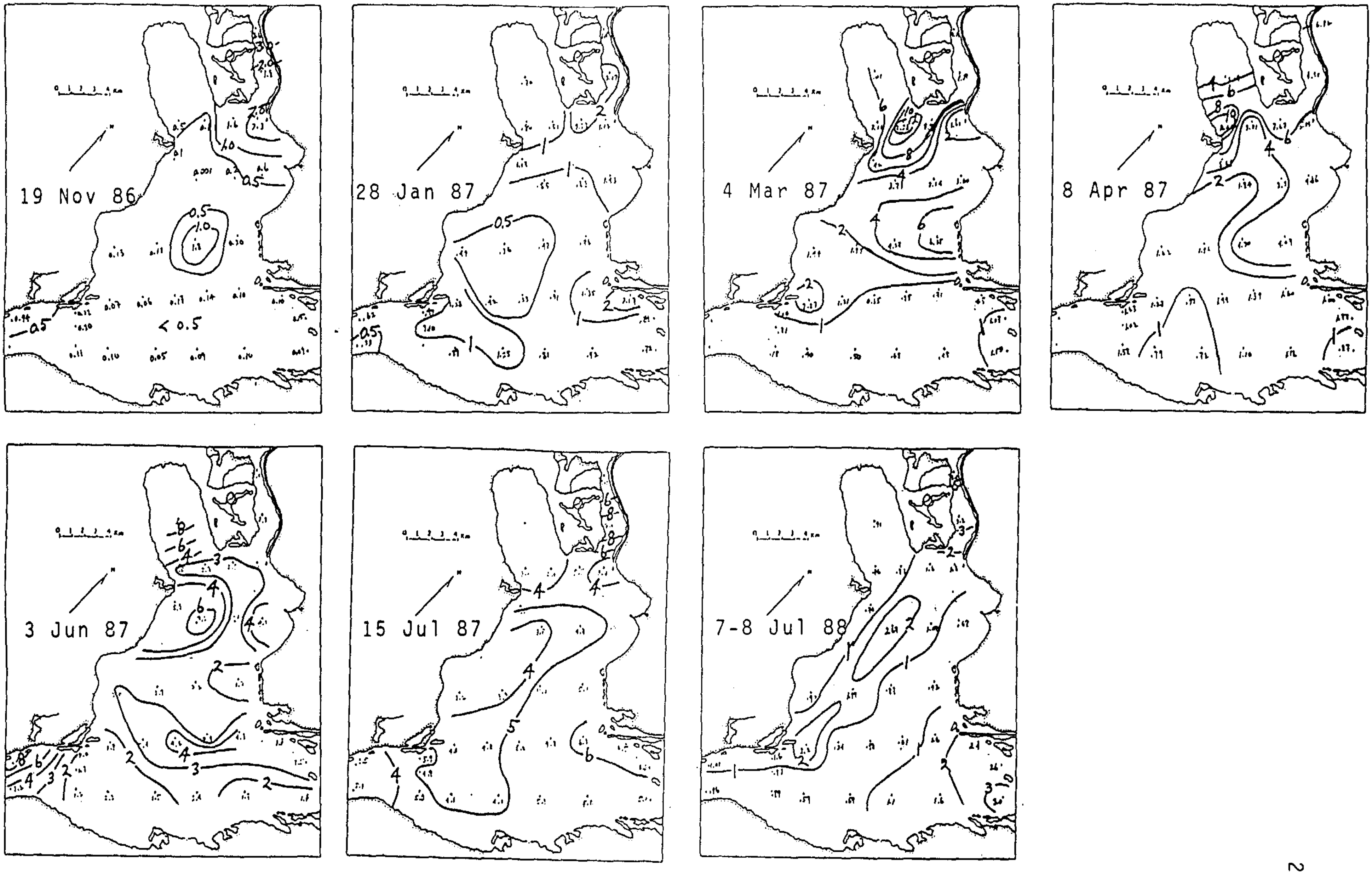


Figure 11. Surface ammonium (umole/l) in San Antonio bay.

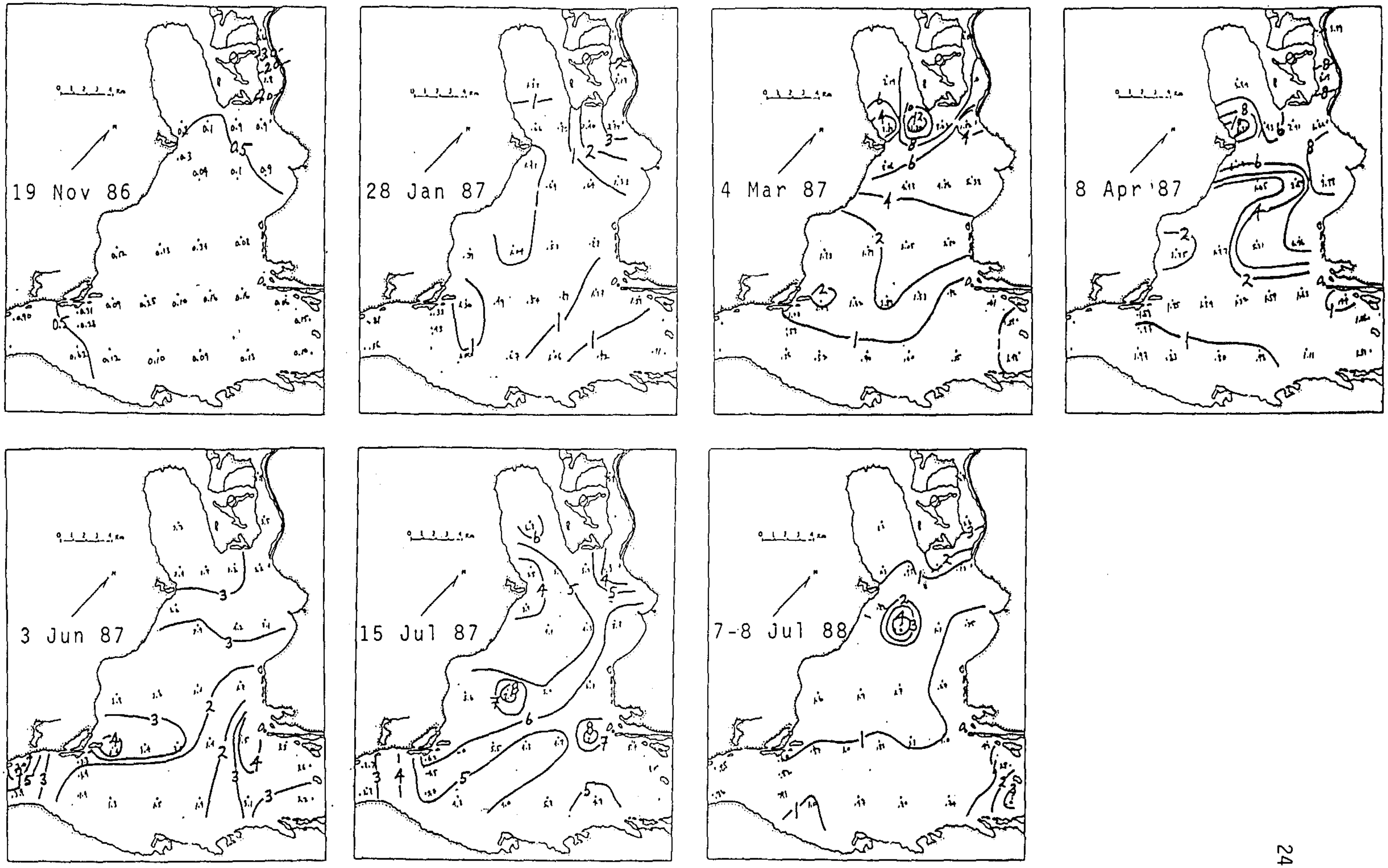


Figure 12. Bottom ammonium (umole/l) in San Antonio bay.

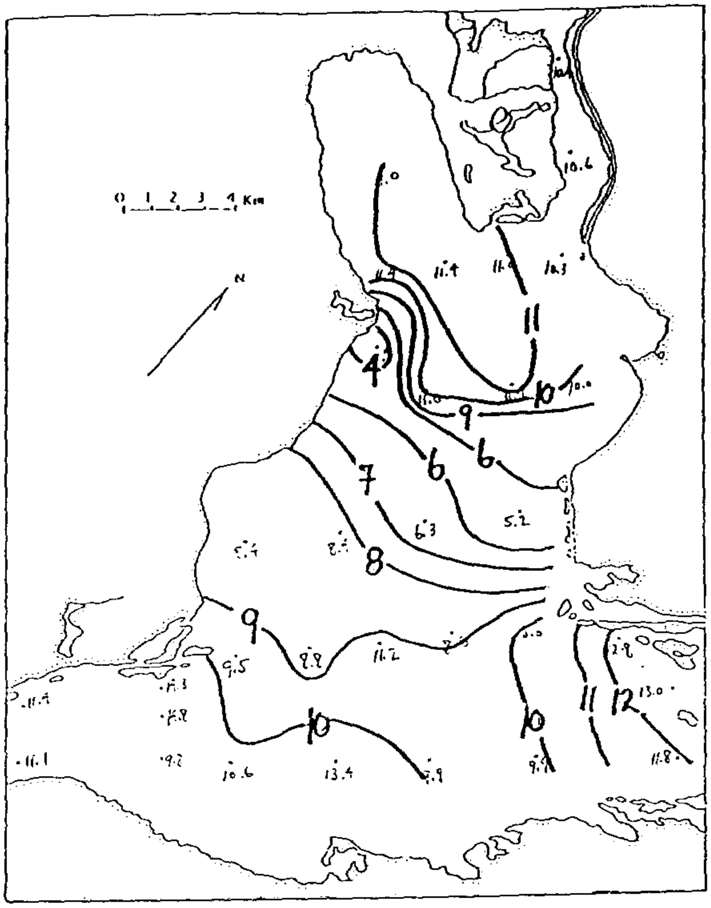


Figure 13. Bottom oxygen (mg/liter) on 8 April 1987 in San Antonio Bay.

salinity-low oxygen layer was approximately 30-50 cm thick in a layer along the bottom in a water depth of 1.5 to 1.75 m. Reduced oxygen concentrations were observed across the central San Antonio Bay and may be linked to import of higher salinity water from the Victoria Barge Canal into this area.

Temporal Trends

The repeated sampling of a set of fixed stations allows for an analysis of local changes over the time period sampled. This analysis is possible for all of the survey stations but it is most useful at the experimental sites A and C where most of the rate processes were determined. In essence this shows some of the behavior of the ecosystem during the study time and gives the background conditions for the experimental sites throughout the sampling period. Local changes that occur during a single sampling period are also interesting and are important in defining the small scale variability in the bay ecosystem. These diurnal time series measurements include both variability of the physical forcing such as winds and tides but also biological variability such as light dependent nutrient uptake or vertical migration of zooplankton.

Long Term Trends - Station A

The long term trends at station A (Fig. 2) located at the head of San Antonio Bay are representative of a low salinity regime near the inputs of freshwater. The San Antonio Bay hydrosonde was located near enough to Station A to provide a general trend of salinity, temperature, dissolved oxygen and pH. The *in situ* measurements of salinity at Seadrift and Mesquite Bay from 1986 from 1986 through 1988 displays a strong influence of river inflow

(Fig. 15). At peak river flow, the salinities near Seadrift decreased to less than 0.5 o/oo and remained low for more than six months. Only two short periods of about two weeks each occurred when salinity exceeded 4 ‰. So in effect, upper San Antonio Bay remained very fresh for more than 6 months. Mesquite Bay (Fig. 23) also exhibited a strong decrease in salinity from about 16 to 8 ‰ but the values remained relatively low for a shorter duration and the values didn't decrease to such low levels when compared to the upper bay. The mean daily flow from the Guadalupe River was quite different during our sampling period of late 1986 through summer of 1987 compared to the following autumn and spring of 1988 (Fig. 14). Specifically, the large inflow events lowered the salinity of upper San Antonio Bay to less than 1‰ and in general salinity remained below 2‰ from mid-January until mid-May and finally was undetectable or below 1‰ again from June through July. Temperature sensors did not show an effect in the hourly data that can be directly linked to the high inflow events. The temperature variations over the 8 month period of record (Fig. 15) is more closely related to weather systems (northers) which pass through the area and chill the water, especially between January and April. A steady increase in temperature was recorded after April, however weather changes still produced rapid changes in water temperature of about 4°C at the end of May and beginning of June when the heavy precipitation occurred. The hydrosonde measurements of dissolved oxygen and pH (Fig. 16) showed some instrumental drift. The oxygen sensor displayed a long-term decline from 11 to 7 mg/liter as the water temperature increased. The daily variations of oxygen production and utilization was especially apparent during April and May. pH did not have any strong trends during the 8 month period except for a short decrease during the largest inflow event in June.

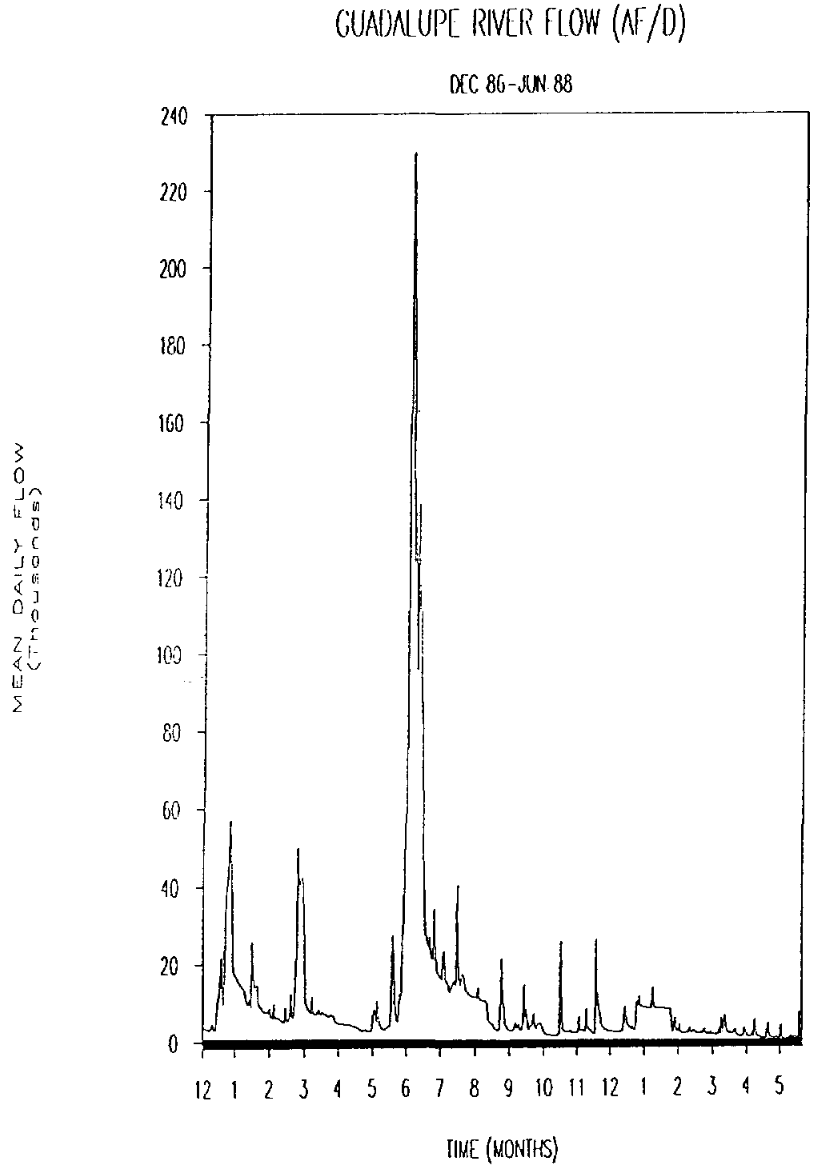


Figure 14. Mean daily gaged flow of Guadalupe River for December 1986-June 1988.

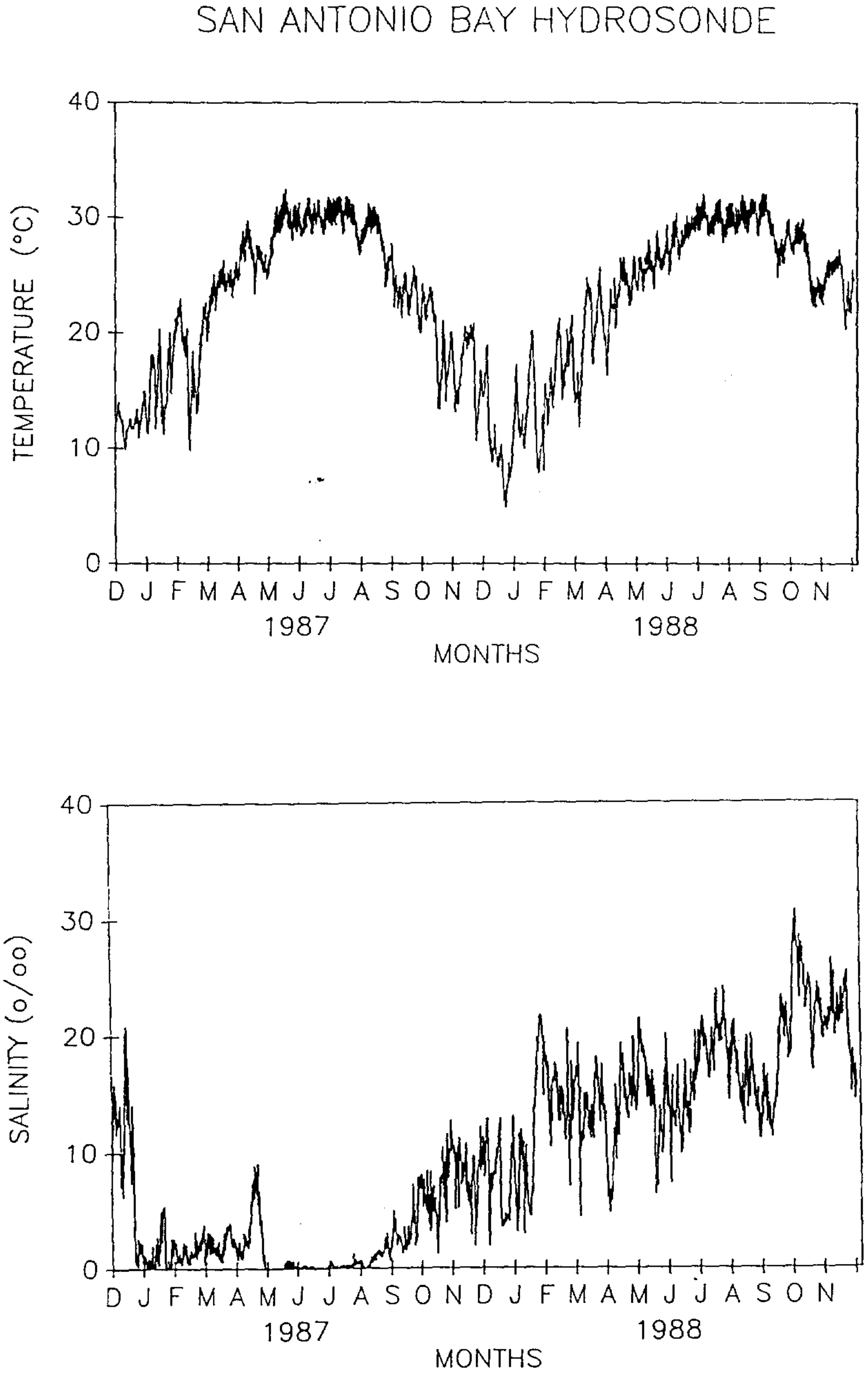


Figure 15. Temperature (upper) and salinity (lower) measured by an in situ recorder in San Antonio Bay near Seadrift, Texas every three hours from December 1986-November 1988.

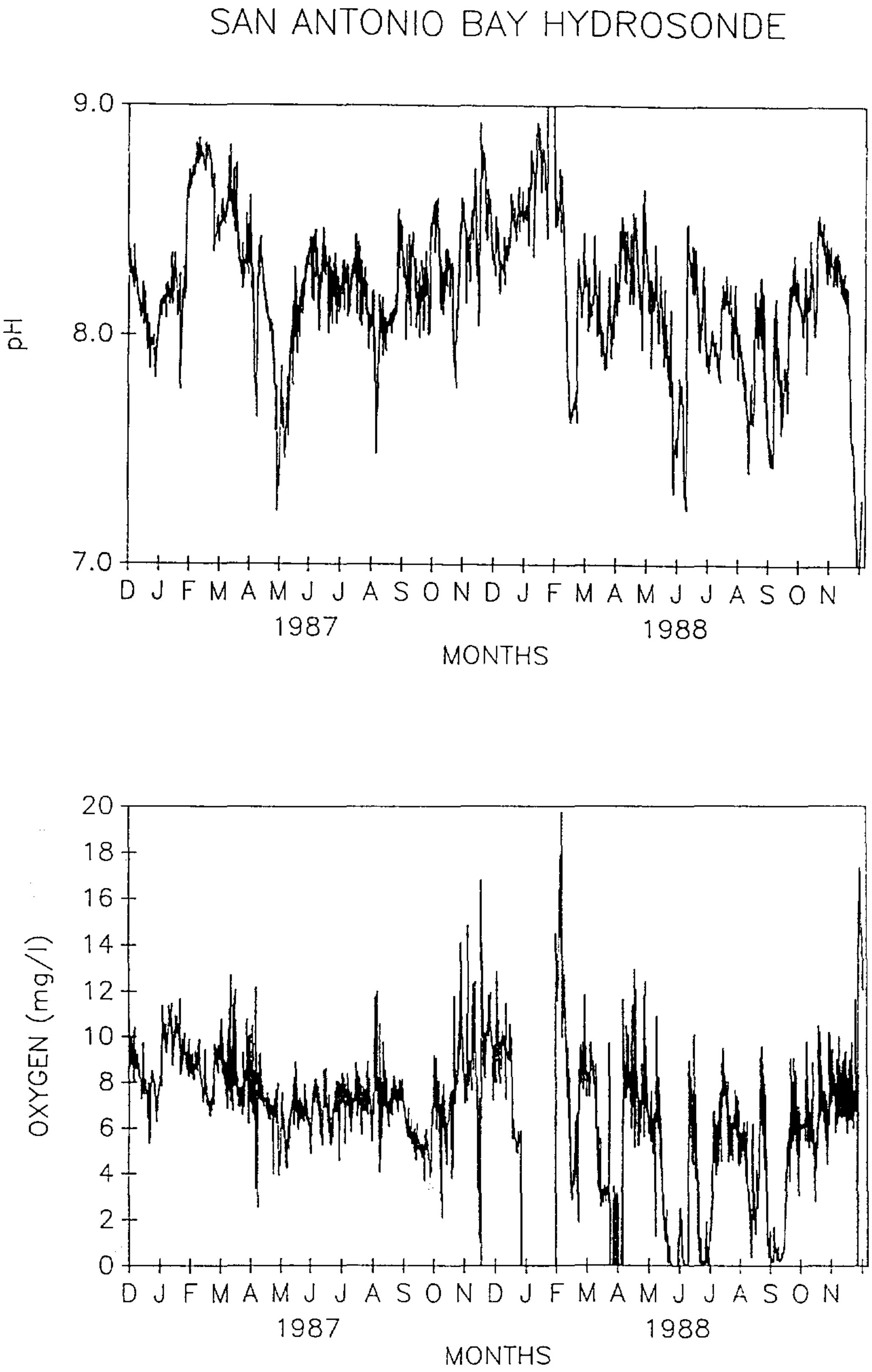


Figure 16. pH (upper) and dissolved oxygen (lower) measured by an in situ recorder in San Antonio Bay near Seadrift, Texas every three hours from December 1986-November 1988.

The long-term trend of survey data collected at the experimental sites A and C displayed the same general trend of temperature and salinity (Fig. 17). The poor time resolution of the station data is very apparent relative to the fixed Eulerian measurements and present a biased view of conditions in the bay if care is not taken. The temperature trend from station data indicated that both surface and bottom values remained about 15°C in the period of January through March 1987 and then a sharp increase of temperature occurred in April through July. The hourly temperature records in Seadrift Hydrosonde showed that warming of the waters actually started in January, was interrupted by frequent cooling periods and increased at a more uniform rate after April (Fig. 15). Salinity did not vary as much during the same period because it was very low and remained very low. The freshwater inflow remained in the ecosystem much longer than heat which is more closely related to the instantaneous weather.

The other measurements collected at the experimental station sites did not have *in situ* Hydrosonde data for comparison. The long term trend is probably correct but the short term variations occurring in San Antonio Bay are not well represented.

The nitrate and silicate concentrations at Station A exhibited identical behavior. The riverine inflow delivered large concentrations to the upper bay throughout the sampling period with values for nitrate remaining around 100 and silicate at 150-200 ug-at/liter (Fig. 18). These concentrations represent saturating levels of both nitrogen and phosphorus as far as the phytoplankton populations are concerned. A very large increase was observed in June 1987 which probably corresponded to the peak water flow from the Guadalupe River. Both nitrate and silicate are required for diatom growth although many other species of phytoplankton do not have a critical requirement of silicate. The distributional

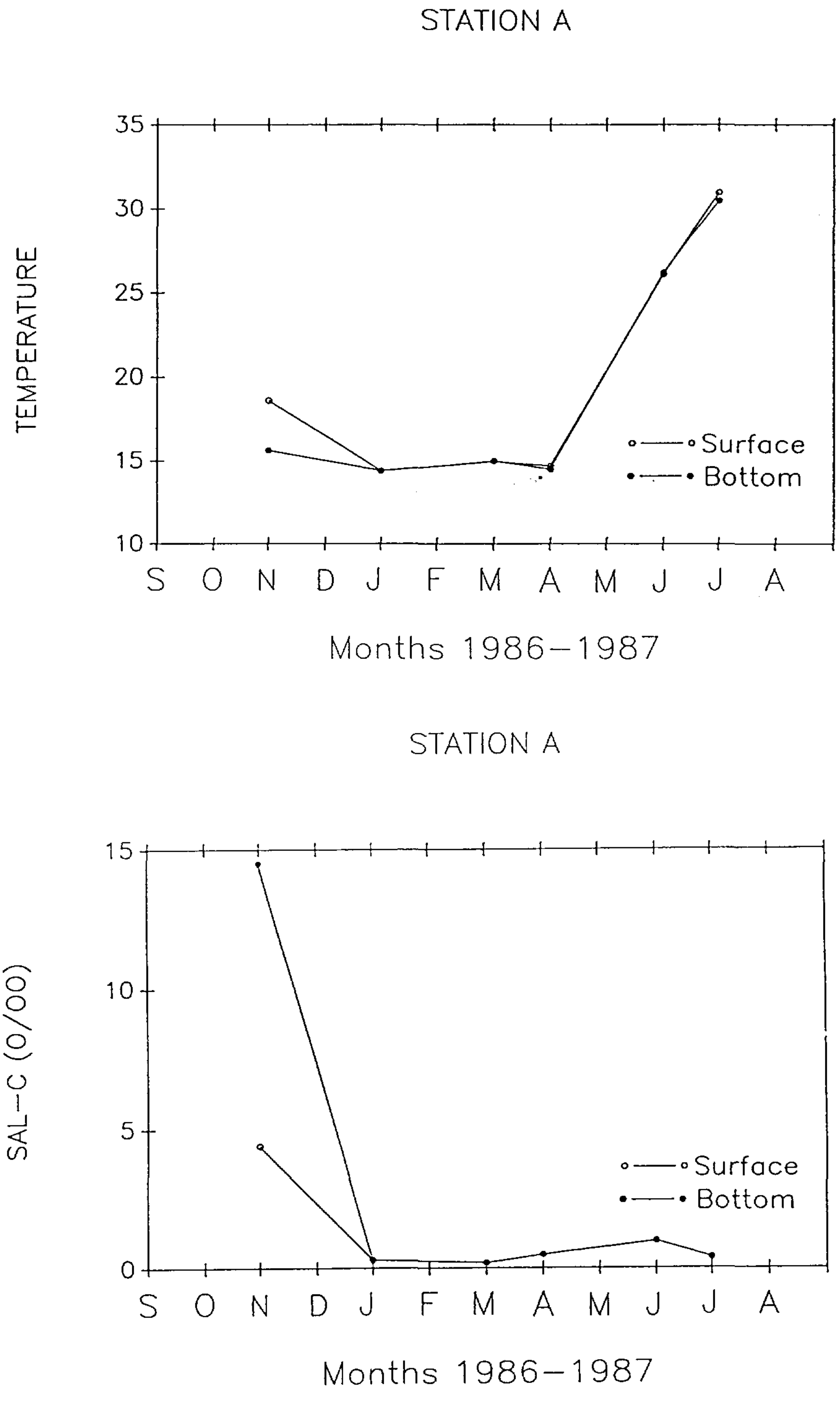


Figure 17. Temperature (upper) and salinity (lower) measured at station A during surveys from November 1986-June 1987.

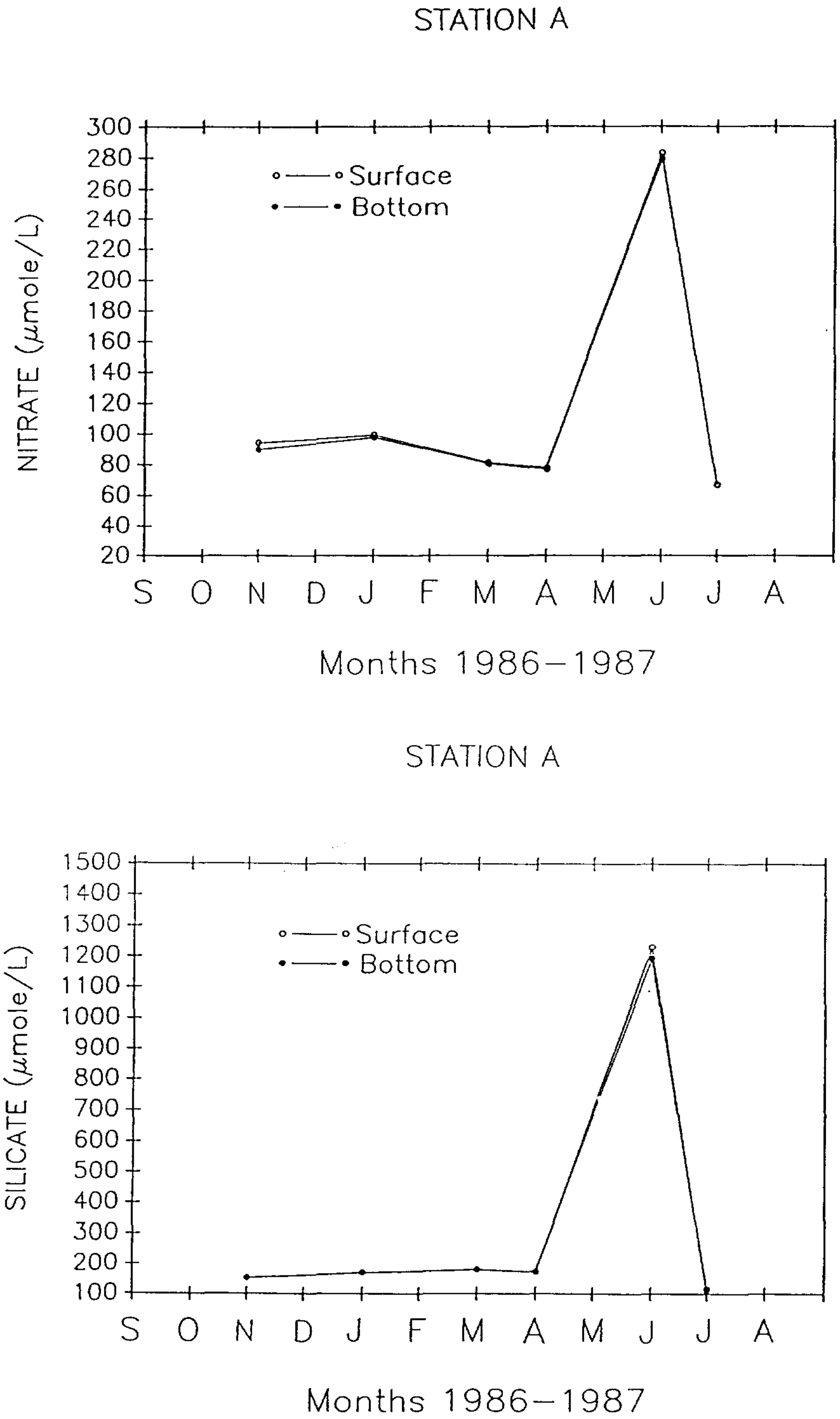


Figure 18. Nitrate (upper) and silicate (lower) measured at station A during surveys from November 1986-June 1987.

surveys indicate that both nutrient species are heavily utilized as shown by their gradients down the bay. Nitrogen is reduced to limiting concentrations but silicate never reaches depletion levels that would affect diatom growth however.

Orthophosphate, another important phytoplankton nutrient, displayed much different behavior but like silicate the concentrations never decrease to values that would impare phytoplankton growth. The freshwater inflow increased phosphate concentrations from 5 to above 9 ug-at/liter during the moderate inflow events but during the largest freshwater inflow, the surface waters had decreased concentrations (Fig. 19). The decrease may be attributed to the interaction of the phosphate with inorganic particulate material when the salinity is extremely low (Edmondson and Lehman, 1981; Lehman and Edmondson, 1983; Malone, personal communication). Later increases in salinity then release the phosphate back into the dissolved phase.

Chlorophyll a and phaeopigments in the water column at Station A are indicative of the phytoplankton biomass and older non-photosynthetic partially degraded phytoplankton respectively. Of course, wind mixing may resuspend benthic chlorophyll and phaeopigments that had settled to the bottom or grown in place. The biomass of chlorophyll a is often indicative of the net effect of a perturbation in an ecosystem. The surface chlorophyll a concentration increased throughout the sampling period from about 1 to 12 μg/liter (Fig. 20). The bottom chlorophyll concentration differed from the surface values under conditions of phytoplankton sinking (e.g. November) or very active growth in the low salinity, high nutrient surface layer (e.g. April and July). The phaeopigments were more uniform over the time period but the phaeopigments were a larger percentage of total

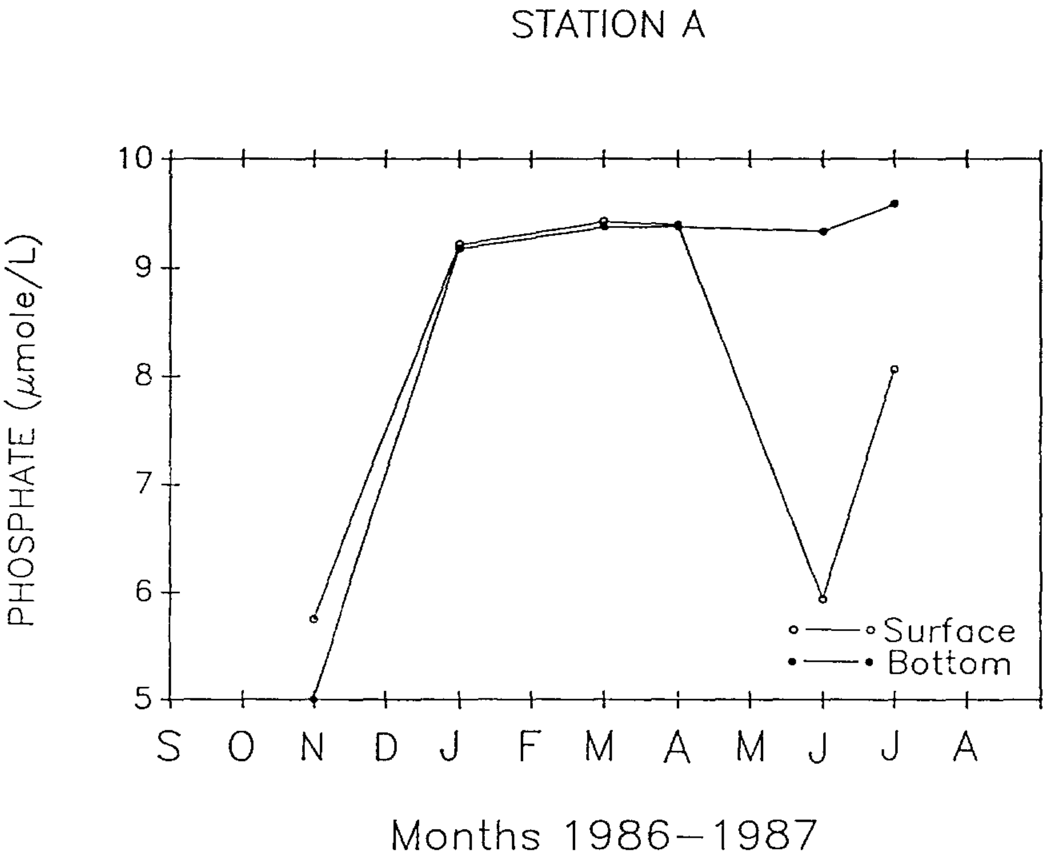


Figure 19. Orthophosphate measured at station A during survey from November 1986-July 1987.

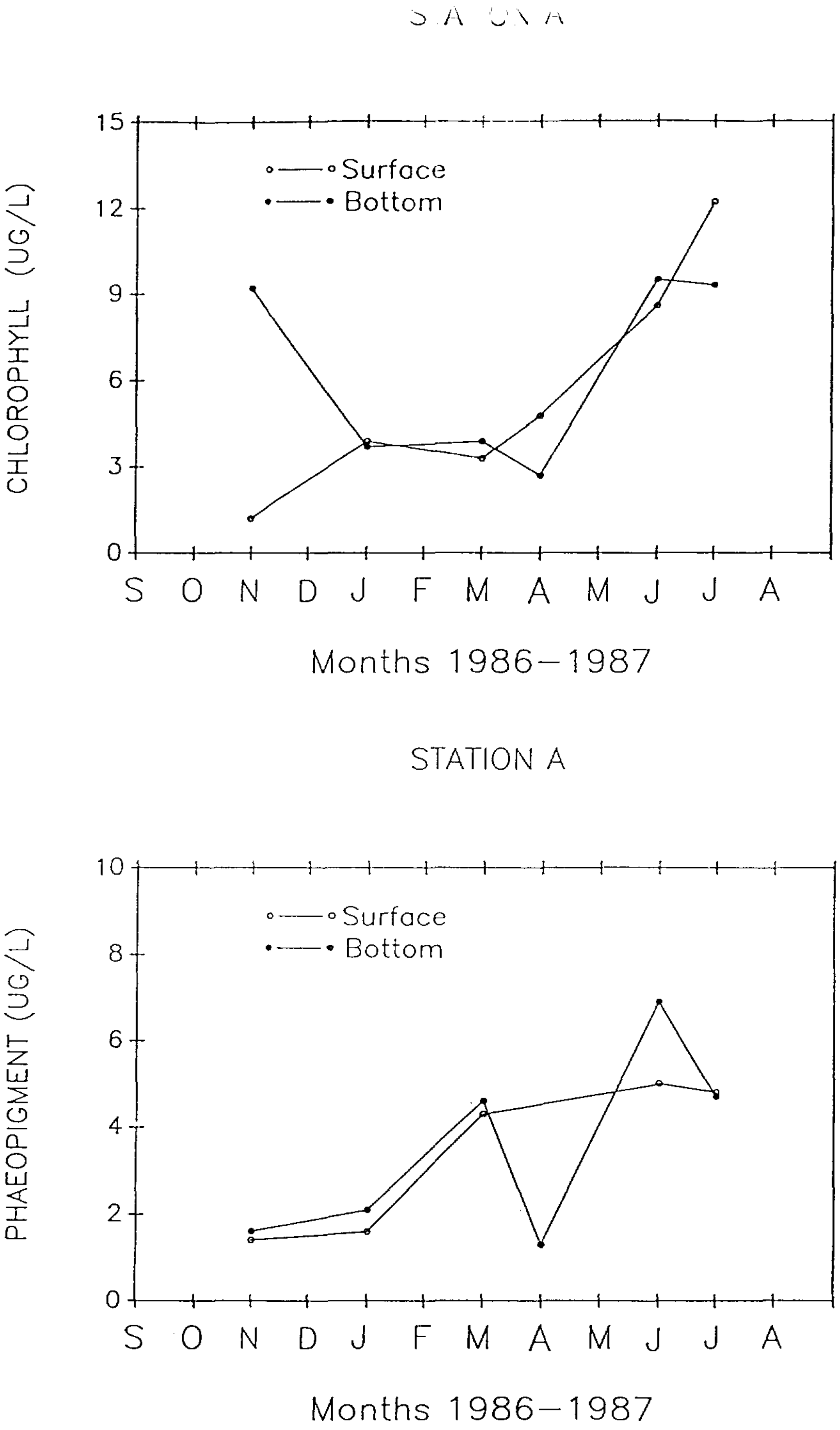


Figure 20. Chlorophyll (upper) and phaeopigment (lower) measured at station A from November 1986-July 1987.

pigments during the winter months and decreased with increased phytoplankton production in the late spring and summer.

Nitrite and ammonium at Station A are products of transformations occurring in the ecosystem. Ammonium is primarily produced from the decomposition of organic matter (protein) and nitrite is either the reduced form of nitrate or the oxidized form of ammonium. Ammonium and nitrite exhibit similar cyclic trends so the nitrite is very likely to result from the nitrification process of converting ammonium into nitrate (Fig. 21). The concentrations of both ammonium and nitrite are relatively small in the riverine inflow so they are the products of processes actively occurring in San Antonio Bay. The concentrations are also significant in terms of available nitrogen for phytoplankton growth. Concentrations of nitrate, nitrite and ammonium greater than 2 ug-at/liter have been shown to easily support maximum phytoplankton growth (Dugdale, 1976). The variations of nitrite and ammonium concentrations appear to be related to the freshwater inflow which may be explained by the relatively faster rates of nitrification that have been reported for estuarine systems (Chen *et al.* 1976) where the rate of nitrification was found to be inversely proportional to salinity.

Hourly Time Series - Station A

Hourly measurements of temperature, salinity, nutrients and chlorophyll were collected over a 24 hour period, when possible, to ascertain the short term variations that were occurring in these parameters. The variability observed in these parameters, produced by both physical and biological processes, provides very useful information about the time response of the ecosystem especially when a physical change like a weather front appears.

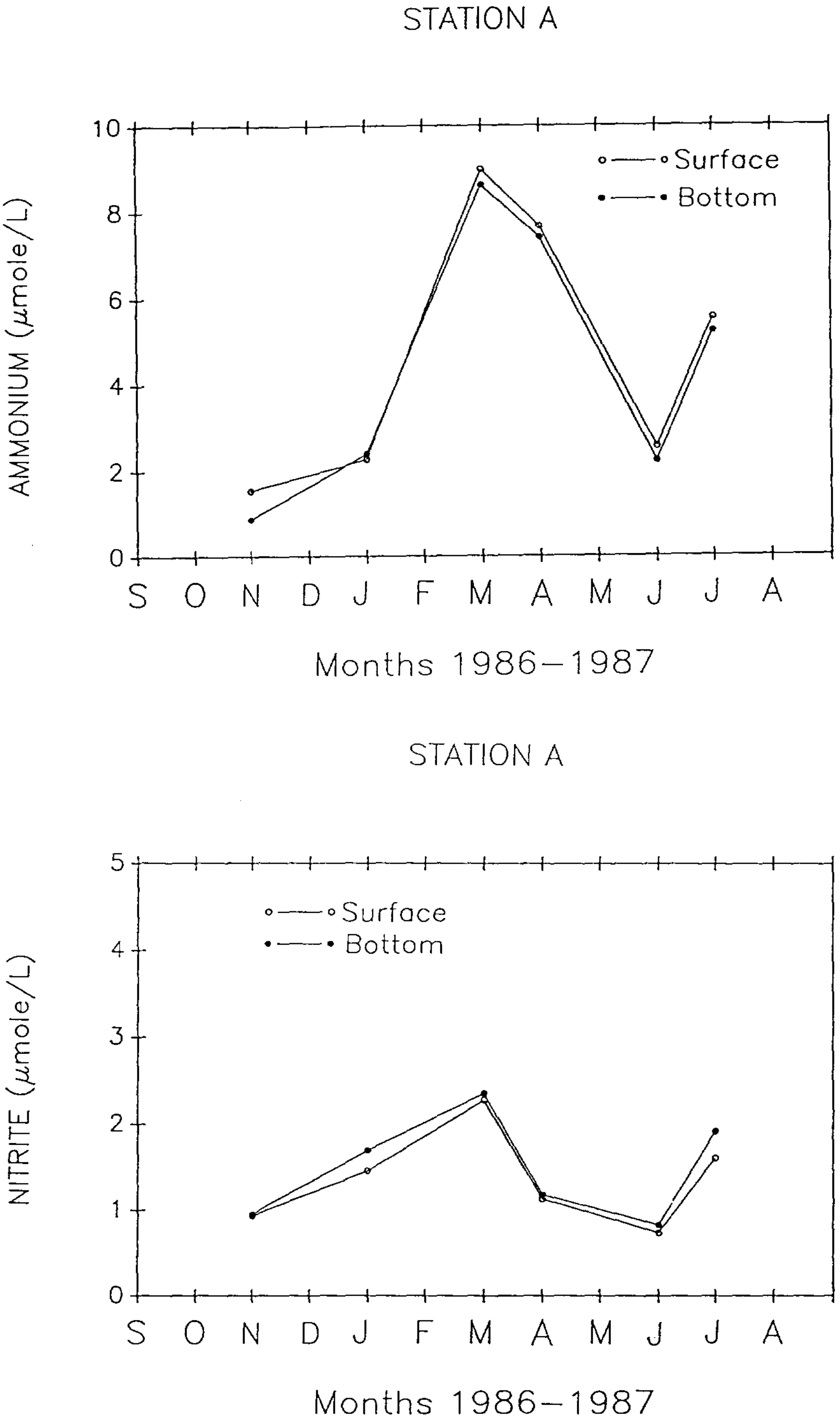


Figure 21. Ammonium (upper) and nitrite (lower) measured at station A from November 1986-July 1987.

Many of these time series measurements are detailed in time series plots in the appendix. A few examples will be discussed here to describe the most interesting results.

The April 1987 time series at Station A was not complete because data was not collected during daylight hours due to a lack of equipment and personnel. The two night series can be compared for differences in temperature, salinity, nutrients and chlorophyll (Fig. 22). All of the available measurements depict different behavior between the two nights which reflects changes in the bay during daylight hours. The trends of change remained relatively constant during each night but a large change occurred for several of the variables during the intervening day. The temperature dropped slightly during the first night, increased about 2.5°C during the day and then decreased rapidly to about 14°C the second night. The salinities were all low (<1.5‰) and the decrease during the first night of about 0.4‰ at the surface and 0.6‰ at the bottom were the only changes of significance in the record. The nutrients and plant pigments displayed marked changes which help explain the changes that occurred. Silicate, ammonium, phosphate and chlorophyll concentrations were high the first night and very much lower the second. Nitrate and phaeopigments were lower the first night and higher the second. It appears that very recently discharged freshwater was located at station A during the first night and older water with about the same salinity was present the second night. The decrease in silicate, phosphate were probably the result of use by autotrophic processes but the ammonium loss and the nitrate gain is likely to indicate relatively high nitrification (production of nitrate from ammonium) rates. This hypothesis is strengthened by a decrease of nitrite from about 4 ug-at/liter down to 1 ug-at/liter. The approximately 30 ug-at/liter increase in nitrate is almost matched by the decrease of 25 ug-at/liter of ammonium and 4 μmole/liter of nitrite.

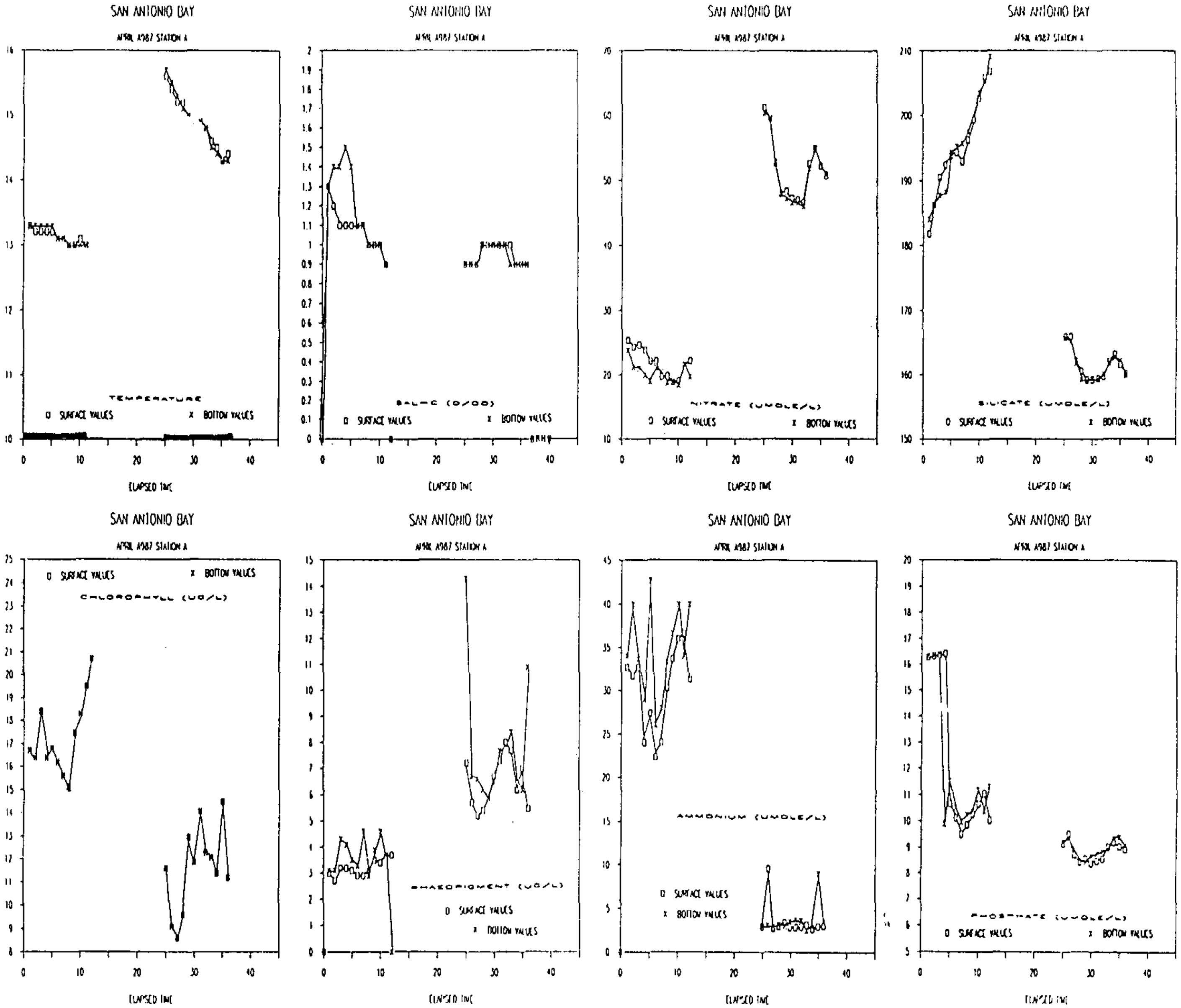


Figure 22. Hourly time series measurements of temperature, salinity, nitrate and silicate (upper) and chlorophyll, phaeopigment, ammonium and phosphate (lower) at station A in San Antonio Bay on 7-8 April 1987.

Unfortunately the oxygen sensor was not working properly so no estimates of oxygen consumption or production can be calculated.

The July 1987 time series at station A occurred after the peak freshwater inflow event (June) but the freshwater over the entire San Antonio was at its fullest extent during observations. The hourly observations included two nights but the intervening daylight observations are missing because of lack of available work space on the research vessel. The diurnal temperature variation was about 1.5°C both nights (Fig. 23) and the surface waters appeared to cool slightly faster than near bottom. The salinity trended up during the observations from about 3‰ to about 3.9‰ and surface and bottom values were alike. Nitrate and phosphate both increased the first night and then continued to increase the second night and both experienced a sharp decline and rebound in the early morning. The intervening day period had no apparent effect on nitrate and phosphate concentrations. Silicate increased and levelled off the first night, decreased during the day and then went through a small increase and decrease on the second night. The diel variation of oxygen was about 1.5 and 2 mg/liter during the two nights and the surface values were always slightly larger than near bottom. The surface production of oxygen by autotrophic processes and the benthic respiration maintained the observed concentration differences. Atmospheric exchange of oxygen must be quite small because the oxygen concentrations decrease rapidly at night. The ammonium concentrations experienced a few wide variations but predominately ranged from 3 to 4.5 ug-at/liter with the bottom samples tending to have a concentration of about 1 ug-at/liter higher than the surface.

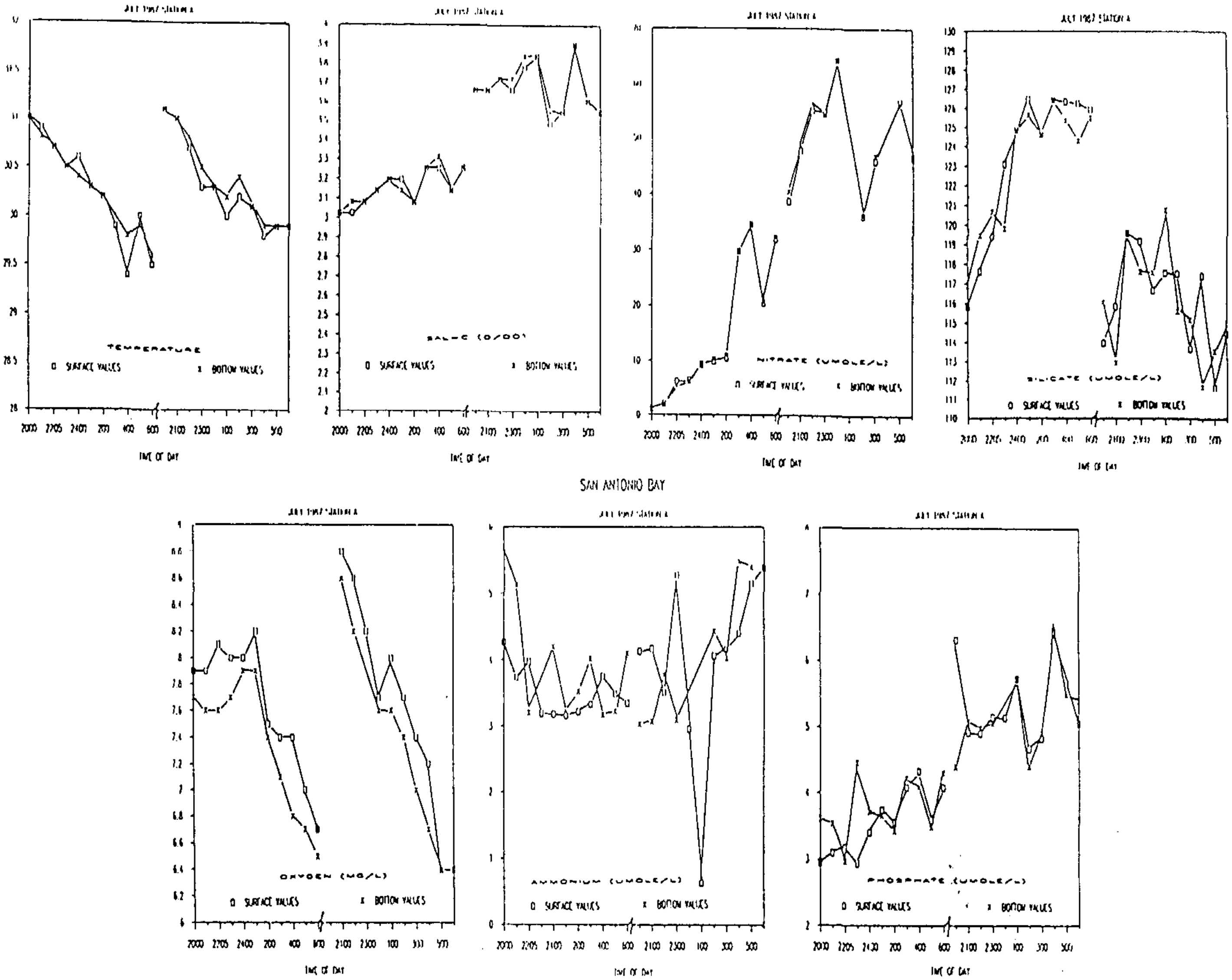


Figure 23. Hourly time series measurements of temperature, salinity, nitrate and silicate (upper) and oxygen, ammonium and phosphate (lower) at station A in San Antonio Bay on 13-15 July 1987.

Long Term Trends - Station C

Station C was located about 10 miles down San Antonio Bay from Station A. The location had higher salinities due to mixing and dilution with marine waters and evaporation processes. Some of the characteristics at this location (e.g. temperature) were very similar to Station A (Fig. 2). The Hydrosonde location for lower San Antonio Bay estuary was in Mesquite Bay about 11 km distant from Station C. The hydrosonde location could have somewhat similar properties to Station C and the likelihood of other external influences was very small because Cedar Bayou was not opened to the Gulf of Mexico until September 1987. The temperature data from the Mesquite Bay hydrosonde recorded the passage of several weather systems which cooled the waters by more than 8°C. The very shallow Mesquite Bay waters had cooler temperatures during both winter and summer seasons (Fig. 24) and the duration of low temperatures appear to be observed longer than at Seadrift so the area of Mesquite Bay may have slower water circulation patterns than upper San Antonio Bay. The salinity in Mesquite Bay showed a decrease from 16 to about 8 ‰ but the values remained relatively low for a shorter duration than Seadrift and the values didn't decrease to such low levels. The oxygen observations in Mesquite Bay oscillated on approximately a two week time scale in a fashion similar to upper San Antonio Bay and the range of variations was quite similar (Fig. 25). pH values in Mesquite Bay were not reliable due to offsets in much of the data. The nominal pH of Mesquite Bay ranged between 8.2 and 8.6.

The long term trend of survey data at station C showed that salinity as expected maintained higher levels except in July when major freshwater had entered the system. Bottom salinities were occasionally as much as 5‰ higher than surface water (Fig. 26). This low salinity surface water transited down the bay on the west side and still had not

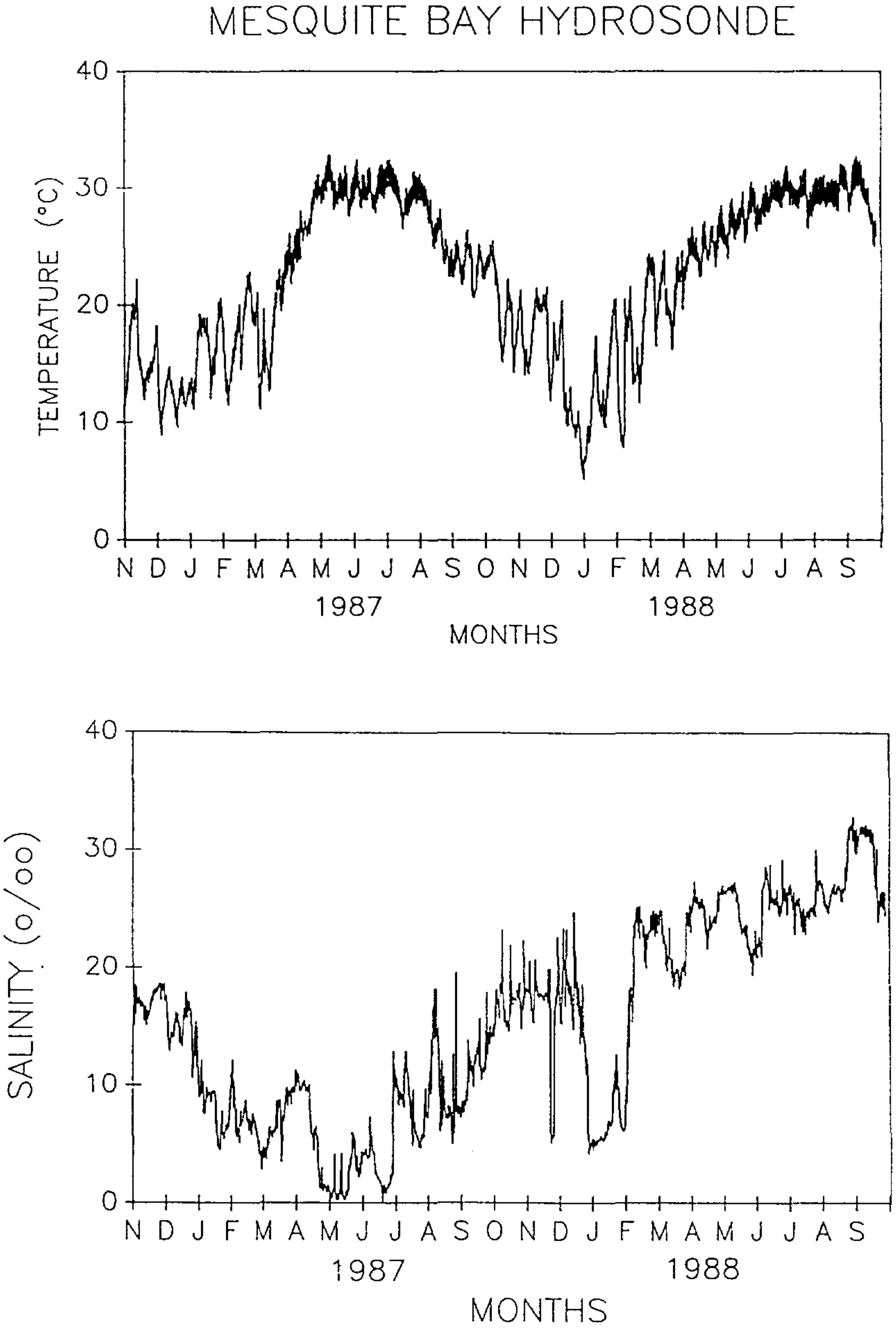


Figure 24. Temperature (upper) and salinity (lower) measured by an in situ recorder in Mesquite Bay every three hours from November 1986-September 1988.

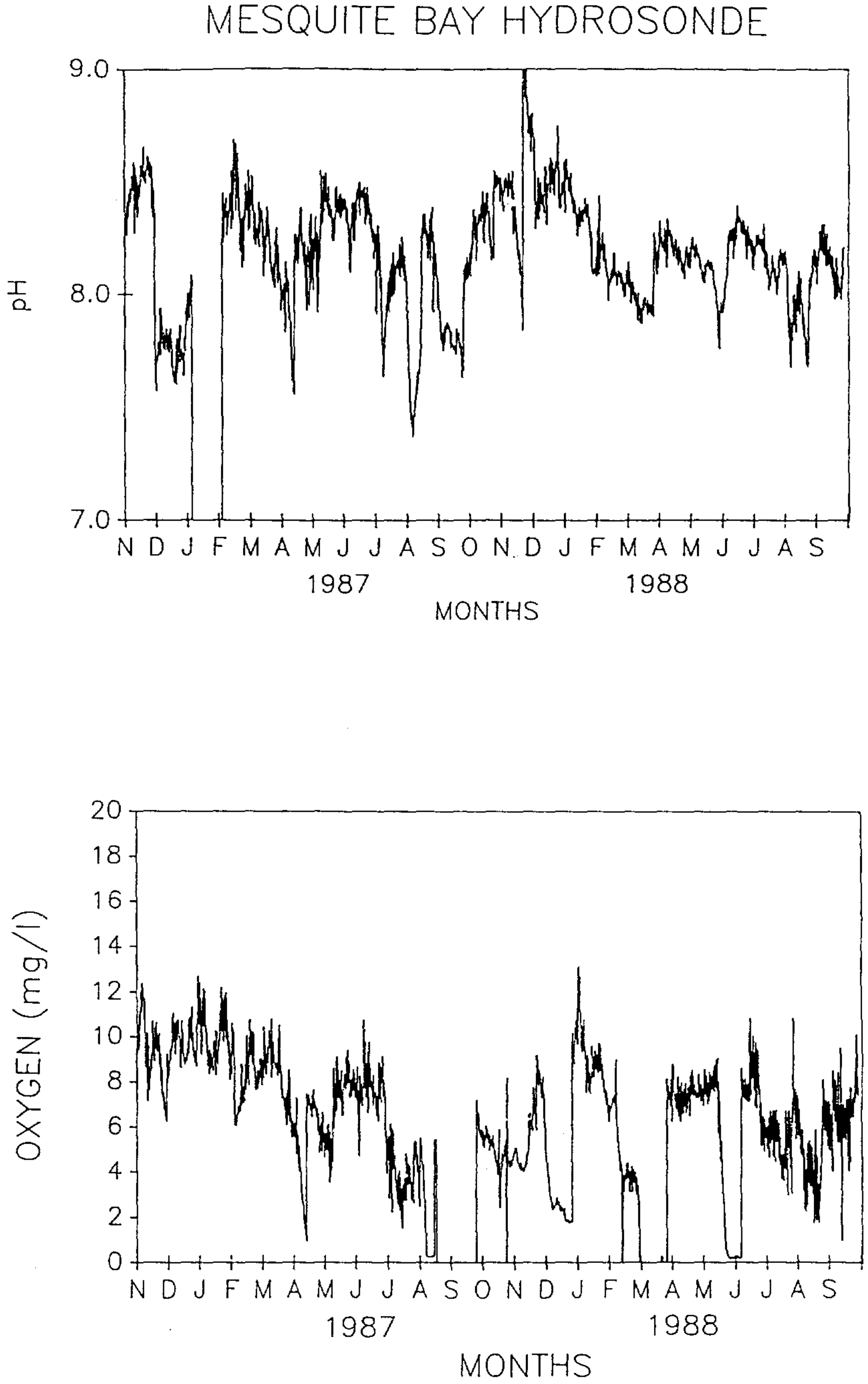


Figure 25. pH (upper) and dissolved oxygen (lower) measured by an in situ recorder in Mesquite Bay every three hours from November 1986-September 1988.

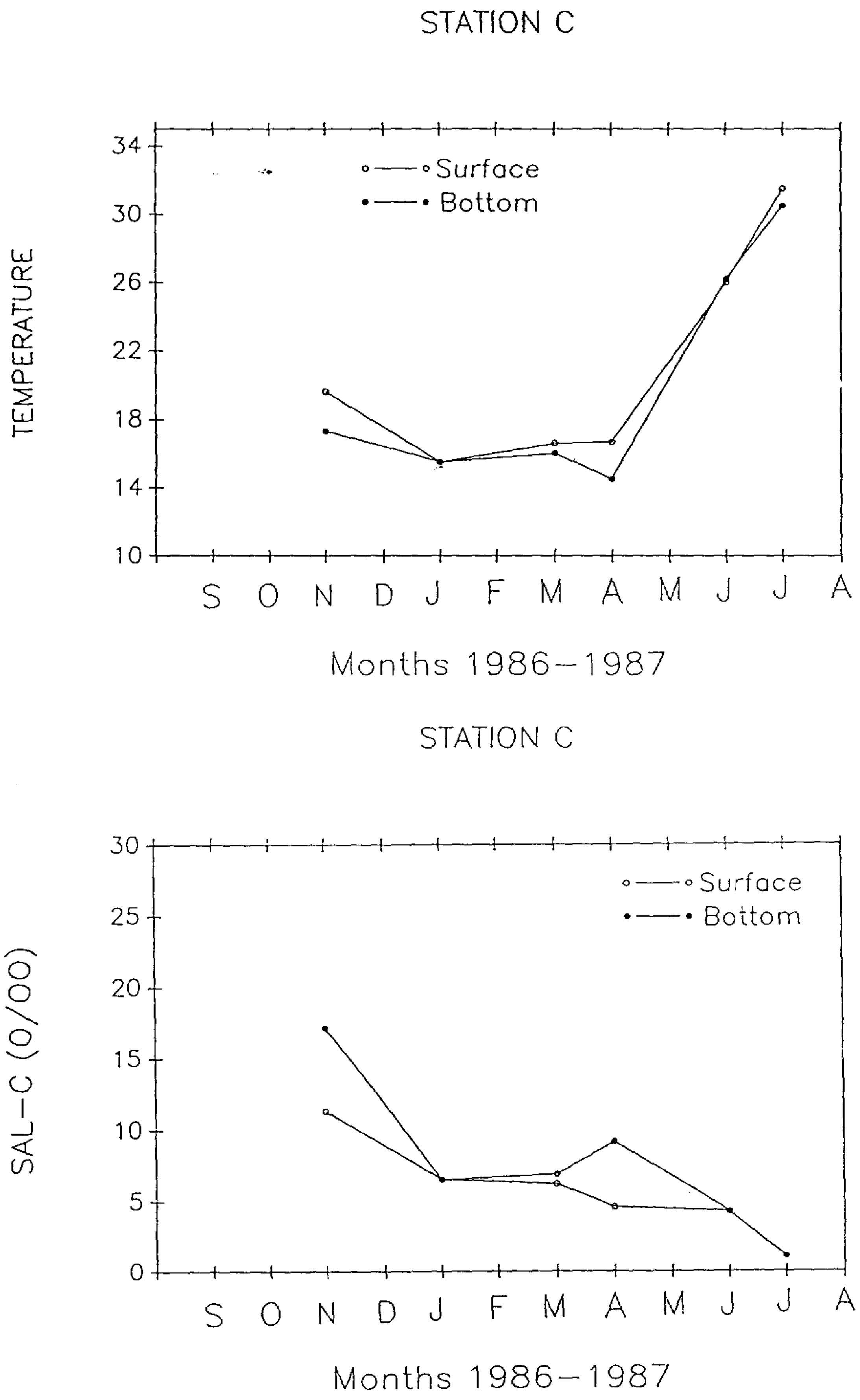


Figure 26. Temperature (upper) and salinity (lower) measured at station C during surveys from November 1986-July 1987.

completely mixed with deeper high salinity water. The temperature was occasionally higher at the surface by about 2°C. Both temperature and salinity from the survey data were very similar to the hydrosonde in Mesquite Bay. Nitrate concentrations were often quite high and variable depending on many conditions. Typical concentrations of nitrate at station C were about 25% of those at station A. There was often a strong gradient of nitrate observed in the surface distributions (Fig. 6) so this strong horizontal gradient was also observed in hourly time series data (Fig. 27) as a result of tidal movement of the gradient (front) back and forth past the station location. In general, the surface samples had larger nitrate concentrations especially when the low salinity surface waters were present. These quite large nitrate concentrations were especially conducive to phytoplankton growth so it was not too surprising to also observe large chlorophyll concentrations where relatively large decreases of nitrate occurred. Silicate concentrations remained high at Station C although as much as 50% was utilized compared to Station A (Fig. 26). Orthophosphate increased during the sampling period from a value of 2 in November to about 9 ug-at/liter in June (Fig. 28). The increase in concentration through the sampling period is probably indicative of recycling rather than new inputs or lack of uptake.

Chlorophyll a concentrations at Station C were large (>10 μg/liter) during the entire sampling period but especially high concentrations (>40 μg/liter) were observed throughout the water column in March (Fig. 29). Several other stations around this location had similar values of chlorophyll a concentration (Fig. 9 and 10). The trend of chlorophyll a concentrations at station A was not as large but there is a suggestion of an increase relationship which could indicate either a down bay flow of material or a shift of primary production down the bay. The phaeopigment concentrations were quite similar to station

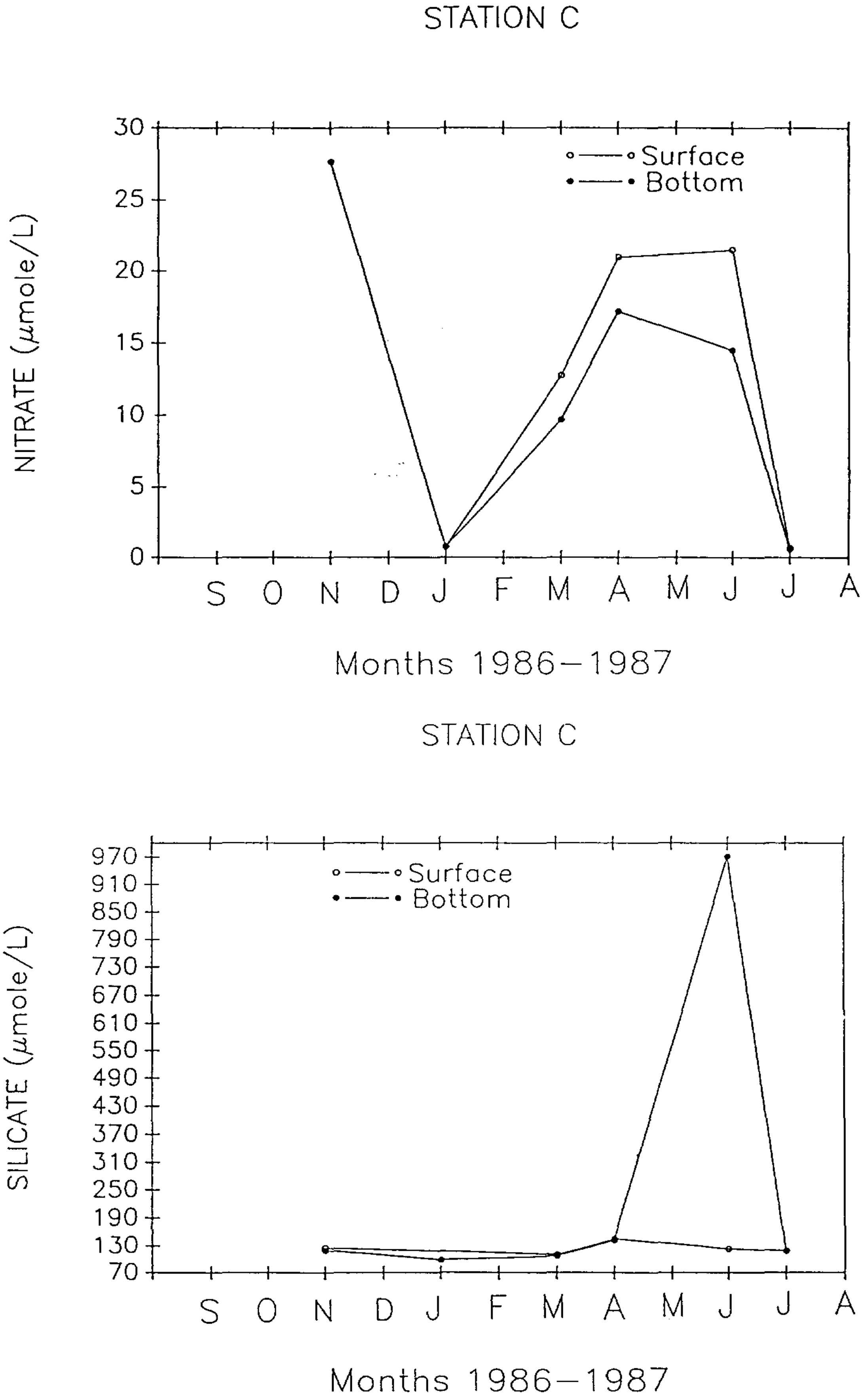


Figure 27. Nitrate (upper) and silicate (lower) measured at station C during surveys from November 1986-July 1987.

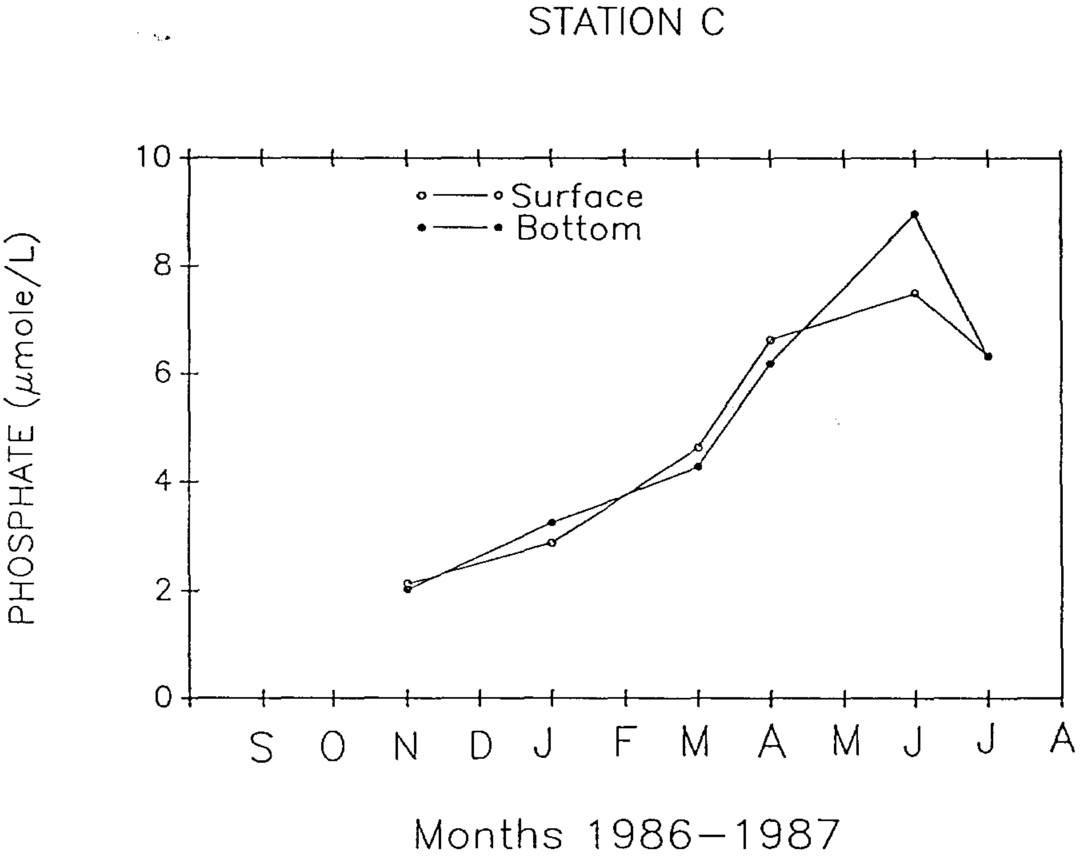


Figure 28. Orthophosphate measured at station C during surveys from November 1986-July 1987.

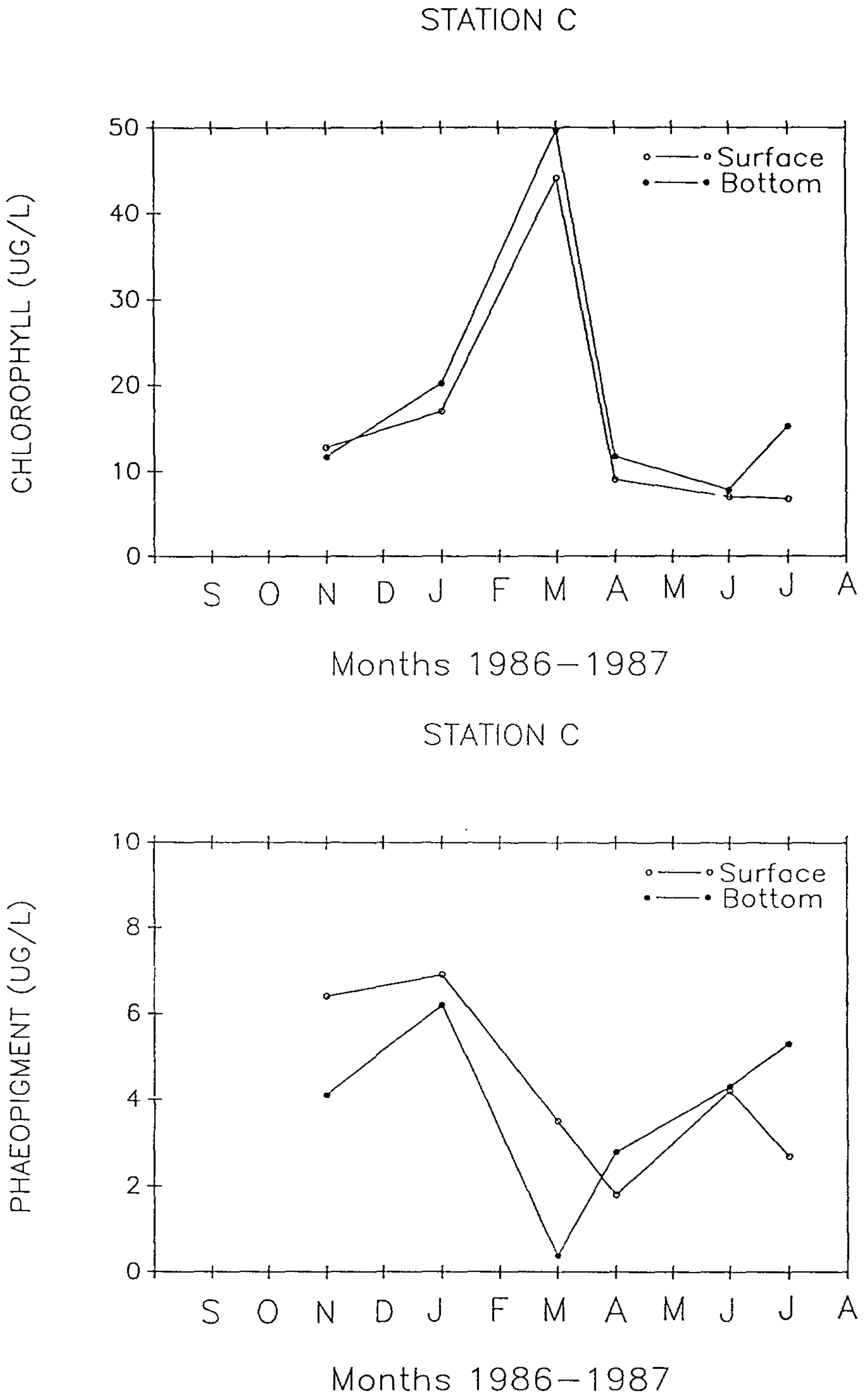


Figure 29. Chlorophyll (upper) and phaeopigment (lower) measured at station C during November 1986-July 1987.

A but no increase was noted with time on Station C. The phaeopigment concentrations were very low in the bottom samples when the chlorophyll a was high in March (Fig. 29) which would be expected if the phytoplankton were very actively growing. Surface phaeopigment concentrations were higher than bottom values in the winter and spring but bottom concentrations increased above surface values in spring and summer. If these observations are valid then the ecosystem may be dominated by water column consumption of phytoplankton by zooplankton in the winter and benthic consumption of organic matter in the sediment in the summer.

Ammonium concentrations at Station C ranged from 0.1 to 6 ug-at/liter over the 8 month sampling period. The initial low concentrations would not support active phytoplankton growth but certainly by March the concentrations had increased to support maximum phytoplankton growth rates (Fig. 30). The increased concentrations during summer probably resulted from enhanced rates of decomposition in the warm waters near the bottom which corresponded nicely to the phaeopigment observations. Nitrite concentrations were somewhat lower at Station C compared to the upper bay at Station A. Nitrite concentrations did rise above 1 ug-at/liter with highest concentrations near the bottom in the summer (Fig. 30).

Hourly Time Series - Station C.

The hourly time series measurements at Station C were taken during the night when equipment was available for analyses and testing. The time series of nitrate at Station C in November showed the nitrate concentration in the surface layer was much larger than the bottom during a 4 hour period at midday (Fig. 31). When the time series for January

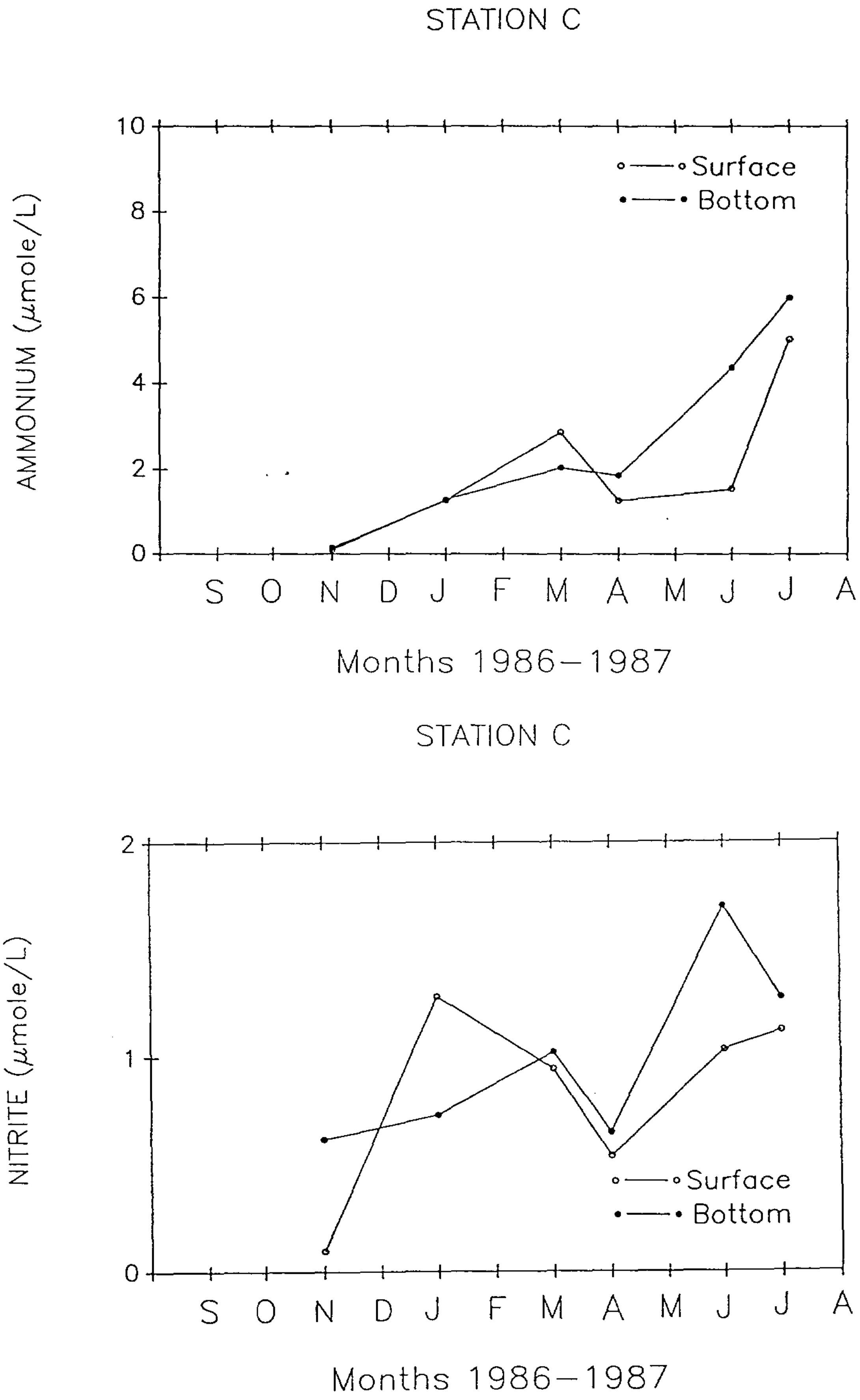


Figure 30. Ammonium (upper) and nitrite (lower) measured at station C during surveys from November 1986-July 1987.

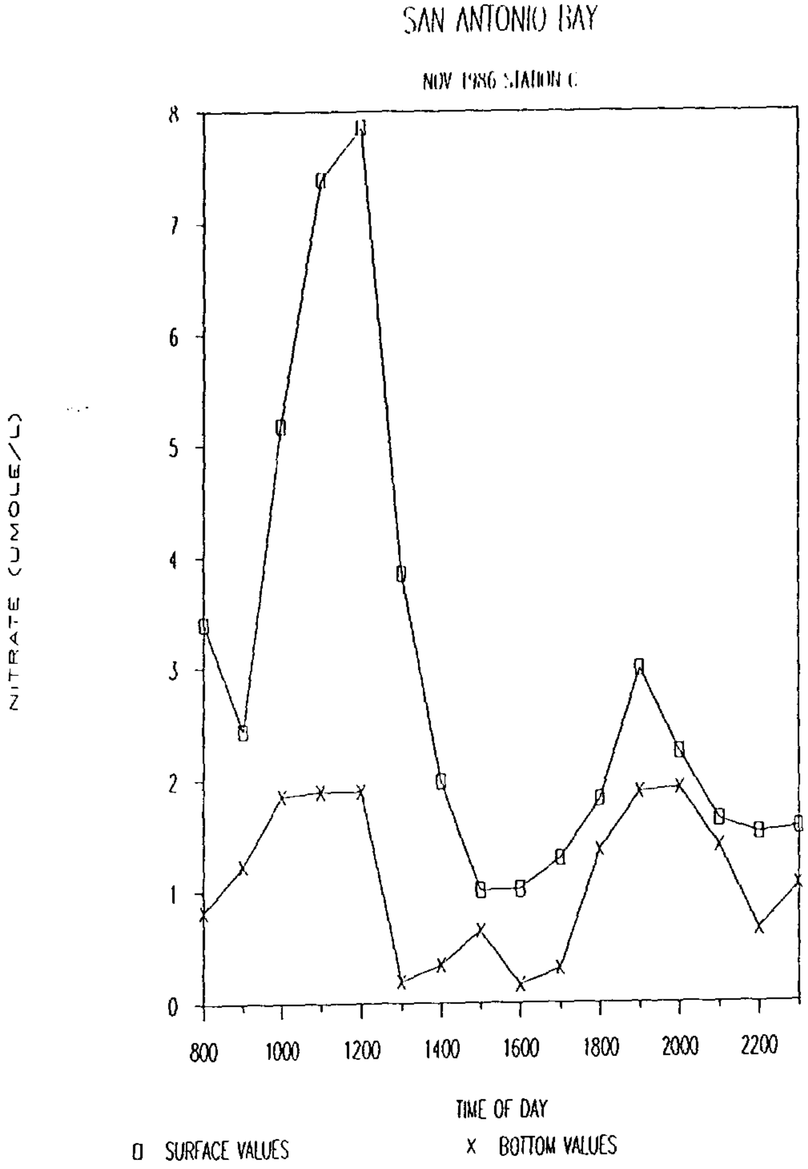


Figure 31. Hourly time series measurement of nitrate at station C in San Antonio Bay on 20 November 1986.

is included, it is apparent that very large vertical differences of nutrient content exist frequently in the bay system (Fig. 32).

In this instance, vertical differences of nitrate, silicate and phosphate were about 40, 50 and 3 mmole/liter respectively. Later, in April, a stratified water column had greater than 1.5°C difference between surface and bottom, salinity differences were as great as 4‰ and nitrate and ammonium concentrations occasionally differed between surface and bottom by 4 and 1 ug-at/liter respectively (Fig. 33). No samples were collected during daylight hours but strong sunlight followed by the afternoon sea breeze increased the temperature and mixed the water column. The resulting temperature and nitrate were identical at the surface and bottom while small deviations in salinity and ammonium were still observed.

DISCUSSION

Nutrient Inflow

The study period of November 1986 through July 1987 was anomolous with regard to freshwater inflow since the 35 year mean gaged flow of about 5000 acre-feet/day[1] increased to as much as 230×10^3 acre-feet/day, a factor of increase of about 46 times. The duration of high river discharge remained above normal for 6 of 9 months starting in December 1986 and ending in August 1987 (USGS Water Resource Data, Texas, Water Year 1987). The total gaged flow of the Guadalupe River for the water year 1984 was only 347,700 acre-feet while 1987 was 3,879,000 acre-feet which is over an order of magnitude variation for the yearly totals. The annual mean volume for the years 1941 to 1976 was 1,810,000 acre-feet so 1987 was at least double the long term mean in terms of total water

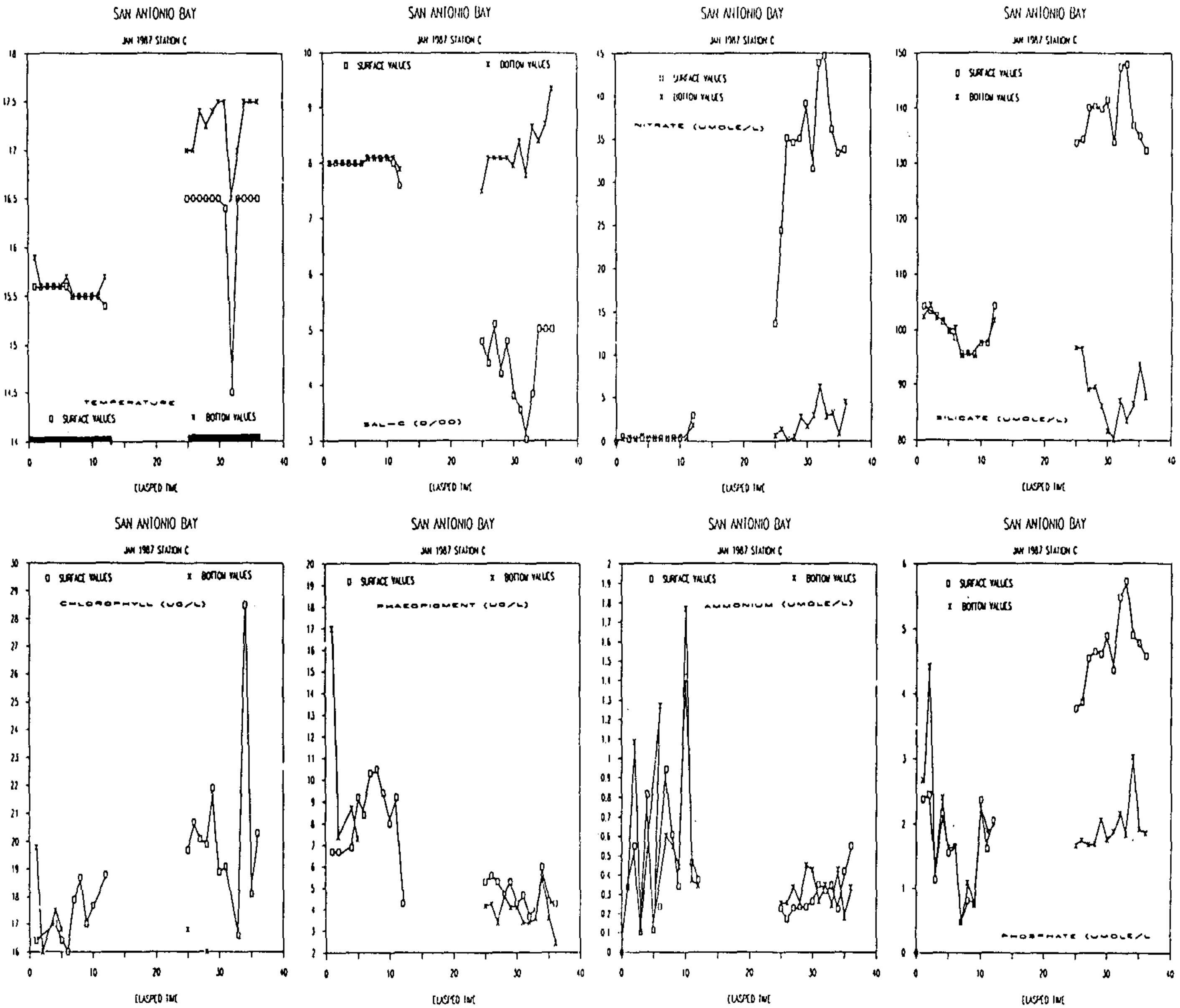


Figure 32. Hourly time series measurement of temperature, salinity, nitrate, and silicate (upper) and chlorophyll, phaeopigment, ammonium, and phosphate (lower) at station C in San Antonio Bay on 28-29 January 1987.

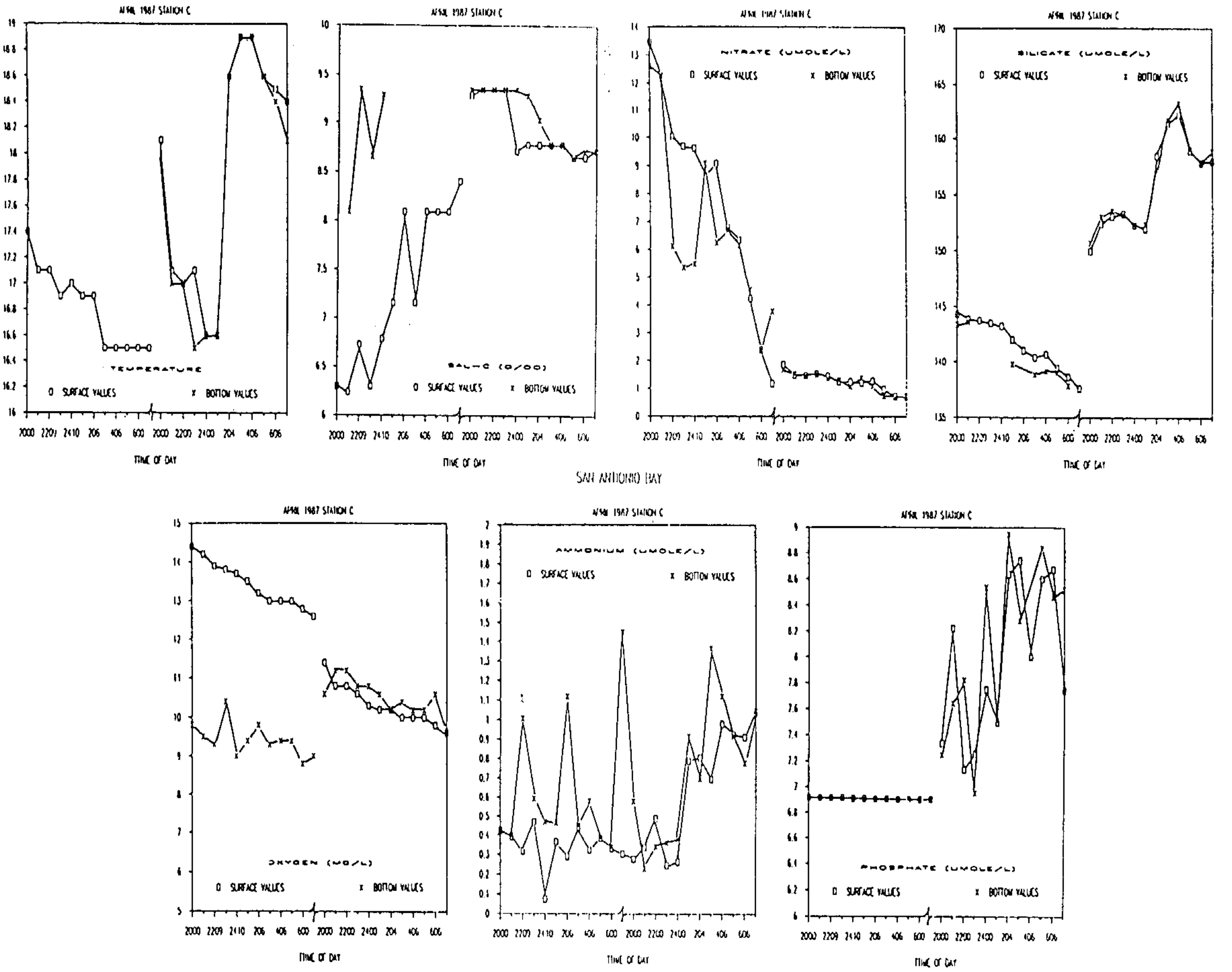


Figure 33. Hourly time series measurement of temperature, salinity, nitrate and silicate (upper) and oxygen, ammonium and phosphate (lower) at station C in San Antonio Bay on 8-10 April 1987.

flow (Table 1). The monthly discharges also indicate the tremendous discharges during June 1987.

The quarterly water quality analyses of USGS does not provide specific information about nutrient concentration variations with changes in river flows. The USGS quarterly analyses of nitrate plus nitrite, orthophosphate and dissolved silicon in the Guadalupe River at Victoria were reasonably similar to samples collected at the river mouth (Table 2). The differences in concentrations between the two data sets could easily be the result of different sampling dates or point and non-point inputs between the two sampling sites. The USGS water quality data for the San Antonio River at Goliad indicates a much larger nitrate concentration (~ 350 ug-at/liter) compared to analyses for the Guadalupe River at Victoria (~ 44 ug-at/liter). The observed nitrate concentrations at the mouth of the Guadalupe River below the confluence of the two rivers ranged from 68 to 135 ug-at/liter which is only slightly smaller than 160 ug-at/liter that would be predicted by relative flow rates and respective concentrations. It is interesting to speculate on the different sources of loading for the two rivers. The sum of dissolved inorganic nitrogen (DIN) species (nitrate, nitrite and ammonium) should be predominantly in the oxidized form (nitrate) while in the river, because of rapid nitrification in freshwater. In the estuarine system, ammonium and nitrite are more common and these species can and do dominate the DIN pool.

As predicted, the riverine nitrate concentrations were much larger than nitrite or ammonium (Table 2) for both USGS analyses and this study. The mean concentration of nitrate plus nitrite was 93.5 ug-at/liter and ammonium was 5.3 ug-at/liter. When reviewed for all the sampling of both USGS and this study, a mean of 81.7 ug-at DIN/liter were present in the Guadalupe River during 1986-1987. The November 1986 DIN measurements

Table 1. Monthly total discharge of Guadalupe River (ft^3/sec) at Victoria, Texas.

	1983	1984	1985	1986	1987
Jan		23,194	62,850	55,830	138,770
Feb		19,113	43,799	49,360	89,320
March		23,883	72,140	38,580	141,460
April		13,685	77,100	29,279	64,080
May		11,387	49,440	48,006	69,110
June		8,719	80,510	95,450	712,360
July		3,456	77,930	36,983	209,520
Aug		3,247	31,679	20,983	138,660
Sept		3,753	21,666	35,936	70,900
Oct	21,775	19,517	50,840	73,765	
Nov	26,754	20,203	105,820	76,090	
Dec	16,318	26,999	100,040	171,390	

	Water Year (Oct-Sept) Summaries ft^3/sec	Acre-ft	Acre-ft/day	m^3/day
1984	480	347,700	952	1.17x10^6
1985	1,599	1,158,000	3,172	3.91x10^6
1986	1,827	1,323,000	3,624	4.47x10^6
1987	5,358	3,879,000	10,627	1.31x10^6
35 year mean (1941-1976)		1,810,000	4,958	6.11x10^6

From: USGS Water Resource Data, Texas, Water Year 1987

Table 2. Dissolved nutrient concentrations (ug-at/liter) in Guadalupe River at Victoria, Texas[1] and mouth at San Antonio Bay[2].

Date	Nitrate plus Nitrite	Ammonium	Dissolved Inorganic Nitrogen	Dissolved Organic Nitrogen	Phosphate	Dissolved Silicon
23 Oct 1986[1]			35.0	71.4	1.25	183
19 Nov 1986[2]	135	3.6	128.6		7.65	154.8
28 Jan 1987[2]	98	2.2	94.2		9.40	172.4
11 Feb 1987[1]			70.7	50.0	1.25	166
4 Mar 1987[2]	89	8.4	97.4		9.70	181.8
8 April 1987[2]	100	7.6	106.5		9.51	174.1
3 June 1987[2]	71	2.9	79.9		9.36	1233
23 June 1987[1]			67.8	70.0	1.56	233
15 July 1987[2]	68	8.6	77.2		13.01	120.8
19 Aug 1987[1]			59.3	47.1	.67	233
6-8 Oct 1987[4]	64			27.8	1.41	
7 July 1988[2]	102	3.2	105.2		12.4	75.4
Mean (1986-1987)	93.5	5.3	81.66	59.6	6.34	285.2

[1] From: USGS Water Resource Data, Texas, Water Year 1987

[2] mouth of Guadalupe River in San Antonio Bay

[3] sum of nitrate plus nitrite plus ammonium

[4] From: The Academy of Natural Sciences of Philadelphia, Report 88-23

probably represent the "best" low flow value of 128.6 ug-at/liter. Likewise, the July 1987 sampling during high flow conditions in the Guadalupe River had decreased to 77.2 ug-at/liter. These values along with the yearly calculated means are used in nitrogen influx estimations. Although dissolved organic nitrogen (DON) was not measured in the NIPS study, it is interesting to note that USGS reported a mean concentration of 59.6 ug-at/liter which ultimately flows into San Antonio Bay.

In a similar fashion, silicate concentrations during the November 1986 low flow sampling was 154.8 ug-at/liter and was 120.8 ug-at/liter in July 1987. The variability is quite large so the overall mean concentration of 285 ug-at/liter is probably too high. The NIPS mean for silicate was 146.6 ug-at/liter if the one extremely high value is discarded.

Orthophosphate values reported by USGS at Victoria were always lower than the river mouth hence the difference in phosphorus in fresh and marine water is apparent. The orthophosphate concentration was 7.6 ug-at/liter in November 1986 and it increased to 13.0 ug-at/liter during the high river flow in July 1987. The overall phosphate mean of 6.3 ug-at/liter increased to 10.1 ug-at/liter when only NIPS data at the river mouth was considered.

During mean conditions about 6.98×10^3 Kg N/day enters San Antonio Bay from gaged flow. This compares to 2.21×10^3 Kg N/day under low flow conditions and 1.68×10^5 Kg N/day under extreme high flow conditions (Table 3). Since continual monitoring of gaged flow occurs, the weak points in this analysis are the infrequent water chemistry measurements plus the error associated with not using additional water inputs like ungaged flow, direct precipitation, and return flow. The introduction of excess nitrogen during a

Table 3. Characteristics of San Antonio Bay during high, low and mean inflows of freshwater for 1986-1987.

	Units	High Flow	Low Flow	Mean Flow
Inflow of Guadalupe River	AF/D	126x10^{3}	1x10^{3}	4.95x10^{3}
Inflow of Guadalupe River	m^{3}/day	1.56x10^{8}	1.23x10^{6}	6.11x10^{6}
Residence Time[1]	days	4.8	613	123
Nitrate in Guadalupe River	ug-at/liter	67	120	90
Nitrate Inflow	mg-at/day	1.0x10^{10}	1.48x10^{8}	5.5x10^{8}
Nitrate Inflow	KgN/day	1.5x10^{5}	2.07x10^{3}	7.7x10^{4}
DIN in Guadalupe River[2]	ug-at/liter	77.2	128.6	81.7
DIN Inflow	mg-at/day	1.2x10^{10}	1.58x10^{8}	4.99x10^{8}
DIN Inflow	Kg/day	1.68x10^{5}	2.21x10^{3}	6.98x10^{3}
DIN Outflow	mg-at/day	1.09x10^{8}	8.61x10^{5}	4.28x10^{6}
DIN Outflow	Kg/day	1.53x10^{3}	1.21x10^{1}	5.99x10^{1}
DIN Inflow-Outflow	Kg/day	1.65x10^{5}	2.2x10^{3}	6.9x10^{3}

[1] Volume of San Antonio Bay = 0.754 km^{3} = 7.54x10^{8}m^{3}

[2] DIN = Nitrate plus Nitrite plus Ammonium

Mean depth of San Antonio Bay = 1.4 m (Armstrong, 1987) high flow year like 1987 is more than 24 times larger than a "normal year" while during low flow conditions the introduction of nitrogen may fall to about 30% of normal. This points out the extreme difference that a high flow event can make in an estuary while low flow periods are relatively small changes.

Bulk Nutrient Inventory

The bulk nutrient inventory increases in San Antonio Bay during years of large freshwater inflow because more nutrients, especially nitrogen, are entering but essentially the same low concentrations are exiting the bay proper. The greatest difference therefore occurs in the central areas of the bay. During normal inflows 6.98×10^3 Kg DIN/day enters the bay while not more than about 60 Kg/day DIN is lost through advection (Table 3). This loss was calculated from the ambient nitrogen concentration in lower San Antonio Bay of 0.7 ug-at/liter (Fig. 6) and not the mean concentrations over the entire bay (Table 4). At high flow rates a net increase of nitrogen of 1.65×10^5 Kg/day is utilized in the bay while at low and normal flow rates, 2.2×10^3 and 6.9×10^3 Kg/day are used respectively. This analysis is only a first approximation because other inputs and losses have not been considered. In the case of the year 1987 in San Antonio Bay the increased flow for over 6 months could increase the "bulk" nitrogen loading in the bay ecosystem by 2.5×10^6Kg DIN which is about double the normal input. This input of nitrogen is only the beginning of many biological and chemical processes that incorporate, transform and accumulate nitrogenous substances.

Table 4. Mean values measured in San Antonio Bay during NIPS surveys, November 1986 - July 1988.

Parameter	Units	Nov 86	Jan 87	Mar 87	Apr 87	June 87	July 87	July 88	Mean 86-87
Temperature	°C	17.61	14.78	16.51	15.32	26.32	30.51	29.27	20.18
Salinity-Refract.	‰	10.5	2.05	9.2	3.7	6.5	1.4	24.1	5.56
Nitrate	ug-at/liter	30.9	28.67	25.01	27.82	43.05	8.35	5.82	27.30
Nitrite	ug-at/liter	0.48	0.78	1.38	0.71	1.44	1.59	0.26	1.06
Ammonium	ug-at/liter	0.56	0.95	2.82	2.64	3.41	4.83	1.43	2.54
DIN	ug-at/liter	31.94	30.40	29.21	31.17	47.90	14.77	7.51	30.90
Org. Nitrogen	ug-at/liter	42.9	28.6	78.6	-	-	42.9	-	42.9
Phosphate	ug-at/liter	2.37	4.41	4.68	6.49	6.44	6.44	3.64	5.14
Silicate	ug-at/liter	114.1	131.4	117.6	142.6	500.8	104.4	74.8	185.1
Chlorophyll *a*	ug/liter	10.6	12.7	20.2	9.2	9.7	8.9	9.7	11.9
Phaeopigments	ug/liter	3.9	4.6	4.1	4.2	6.2	3.8	3.0	4.5
Secchi Depth	m	-	-	.32	1.24	.24	.35	.57	.54

Atmospheric Nitrogen Input

The primary precipitation falling directly on the bay contains a variety of substances including nitrogen nutrients and in both reduced and oxidized forms (e.g. ammonium and nitrate). Precipitation data was obtained from Victoria, Beeville and Attwater Prairie Chicken, Texas from the National Atmospheric Deposition Program and several rainwater samples were collected from the meteorological station at the Marine Science Institute (MSI) and analyzed for nutrient content (Table 5). The quantity of various consitutents in samples collected at MSI varied a great deal for unknown reasons. It is known that periodic sampling during a precipitation event will show a decline in most constituents with time. These samples were composites of the entire event but the duration of collection obviously varied with the particular storm. It is possible that the concentrations observed in the composite samples were somewhat related to the amount of precipitation and the origin or direction of the storm. Dry deposition was an additional input but there is currently no known data for the region.

The concentrations of ammonium and nitrate were very similar from all these collection sites at Victoria, Beeville and Attwater Prairie Chicken with mean values ranging from 8.8 to 12.7 and 10.9 to 12.9 ug-at/liter respectively. The total DIN averaged from 19.7 to 25.7 ug-at/liter. The quantities of nitrate and ammonium in rainwater at the MSI in Port Aransas were similar over the duration of collection in 1988-1989 but were much larger than the other nearby reporting stations. The differences may be due to sample contamination so this data was not used in subsequent flux calculations. Nitrite concentrations were insignificant so the mean DIN for all Port Aransas samples was 99.9 ug-at/liter of rainwater. Orthophosphate and silicate had mean concentrations of 3.6 and

Table 5. Annual mean amounts of precipitation (cm) and nitrogen concentrations (ug-at/liter) at Victoria, Beeville and Attwater Prairie Chicken, Texas.

	NH_4	NO_3	DIN	Precipitation
Victoria				
1980	19.4	14.3	33.7	58.82
1981	10.0	10.6	20.6	113.65
1982	11.2	10.3	21.5	84.04
1983	15.3	14.2	29.5	107.02
1984	10.0	12.1	22.1	87.43
1985	10.0	11.8	21.8	100.59
1986	10.0	12.3	22.3	102.32
Mean	12.3	12.2	24.5	93.41
Beeville				
1984	11.2	11.4	22.6	57.16
1985	12.3	11.6	23.9	74.90
1986	14.7	15.8	30.5	80.56
Mean	12.7	12.9	25.7	70.9
Attwater Prairie Chicken				
1984	8.2	10.3	18.5	41.21
1985	8.2	10.0	18.2	113.93
1986	10.0	12.3	22.3	121.49
Mean	8.8	10.9	19.7	92.21
Port Aransas*				
1988	65.9	59.6	130.3	-
1989	48.1	49.3	100.2	-

*Mean values of 7 values in 1988 and 20 values in 1989; not an annual mean

2.9 ug-at/liter in the rainwater. The only nearby source of these nutrients would be from sea spray.

Using an average rainfall for the region of San Antonio Bay of about 38.4 inches of rainfall/year (equivalent to 97.6 cm/yr) (Armstrong, 1987), the direct annual addition is about 5.4×10^8 m^3 of rainwater and the DIN added is about 1.72×10^5 Kg N/yr. The DIN input by the Guadalupe River is estimated to be 2.55×10^6 Kg/yr in an average year so rainfall represents 6.3% of the sum of gaged inflow and direct precipitation. The ungaged inflows need to be added to this value in order to be very significant however this calculation shows that rainfall may be a significant source of nitrogen in addition to the rivers especially during low inflow periods caused by lack of precipitation in the upper reaches of the watershed.

Ergoclines (Fronts and Pycnoclines)

The presence of interfaces between different water types either in horizontal or vertical directions and the water-benthic interface are locations where biological and physical processes are often enhanced and therefore increased production can occur (Legendre, 1986). The increased physical mixing that occurs at a discontinuity has the units of work hence the term ergocline arises. Although no specific measurements were targeted toward surface fronts, the strong gradient of nitrate (40-80 ug-at/liter) generally corresponded quite well with relative distributions of surface salinity, turbidity (Secchi depth) and chlorophyll a concentration. The presence of a front indicates that very little physical mixing is occurring across the frontal zone but several recent investigations have found lateral transport in opposite directions (shear) along a frontal zone. These differential flows create small scale turbulence and thus lateral mixing. A phytoplankton cell at the frontal interface can therefore be mixed with small amounts of water along or across the front and as a result be located at the boundary of sufficient nutrients and available light.

The low salinity conditions during the unusually large freshwater inflow period in 1987 reduced the magnitude of salinity fronts to the range of 0.10 to 1.29 ‰/km however in July 1988 the increased salinity field produced 2.16 ‰/km (Table 6). Nitrate concentrations across the fronts ranged from 1.31 to 17.48 ug-at/liter/km during the high flow period and only 0.21 ug-at/liter/km in July 1988. The corresponding chlorophyll concentration ranged from 1.08 to 5.98 μg/liter/km during low flow and 2.01 μg/liter/km in July 1988. Primary production measurements and direct nutrient utilization experiments were not measured on this small scale because time and resources were limited, however it is possible to estimate primary production in these areas of large gradients.

Very little vertical stratification was observed in San Antonio Bay. The most apparent stratification occurred in April 1987 during a period of moderate freshwater inflow and relatively high bottom salinities that probably originated in the Victoria Barge Channel. Low oxygen concentration (3.9-5.2 mg/l) along the bottom corresponded with ammonium concentrations as large as 6 ug-at/liter and near bottom chlorophyll concentrations greater than 10 mg/liter.

Table 6. Small scale surface horizontal gradients of salinity, nitrate and chlorophyll a in San Antonio Bay, Texas.

Date	Distance Km	Salinity ‰/Km	Nitrate ug-at/liter/Km	Chlorophyll a ug/liter/Km	Locations Compared
Nov. 1986	5.18	0.52	4.75	1.83	Sta 17-30
Jan. 1987	1.48	1.29	17.48	4.45	Sta 16-17
March 1987	2.22	0.90	5.36	5.98	Sta 29-16
April 1987	3.70	0.86	5.40	1.84	Sta 30-16
June 1987	2.96	0.40	1.59	1.08	Sta 28-30
July 1987	7.04	0.10	1.31	2.18	Sta 14-16
July 1988	4.81	2.16	0.21	2.01	Sta 4-10

Temporal Variability

The long term temporal variations can show the seasonal and/or annual cycle of processes and will help define the range limits on the ecosystem over the time scale of weeks or months. It is tempting to consider the variability for the year long record as "normal" but the low salinity conditions that prevailed for several months should be considered a high flow anomolous event. The annual cycles of concentrations were shown for experimental stations A and C however the range of variation for the entire set of stations is usually more extreme. It is interesting to note that even though a tremendous amount of freshwater inflow occurred in San Antonio Bay during the NIPS sampling, many of the measurements displayed normal ranges, e.g. temperature (Table 7). A comparison with 19 years of data collected along the Gulf Intracoastal Waterway shows that the nitrate and phaeopigments were much larger in NIPS measurements than the typical midbay stations although direct comparisons should not be made because one set is a single location for many years and the other set is many locations for a single year.

The short term variability was examined on experimental stations A and C in order to assess the diel changes that occurred. The physical changes of salinity and temperature were the result of advection, inflow, winds or sunlight while biological changes will result from growing microbiological and plankton populations. Some of the rates of change are not really obvious but a closer examination explains the situation. For instance, the rate of salinity change at station A in July 1987 is relatively small even thought the major amount of freshwater had lowered the salinity of most of the San Antonio Bay water to

Table 7. Range of values for parameters measured in San Antonio Bay during NIPS Surveys November 1986-July 1987.

Parameter	Units	Max[1]	Min[1]	Range[1]	Max[2]	Min[2]	Range[2]	No.[2]
Temperature	°C	31.8	12.3	19.5	34.8	6.0	28.8	169
Salinity	‰	18.0	0	18.0	-	-	-	-
Nitrate	ug-at/l	431.9	0.03	431.9	50.0	0	50.0	64
Nitrite	ug-at/l	4.37	0.03	4.34	-	-	-	-
Ammonium	ug-at/l	13.80	0.01	13.79	114.3	0	114.3	64
Phosphate	ug-at/l	13.97	0.30	13.67	11.9	0	11.9	52
Silicate	ug-at/l	1232	27.9	1204	-	-	-	-
Chlorophyll *a*	ug/liter	50.1	0.59	49.5	120	0.5	119	47
Phaeopigments	ug/liter	37.9	0.3	37.6	20	0	20	36
Secchi Depth	m	2.8	0.05	2.7	1.17	.10	1.07	31

[1] NIPS for November 1986-July 1987 for a total of 456 samples

[2] TWC Report for Intracoastal Waterway marker 17 (1969-1988)

less than 1 ‰ (Table 8). Since the low salinity remained at site A during the 10 hours of observations, the rate of change was small. However, the rate of salinity change, 0.26‰/hr, and 0.273‰/hr were relatively large at station A in June 1987 and station C in April 1987. There are many deficiencies in this data as far as temporal and spatial resolution, nevertheless it does provide some interesting and semiquantitative information.

The rate of change of nitrate was very large at station A in April and July 1987. Since salinity changes for those data sets don't look especially large, it is tempting to speculate that recently discharged Guadalupe River water advected past the station site or nitrification may be occurring at high rates.

It is also interesting to note that silicate has the most consistently large rates of change which is probably explained by its high concentrations in river water, ever present gradient down the bay and its lack of rapid microbiological regeneration.

Circulation and Conservative Properties

There was no specific circulation studies funded while San Antonio Bay studies were being conducted so the general flow characteristics are uncertain. However, the distribution of conservative and non-conservative properties provide some insight into possible flow patterns.

During each San Antonio Bay survey, additional measurements were collected in the Gulf Intracoastal Waterway (ICW) and Victoria Barge Channel in an effort to determine if these deep channels were transporting high salinity bottom water into the central bay. A comparison of surface and bottom salinity (Figs. 4 and 5) indicates that enhanced bottom

Table 8. Rate of change of Nutrient Concentrations at Experimental Stations A and C in San Antonio Bay.

Station A	Date	Sal.	Temp.	Nitrate	Nitrite	Ammonium	Phosphate	Silicate	Chlorophyll	t
	Nov/86	.017	.072	1.18	.122	1.04	.222	1.36	.356	36
	Jan/87	.260	.100	.700	.055	.060	.170	.600	.700	10
	April/87	.055	.191	3.81	.082	.273	.309	3.64	.218	11
	July/87	.090	.150	6.40	-	.470	.350	1.40	-	10
Station C										
	Jan/87	.139	.056	1.25	.011	.050	.147	1.44	.167	36
	April/87	.273	.218	1.14	.155	.118	.182	2.27	-	11
	July/87	.058	.292	.058	.117	.625	-	1.67	-	12
	July/88	.100	.125	.029	.004	.054	.150	.917	.150	24

Units:

Salinty	‰/hr
Temperature	°C/hr
Nitrate	ug-at/liter/hr
Nitrite	ug-at/liter/hr
Ammonium	ug-at/liter/hr
Phosphate	ug-at/liter/hr
Silicate	ug-at/liter/hr
Chlorophyll	ug/liter/hr
t	hrs

salinity in November 1986 and April 1987 may have originated in these channels and entered San Antonio Bay on the east and south sides. The extreme vertical stratification ($\Delta\sigma$ t = 5-11) did not produce any oxygen or nutrient effects but chlorophyll concentrations were somewhat different between surface and near bottom. Since oxygen reduction had not occurred it may have been a short term phenomenon.

During high freshwater discharges in the spring, the distribution of low salinity water appeared to be "steered" by the numerous shallow oyster reefs in the central bay north of ICW. A coupling of bottom water flowing north up the Victoria Barge Channel could enter the oyster shell dredge channels on the east side of the bay and then flow southward. The drift of research boats on relatively clam days and the salinity distributions observed at the surface and bottom in June 1987 (Figs. 4 and 5) tend to support that supposition.

Nutrient Uptake Processes

Nutrients are utilized in the water column by both autotrophic and heterotrophic processes. Experiments were performed by two groups in an effort to better quantify the amount of nitrogen used by microbiological and phytoplankton populations. The details of the microbiological investigations are discussed in Nitrogen Cycling and Bacterial Production by Drs. Benner and Yoon (Component 7) and the Carbon Productivity of Phytoplankton by Dr. Stockwell (Component 2).

The particulate nitrogen (PN) concentrations at station A was determined during four experimental periods in conjunction with ^{15}N-labeled nitrate uptake measurements. Unfortunately the nitrogen isotope samples were lost during analysis due to instrumental malfunction. The mean PN values (Table 9) of the four data sets ranged from 12.0 to 17.9

Table 9. Phytoplankton nitrogen and carbon composition at station A in San Antonio Bay.

Date	PN (μg-at/liter)	PC (μg-at/liter)	PC/PN (at/at)
Nov 86	16.57	109.3	6.60
	10.37	106.2	10.24
	15.69	117.1	7.46
	19.44	107.5	5.53
Mean (S.D.)	15.52 (3.79)	110.0 (4.9)	7.46 (2.02)
Jan 87	15.31	188.7	12.33
	13.61	257.0	18.88
	12.23	243.1	19.88
Mean (S.D.)	13.72 (1.54)	229.6 (36.1)	17.03 (4.10)
April 87	10.57	146.9	13.90
	14.37	243.8	16.97
	11.21	195.9	17.48
Mean (S.D.)	12.05 (2.03)	195.5 (48.5)	16.12 (1.94)
July 87	16.70	162.7	9.74
	7.09	72.3	10.20
	15.42	147.8	9.58
	16.28	169.2	10.39
	17.75	157.3	8.86
	14.62	131.6	9.00
	27.85	247.6	8.89
	27.53	229.1	8.32
Mean (S.D.)	17.91 (6.86)	164.7 (54.8)	9.37 (0.72)

μg-at/liter which are relatively stable values for the change in seasons and the increase in freshwater inflow that occurred during sampling period. The particulate carbon (PC) mean values from the same samples ranged from 110 to 230 μg-at C/liter. The resulting PC/PN values are interesting because they indicate that in November 1986 and July 1987 the water column either had smaller amounts of higher plant carbon (e.g. wood fragments), less marine detrital material, or phytoplankton species shifts compared to January and April 1987.

The ^{14}C-primary production measurements at the four experimental sites for each of the six sampling trips were converted to nitrogen uptake using a PC/PN ratio for phytoplankton. While this is a first approximation of actual nitrogen uptake, this procedure has produced relatively good results compared to direct measurements of carbon and nitrogen uptake (Whitledge, Reeburgh and Walsh, 1986). The range of carbon primary productivity was 215 to 4393 mg C/m^2/day with an overall mean of 1176 mg C/m^2/day (Table 10). When converted to nitrogen productivity, the range was 2.6 to 52.5 mg-at N/m^2/day with an overall mean of 14.1 mg-at/m^2/day. These values represent estimated total nitrogen uptake therefore all inorganic nitrogen (nitrate, nitrite and ammonium) and organic nitrogen (urea and amino acids) uptakes are included but no nitrogen species uptake rates are available.

The primary productivity measurements in the high freshwater inflow period of July 1987 was compared to the normal inflow period in July 1988 by Stockwell. These data were again converted to nitrogen uptake using the same conversion factors (Table 11). The resulting nitrogen uptake ranged from 3.5 to 35.2 mg-at N/m^2/day with an overall mean of

Table 10. Phytoplankton productivity estimates for experimental sites in San Antonio Bay for November 1986-July 1987.

Station	Date	^{14}C Production[1]	Calculated[2] N Production
A	18 Nov 86	590	7.05
A	27 Jan 87	252	3.01
A	4 Mar 87	215	2.57
A	7 Apr 87	402	4.81
A	3 Jun 87	835	9.98
A	14 Jul 87	2520	30.13
B	19 Nov 86	613	7.33
B	28 Jan 87	307	3.67
B	4 Mar 87	1688	20.18
B	8 Apr 87	823	9.84
B	3 Jun 87	676	8.08
B	15 Jul 87	946	11.31
C	20 Nov 86	2021	24.16
C	29 Jan 87	629	7.52
C	5 Mar 87	3314	39.62
C	9 Apr 87	764	9.13
C	4 Jun 87	790	9.45
C	16 Jul 87	297	3.55
D	20 Nov 86	481	5.75
D	30 Jan 87	1054	12.60
D	5 Mar 87	4393	52.52
D	10 Apr 87	836	10.00
D	4 Jun 87	3275	39.16
D	17 Jul 87	510	6.10
Mean (S.D.)		1176 (1121)	14.06 (13.40)

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[1] Measurements from Stockwell. Units are mg C/m^2/day

[2] Calculated based on PC/PN = 6.97 from Redfield *et al.* (1963). Units are mg-at N/m^2/day.

Table 11. Phytoplankton productivity estimates for July 1987 and July 1988 in San Antonio Bay.

	^{14}C prod (mgC/m^2/day)		Chl (mg/m^2)		Calculated[1] N Prod. (mg-at/m^2/d)	
Sta.	1987	1988	1987	1988	1987	1988
A	2520	2942	8.2	72.0	30.13	35.17
B	946	801	14.2	75.5	11.31	9.58
C	297	1302	20.3	65.1	3.55	15.57
D	510	1887	61.8	54.9	6.10	22.56
Mean	1068	1733	26.13	66.88	12.77	20.72

[1] Calc. using a C/N of 6.97 from Redfield *et al.* (1963).

14.7 mg-at/m^2/day. The similar nitrogen uptake estimates in the two comparisons indicate that neither nitrogen nor carbon concentrations are regulating primary production at the four experimental sites in San Antonio Bay. These data may not apply to the entire San Antonio Bay system (lower San Antonio Bay or Mesquite Bay) where DIN concentrations approach 1 ug-at/liter.

Unfortunately, the loss of ^{15}N-labeled specific uptake velocities (μg-at N uptake/ug-at particulate nitrogen/time) does not allow for a direct comparison of nitrate and ammonium uptake by the phytoplankton. If the uptake constants of nitrate and ammonium are assumed to be equal then an approximation of the uptake rates can be calculated from the observed relative nitrogen concentrations and the primary production rates (Table 12). This is a reasonable approach because Benner and Yoon found that ammonium uptake was strongly correlated with ammonium concentrations in both San Antonio and Nueces/Corpus Christi estuaries. The calculated nitrate uptake is much larger than ammonium at station A during the low salinity period in July 1987 however ammonium uptake estimates become more important at stations C and D. During July 1988 under normal salinity conditions, ammonium uptake was calculated to increase relative to nitrate uptake for the entire San Antonio Bay.

These calculated values are somewhat larger than the direct ammonium utilization rates measured by Benner and Yoon (6.5 to 11.7 mg-at/m^2/day) but that is not too surprising when the spatial and temporal variation of nutrients and chlorophyll biomass are considered.

Table 12. Ambient nitrogen concentrations and calculated nitrate and ammonium uptake by phytoplankton.

Date	Station	Nitrate	Ammonium	Nitrate Fraction	PNO_3	PNH_4
July 87	A	67.0	5.5	92	27.7	2.4
	B	2.2	3.9	36	4.1	7.2
	C	0.7	5.0	13	0.5	3.1
	D	0.6	6.2	9	0.6	5.6
	Mean	17.6	5.1	37.5	8.23	4.58
July 88	A	1.2	1.6	43	15.1	20.1
	B	0.5	2.7	16	1.5	8.1
	C	0.4	2.2	15	2.3	13.2
	D	0.6	1.6	27	6.1	16.5
	Mean	0.7	2.0	25.2	6.25	14.5
Units		ug-at/liter	ug-at/liter	%	mg-at/m^2/d	mg-at/m^2/d

Nutrient Regeneration in the Water Column and Sediments

The regeneration of nitrogen in the water column and from the sediments in San Antonio Bay is aptly described by Benner and Yoon for the summer period of July 1988. They found that the rates of ammonium regeneration was up to 3.9 fold higher in bottom water than in surface and the ammonium utilization rates were much higher in bottom water than in surface water. When water column uptake and production of ammonium are combined with the benthic flux of ammonium, a range of 4.51 to 11.02 mg-at $N/m^2/day$ was regenerated. In general, the actual and benthic ammonium flux decreased with distance from the river mouth, while the importance of water column ammonium regeneration increased in deeper water or distance away from the river.

A review of the ammonium concentrations observed during the seven sampling periods from November 1986 to July 1988 shows an apparent difference that probably resulted from the changes in freshwater inflow. For convenience, July 1987 and July 1988 will be compared to reduce any seasonal effects. It can be seen that both surface and near bottom ammonium concentrations were much larger in July 1987 than July 1988 (Figs. 11 and 12). The mean value for all survey stations was 4.83 ug-at/liter in 1987 while 1988 was 1.43 ug-at/liter. It is also interesting to note that starting in November 1986 the mean ammonium concentrations in San Antonio Bay progressed through the sequence of 0.56, 0.95, 2.82, 2.64, 3.41 and 4.83 ug-at/liter (Table 4). At the same time mean nitrite concentrations were 0.48, 0.78, 1.38, 0.71, 1.44 and 1.59 ug-at/liter. The concentration increases in both of these constituents argues for an imbalance of biological processes during the freshwater "event" which increased both ammonium and nitrite concentrations. Combined with the data of Benner and Yoon it is tempting to attribute these increases to benthic flux rates which are normally higher near the mouth of the river. When the volume of San Antonio Bay and the observed increases in ammonium are combined, the resulting increase in ammonium is 4.51×10^4KgN which is equivalent to 6.5 days of normal DIN inflow into San Antonio Bay. However, over an eight month period of time, a regeneration rate of only 0.02 ug-at/liter/day excess over uptake is needed to produce the observed values.

Nitrification, Denitrification and Nitrogen Fixation

The processes of nitrogen fixation introduces new nitrogen into an estuarine ecosystem while nitrification and denitrification transform nitrogen species for subsequent uptake or even loss from the ecosystem.

Benner and Yoon reported that denitrification was occurring at 4.6 to 34.7 ug-at/m^2/hr (0.11 to 0.83 mg-at/m^2/day) with a general inverse relationship with salinity since upper estuary stations had higher denitrification rates than lower estuary stations. The nitrification rates measured were 40.5 to 79.4 μg-at/m^2/hr (0.97 to 1.91 mg-at/m^2/day) but with no clear pattern with respect to salinity. This is in contrast to some reports that nitrification is inversely related to salinity. For instance, Billen (1975) reports that nitrification was maximum at 2‰ and Elkins *et al.* (1981) observed successive peaks of ammonium, nitrite and nitrate going downstream in the Potomac River.

The appearance of increasing ammonium, nitrite and nitrate during the seven periods of sample collection strongly suggests that significant amounts of nitrification and denitrification are occurring in San Antonio Bay. Since nitrite is a possible intermediate product in both nitrification and denitrification it gives no solid clues as to its origin however the oxygen concentrations present seem more conducive to nitrification processes.

Nitrification rates from the Chesapeake Bay have been found to range from 0.7 to 2.4 ug-at/liter/day and 0.24 to 0.96 ug-at/liter/day for the York River (McCarthy, Kaplan and Nevins, 1983).

In terms of denitrification, only a few reports of measurements exist but 35% of organic nitrogen remineralized in Narragansett Bay passes through a denitrification pathway (Seitzinger, 1982).

Nitrogen fixation was not measured in this study so no local data are available for conclusions, however most nitrogen fixation occurs where there is a dearth of available nitrogen in the water column. Most of the known data concerns tidal freshwater with blue-green algae and there are no known measurements to show the nitrogen fixation is of any consequence in estuarine waters (Nixon and Pilson, 1983).

The San Antonio Bay Ecosystem Model

The utility of a model is to draw all the principal elements together in such a way to increase the quantitative understanding of the ecosystem, to bring attention to those components where more work is necessary, and to help design a better field program and experimental plan to focus attention on the most critical elements and their spatial and temporal variations.

The work in the Nitrogen Processes Study (NIPS) has been directed at a better understanding of the San Antonio Bay ecosystem with respect to the quantity of freshwater inflow and subsequent changes in its biological populations (Figures 34-36). The conceptual model that was developed at the initiation of the San Antonio Bay NIPS program has been modified for the actual measurements and calculations. These new data have been combined with historical data, where appropriate, to produce an enhanced model for nitrogen processes that conforms to the conclusions in the following section.

The conceptual model for high freshwater inflow conditions (Fig. 34) in San Antonio Bay primarily used measurements and field conditions observed during July 1987. This sampling period clearly had the lowest salinity conditions throughout the entire bay (Fig. 4). The biomasses are depicted within each box and have units of μg-at/liter. The external inputs sources (e.g. river concentrations) are also in units of μg-at/liter. The fluxes between biomasses designated by arrows represent the process rates within the ecosystem and have units of μg-at/liter/day. The only exception to the preceeding units occurs with macrophytes and seagrasses which have biomass units of mg-at/m^2 and likewise mg-at/m^2/day for production rates. A description of the biomass and flux calculations for Fig. 34 is presented in Table 13.

The ecosystem model for high freshwater inflow represents the simplistic results obtained during the spring 1987 sampling period (Fig. 34). The San Antonio Bay ecosystem is much more complicated than the simple diagram but some interesting bits of information can be observed. As the river inflow increases, the absolute concentrations of nutrients in the water decrease, i.e. the nutrients are diluted with huge quantities of water. The predominant form of nitrogen entering the bay is nitrate which along with ammonium provide nitrogen for phytoplankton uptake. A loss of nitrogen by denitrification amounts to about a 7% of the water column nitrate per day while nitrification may produce about 16% per day. The daily uptake of nitrate and ammonium by phytoplankton amounts to

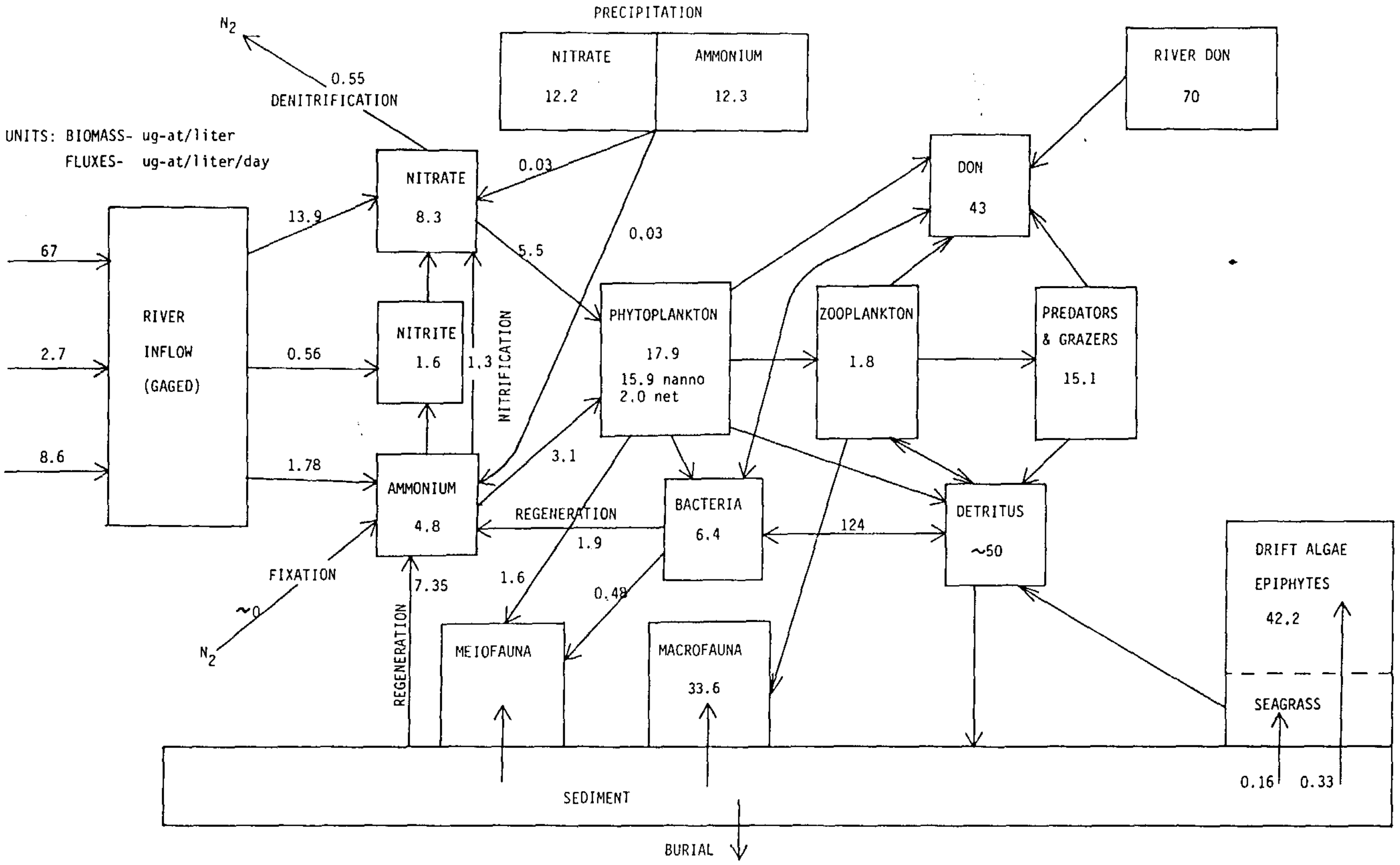


Figure 34. Ecosystem model of San Antonio bay for nitrogen during high freshwater inflow conditions.

Table 13. Ecosystem Model Data Calculations for High Freshwater Inflow Conditions in San Antonio Bay (Fig. 34).

Biomasses

River Nitrate	Table 3	(July 1987)	67μmole/liter
River Nitrite	July 1987	data table Station 2	2.7 μmole/liter
River Ammonium	July 1987	data table Station 2	8.6 μmole/liter
Atmospheric Nitrate	Table 5	mean of Victoria =	12.2 μmole/liter
Atmospheric Ammonium	Table 5	mean of Victoria =	12.3 μmole/liter
River DON	Table 2	June 1987	70 μmole/liter
Bay DON	Table 4	July 1987	42.9 μmole/liter
Bay Nitrate	Table 4	July 1987	8.3 μmole/liter
Bay Nitrite	Table 4	July 1987	1.6 μmole/liter
Bay Ammonium	Table 4	July 1987	4.8 μmole/liter
Phytoplankton	Table 9	mean PN for July 87	17.9 μmole/liter; 86% nannoplankton

Bacteria	Benner-Fig. 2 580 mg C/m^2 using C:N=5 then 6.37 mg-at N/liter
Macrophytes	Dunton-seagrass shoots = 15.2 and roots = 23.7 g dw/m^2; seagrass is 38% C and C:N = 25 (Wolff, 1980) then shoots = 16.5 and roots = 25.7 for a total of 42.2 mg-at/m^2
Zooplankton	Buskey Fig. 4.1a Total zooplankton biomass = 248 mg dw/m^3 using 10% N then 1.77 μg-at/liter
Predators	Calculated from S. Holt data for all fish species
Detritus	Assume 75% of all imports to detritus is standing stock
Macrofauna	Montagna p. 40 mean biomass = 4.68 g dw/m^2 = 470 mg N/m^2 = 33.6 ug-at/liter

Fluxes

Nitrate → Phytoplankton Table 12 X July 87 = 8.23 mg-at/m^2/day ÷ 1.5 m = 5.5 μg-at/liter/day

Ammonium → Phytoplankton Table 12 X July 87 = 4.58 mg-at/m^2/day ÷ 1.5 m = 3.1 μg-at/liter/day

Nitrogen Fixation - See Nixon and Pilson, 1983, pp. 596 = 0

Denitrification - Benner - Table 2 May 34.7 μmole/m^2/hr = 0.83 mg-at/m^2/day ÷ 0.55 μg-at/liter/day

Nitrification - Benner - Table 4 May 79.4 μmole/m^2/hr = 1.91 mg-at/m^2/day ÷ 1.5 m = 1.27 μg-at/liter/day

Actual Benthic Regeneration - Benner - Table 1 11.02 mg-at/m^2/day ÷ 1.5 m = 7.35 μg-at/liter/day

Bacterial Production - Benner - Table 8 310.8 MgC/liter/hr (C:N = 5) then 124.3 Mg-at/liter/day

Water Column Regeneration - Benner - Table 2 2.8 mg-at/m^2/day ÷ 1.5 m = 1.87 μg-at/liter/day

Bacteria → Meiofauna - Montagna p.33 .0202 x 24 = 0.48 μg-at/liter/day

Phytoplankton → Meiofauna - Montagna .0651 x 24 = 1.56 μg-at/liter/day

Table 13. Continued

Seagrass Production - Dunton - 0.8 g N/m^2/yr over 13,505 m^2; = 0.157 mg-at/m^2/day
Total Macrophyte Production - Dunton - 38 g C/m^2/yr and assume C:N = 26 = 0.334 mg-at/m^2/day
Nitrate in Rain 12 mg-at/m^3 x .976 = 11.7 mg-at/m^3/yr = 0.027 ug-at/liter/day
Ammonia in Rain 12.3 mg-at/m^3 x .976 = 12.0 mg-at/m^3/yr = 0.033 ug-at/liter/day
Nitrate Inflow (1.56 x 10^8 m^3/day) (67 mg-at/m^3)/7.54 x 10^8 m^3 = 13.86 ug-at/liter/day
Nitrite Inflow (1.56 x m^3/day) (2.7 mg-at/m^3)/7.54 x 10^8 m^3 = 0.56 ug-at/liter/day
Ammonium Inflow (1.56 x 10^8 m^3/day) 8.6 ug-at/m^3)/7.54 x 10^8 m^3 = 1.78 ug-at/liter/day

about 59% of the DIN pool and the daily ammonium regeneration contributes 193% of the ammonium pool. All of these data indicate that large quantities of ammonium are regenerated by both benthic and water column processes. The detrital decomposition processes of both water column and benthic processes cannot be separated with the data from this study but about two times as much nitrogen is consumed by bacteria per unit area as enters San Antonio Bay via gaged inflow during high water runoff.

During low freshwater inflow (Fig. 35) the daily nitrate flux into San Antonio Bay is reduced to less than 2% of high flow conditions. The actual nitrate concentration in the bay are higher because of nitrification (although the direct measurement doesn't show that) and ammonium utilization has increased almost five fold. The daily nitrogen regeneration measured accounted for only 49 percent of the daily calculated ammonium uptake by phytoplankton so the ecosystem must be depleting its nitrogen storage or additional sources are present that were not considered. The bacterial biomass and its consumption of detrital material and plankton are reduced to about 10 percent or less compared to the high inflow period.

During mean freshwater inflow conditions (Fig. 36) three times more DIN enters San Antonio Bay compared to low flow conditions but the water column nitrogen inventory doesn't change appreciably. The regeneration processes are producing ammonium twice as fast as phytoplankton uptake which reflects a doubling of bacterial biomass and a 5 fold increase in bacterial consumption of organic matter. Under the mean inflow conditions, nitrification appears to increase about 50% over low inflow conditions.

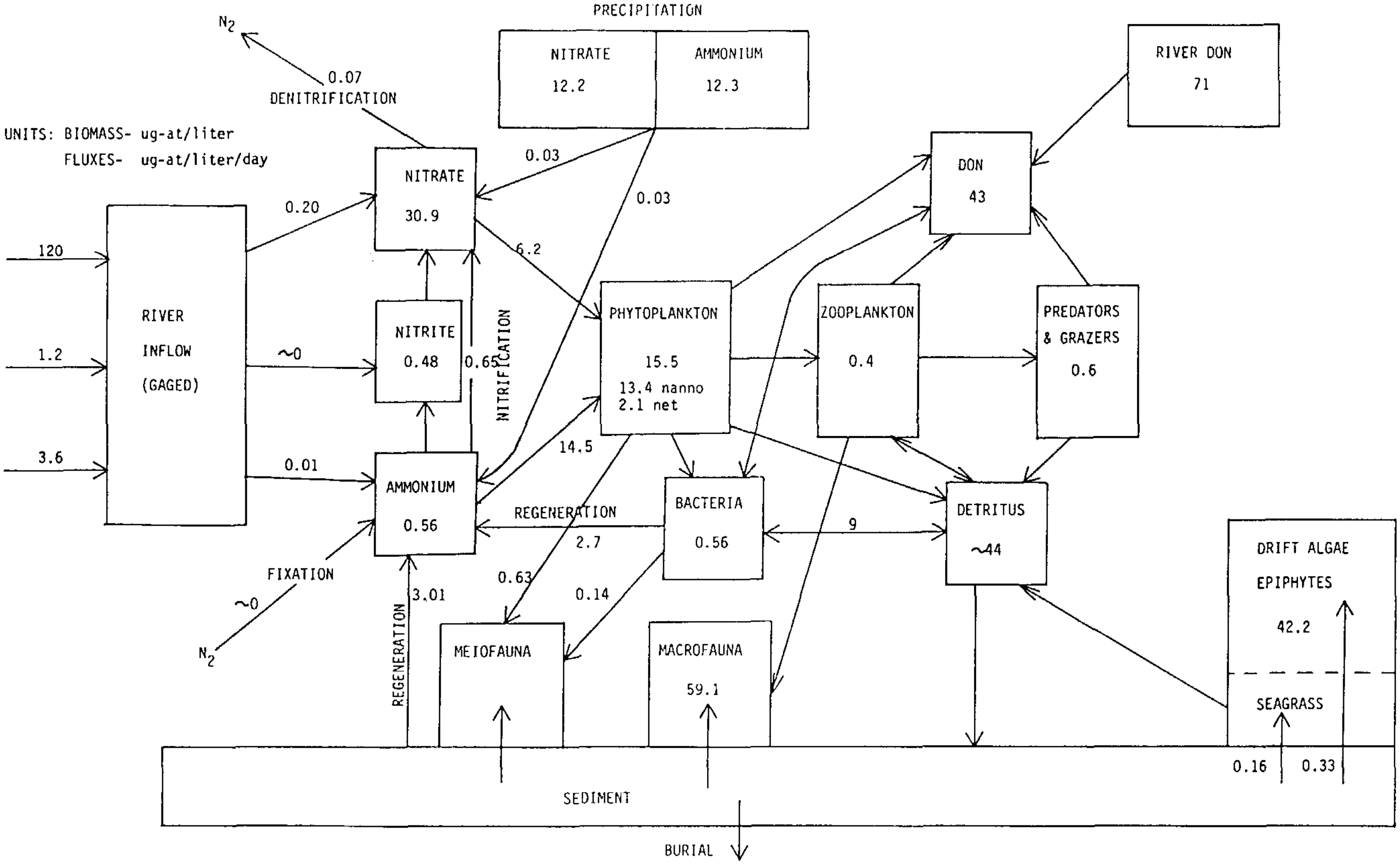


Figure 35. Ecosystem model of San Antonio bay for nitrogen during low freshwater inflow conditions.

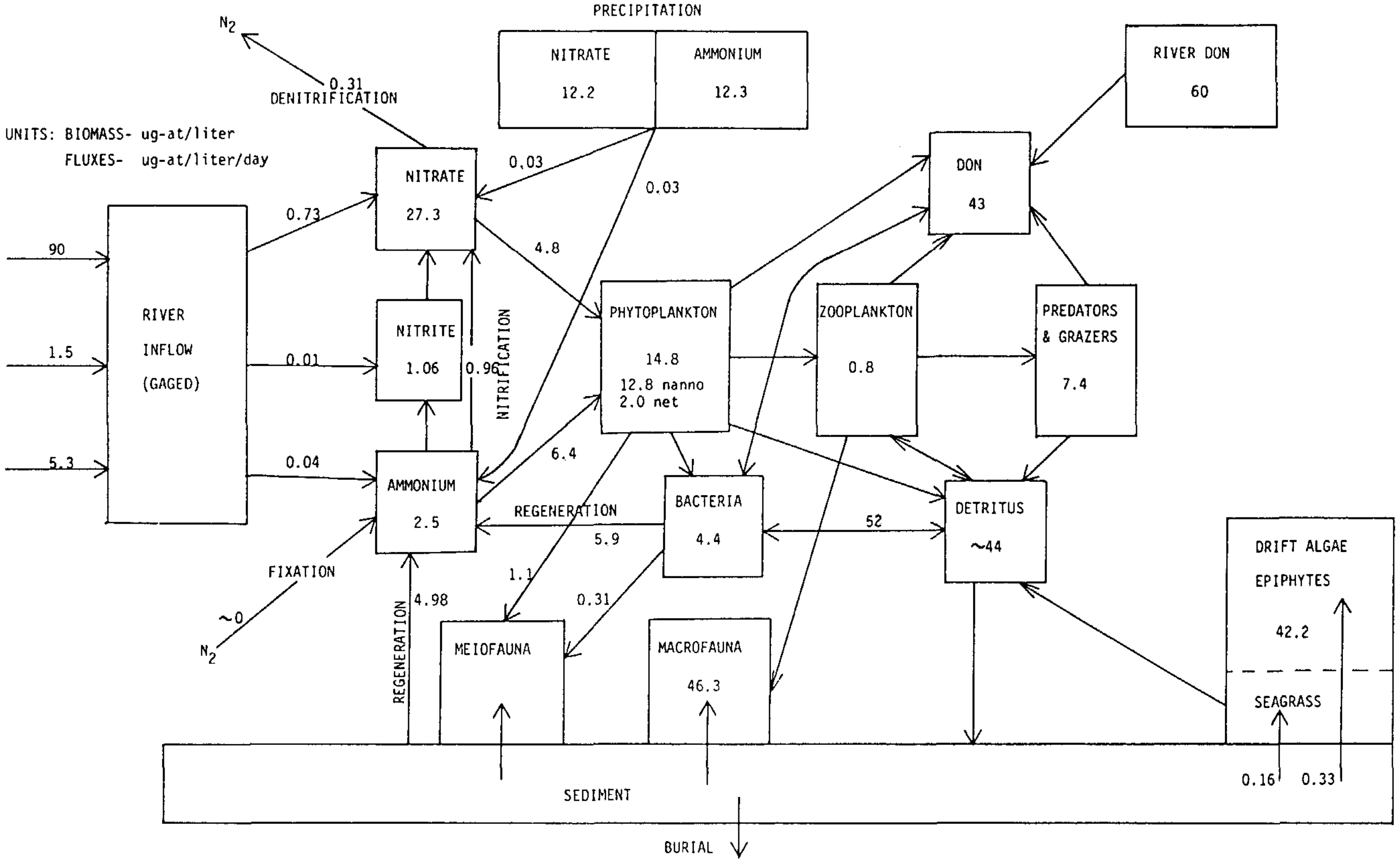


Figure 36. Ecosystem model of San Antonio bay for nitrogen during mean freshwater inflow conditions.

CONCLUSIONS

The inflow of the Guadalupe River into San Antonio Bay has a continuing influence by establishing a salinity gradient down the bay especially along the west side. In contrast the eastern side appears to contain higher salinity water which probably transited up the Victoria Barge Canal. The year 1987 was unusual in terms of freshwater inflow into San Antonio Bay compared to historical records which last documented such an influx in the mid-1970's. The quantities of nutrients (nigrogen, phosphorus and silicon) introduced into the estuary were quite large and the only regions of reduced water column concentrations were in the extreme lower portions of the bay, remote from the freshwater influx.

The most clearly defined gradient of nitrate occurred in the upper to middle regions of San Antonio Bay that coincided with a change in water clarity and an increase in chlorophyll *a* concentrations. The strongest gradient of nitrate was apparently responsive to a combination of freshwater inflow and prevailing winds since the orientation of the isopleths would align along the western shore especially during the most pronounced winds. The concentrations of orthophosphate never fell below 0.30 ug-at/liter while silicate was always above 27.9 ug-at/liter in comparison to a minimum of 0.03, 0.03 and 0.01 ug-at/liter for nitrate, nitrite and ammonium rspectively. Even though concentrations may not accurately reflect rates of turnover, the observed low concentrations would definitely affect phytoplankton uptake rates during daylight hours.

There are presently no direct data to show the preference for ammonium or nitrate by the phytoplankton populations in San Antonio Bay. The upper region of the bay most directly influenced by freshwater influx has an "apparent" nitrogen utilization balance that uses nitrate for about 90% of the total uptake. A short distance away, however, ammonium and nitrate uptake are about equal and in the lower bay, ammonium is greater than 75% of nitrogen uptake. Many studies of nitrogen uptake in the marine environment have shown nitrate to be more sensitive to the amount of ambient light than ammonium. The turbulance of wind mixing in a shallow estuary may be so large that all phytoplankton cells circulate through the lighted zone of murky water. There are no known studies of this microscale problem. The difference in turbidity from river sediments or resuspended sediments from wind mixing could be quite significant because the river water will contain large quantities of nitrate while resuspension would carry ammonium into the water colum. The phytoplankton species may be the best indicators of this difference. For instance, diatoms are more likely to respond to large nitrate concentrations while nannoplankton are normally more important where large ammonium levels are found.

The distribution of nitrate has been observed as an inverse function of salinity or distance down an estuary in several bay systems (e.g. Delaware Bay). Nitrate did display conservative behavior versus salinity for the November 1986 data but not in any of the other six samplings. The biological processes are so dynamic in San Antonio Bay that only winter low temperatures and light reduce them enough for conservative behavior. Other tracers are not helpful because nitrogen has no analogs. Phosphorus and dissolved silicon may be more conservative and hence better correlated with salinity but they are not so useful because of their weaker coupling to primary production processes.

The most direct evidence of the relationship of nutrient concentrations or fluxes from the sediment by resuspension comes from the stirred benthic chambers. There was a clear increase in the ammonium concentrations as the stirring and water flow increased (Montagna Report). The concentration of phaeopigments also increased in the bays during windy periods. The most difficult processes to document in the bay studies were often related to winds which were always changing. The diurnal sea breeze didn't maintain a schedule or a steady range of velocities. The almost continual change in the winds shouldn't be dismissed because the biological populations (especially plankton) hardly ever have enough time to stabilize between the daily and event frequency of winds.

The circulation processes in San Antonio Bay are dominated, in general, by vertical wind mixing. The freshwater inflow to San Antonio Bay did clearly show the primary circulation to be counterclockwise with the relatively fresh water on the west and the higher salinity on the east side of the bay which had been observed in the past. The scale of measurements did improve our knowledge about salinity fronts during the large freshwater inflow. The overlap of the surface freshwater and near bottom higher salinity did produce some reduced nearbottom oxygen concentrations in midbay. The lower regions of San Antonio Bay appeared to accumulate chlorophyll compared to the upper reaches so the vertical mixing beneath the freshwater lense must be reduced. If further deductions are made about water movement from the chlorophyll, then the net flow must be southward towards Aransas and/or Mesquite Bays.

The large influx of freshwater into San Antonio Bay during 1987 brought about 25 times as much nitrogen into the estuarine ecosystem as the normal (mean) year. The perplexing finding that primary production rates didn't appear to increase emphasizes the fact that the bay was not nitrogen limited. That means nitrogen concentrations probably did not greatly affect the short term growth rate of the autotrophic organisms however nitrogen could still be closely coupled to the biomass over longer time scales. When chlorophyll alone is compared to the larger nitrogen inflow, there is not a strong relationship but if all biomass elements of the ecosystem are added together, the budget may balance much better. Other biological processes like denitrification and nitrification are almost certainly enhanced at low salinities (see Benner and Yoon) so the transformations and losses may be the balancing processes that normalize nutrient conditions in San Antonio Bay.

The long term effects of increased freshwater inflow into San Antonio Bay must either be located in the sediments or the biomass of organisms. Actually both of those categories are the only memory devices in an open system. The nutrient properties associated with a larger biomass of organisms or enhanced sediment organic matter would be larger regeneration fluxes and microbiological rates of decomposition. The study was terminated before any such long term effects could be observed. The position and timing of sample collections were designed to maximize the observed effects of freshwater inflow. Several of the station locations in the central portion of San Antonio Bay produced observations that considerable "steering" of water movement was produced by the numerous oyster reefs, especially when located near relatively deep water. The Victoria Barge Channel and the Gulf Intracoastal Waterway, on occasion, appear to convey materials up and across the bay. Several small scale and relative short term studies are needed to further define the significance of these physical features on the circulation processes.

Significant Findings

1. A significant increase of nitrogen nutrients in the form of nitrate are introduced into San Antonio Bay during high runoff events.

2. As much as 23% of nitrogen enters San Antonio Bay as direct precipittion with equal nitrate and ammonium concentrations.
3. Increased concentration of nitrate, nitrite and ammonium were progressively observed during the period of high freshwater inflow.
4. Substantially more nutrients were present in San Antonio Bay during the high flow period compared to the same time and location a year later.
5. Phytoplankton production rates did not significantly increase during the period of high freshwater inflow.
6. Phytoplankton biomass was significantly larger during the period of high freshwater inflow in the lower portion of San Antonio Bay.
7. The benthic production of ammonium decreases with distance from the river mouth.
8. The water column production of ammonium increases with deep water depth and distance away from river mouth.
9. Significant amounts of denitrification is occurring especially in the upper region of the bay with reduced salinities.
10. Nitrification was occurring in the sediments with perhaps a tendency to be higher at the upper regions of the bay.

FUTURE WORK NEEDED

At the conclusion of a study is a good time to assess the results and cite the critical areas of research that still remain unknown. Often these areas were outside the previous study or a lower priority originally. The following general research questions were highlighted during the analysis phase of the present study and are not listed in any order of priority.

1. General Circulation - Very little is known (i.e. few direct measurements) about water circulation throughout San Antonio Bay for the various seasons. Small scale circulation patterns appear to be important especially in areas of Victoria Barge Canal and oyster dredge channels and the oyster reefs in midbay.
2. Dissolved Organic Nitrogen - Appreciable quantities of DON enter San Antonio Bay from the Guadalupe River but little else is known about production, uptake, utilization, absorption or other losses.
3. Complete Nitrogen Budget - A systematic and complete study of all nitrogen species for a small region of the upper bay where the largest salinity gradient exists. It would be necessary to include all dissolved, particulate, sediment and atmospheric components.
4. Phytoplankton Nitrogent Uptake Studies - A concerted effort should be made to study the relative rates of utilization of nitrate, ammonium, urea and DON using ^{15}N-labeled substrate and the dominant class of organisms (e.g. net plankton or nannoplankton).

5. The extent and dynamics of the hypoxic bottom water and its relationship to freshwater inflow, benthic respiratin and physical circulation is poorly known. This could be combined with the complete nitrogen budget tasks.

CHAPTER II

NUECES/CORPUS CHRISTI BAY (NIPS-II)

Study Area

The NIPS-II program was carried out in Nueces/Corpus Christi Bay from September 1987 through August 1988. Thirty-five hydrographic sampling sites were occupied for distribution of properties (Fig. 37). Process rates measurements were collected four of the stations (A,B,C and D) that were along a salinity gradient. Twelve sampling trips were undertaken during the regular study and rate measurements were collected on six trips.

METHODS

Sample Collection

The areal distribution of temperature, salinity, nutrients (nitrate, nitrite, ammonium, o-phosphate and dissolved silicon), chlorophyll a, water transparency (Secchi disk and profiling quantum meter), and dissolved oxygen were determined throughout Nueces/Corpus Christi Bay estuary at 35 sampling sites (Fig. 37) on twelve occasions from late summer 1987 through summer 1988. The surveys were conducted in Nueces Bay during one day starting at the headwaters and Corpus Christi Bay was sampled the following day. Station locations were all located near structures in the water. Water samples were collected from the surface by hand immediately below the surface film. In shallow water (< 6 ft) near bottom water samples were collected with a horizontal water 2 liter sampling bottle (Kahl model CEPWASO 2). All water samples were collected from the same

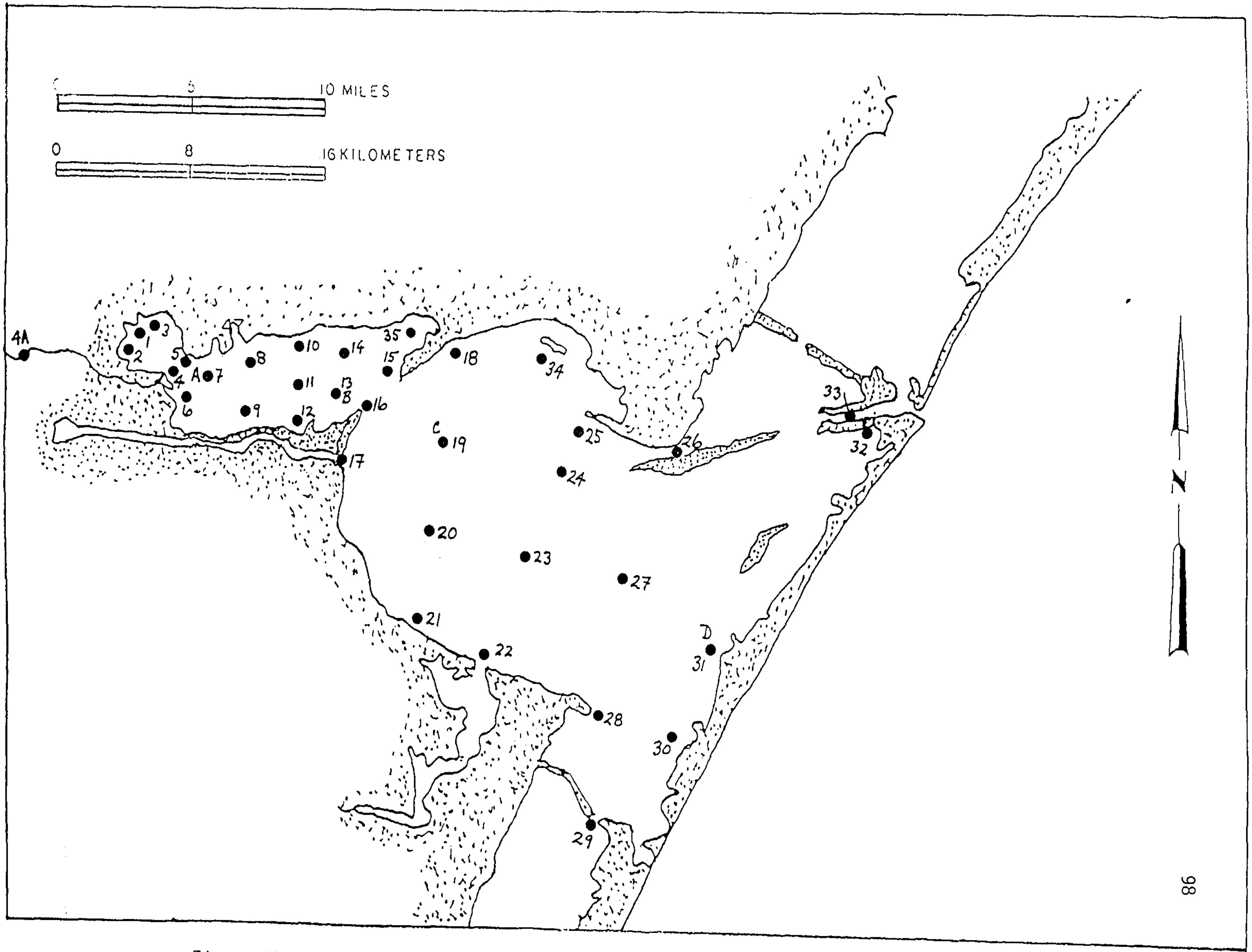


Figure 37. Station locations in Nueces/Corpus Christi bay.

sampling bottle. In deeper water, a 5 liter Niskin bottle was adapted to automatically trip 10-15 cm above the bottom. If bottom disturbance was apparent, the samples were retaken.

Nutrients

The 60 ml subsamples were drawn within 10 min following the cast and analyzed within 6 hours for phosphate, silicate, nitrate plus nitrite, nitrite and ammonium using automated, continuous-flow colorimeters. The samples were held on ice in the dark and transported to the LONGHORN or laboratory. Data acquisition and control were managed by a Hewlett-Packard 9845A computer. The procedures of Whitledge *et al.* (1981) were utilized as they apply to a Technicon AutoAnalyzer II which had been modified with small-volume glassware to optimize stability and sensitivity. The analytical methods of Murphy and Riley (1962) were followed for reactive phosphorous, and Armstrong *et al.* (1967) for silicate and nitrate. Ammonium was measured by the phenolhypochlorite method of Koroleff (1970) as adapted to the AutoAnalyzer by Slawyk and MacIsaac (1972) and modified by Patton and Crouch (1977).

The analytical accuracy was determined by measuring the absorbances of known concentrations of each analyte (standards) at least once every 12 hrs. These were regressed upon concentrations using a least squares method, from which updated chemical factors were derived. The standards of highest concentration were also included among each set of station samples to monitor analytical stability (Whitledge *et al.* 1981).

Time

Time was recorded as local to the nearest minute using a digital watch that was recently checked and set.

Temperature

Temperature was profiled at each station at about 3-5 cm increments to the nearest hundredth of a degree (0.01°C) Celcius using a Sea Bird model Sea Cat CTD.

Salinity (Conductivity; Refractivity)

Salinity was profiled at each station at about 3-5 cm increments using conductance measurements from the Sea Bird model Sea Cat CTD. In addition, a direct estimation of salinity was determined by a hand refractometer for comparison purposes. The refractometer has been shown to be ± 1‰ when calibrated (Behrens, 1965). The CTD has a nominal resolution of 0.01 ‰. Conductance measurements were converted to salinity units using a modified UNESCO relationship (Lewis and Perkin, 1981) that accounts for temperature and pressure factors.

Water Transparency

Water transparency was determined with a standard size Secchi disk to the nearest 5 cm. Only one individual collected the measurements on each field trip. An integrating quantum sensor (Licor model LI-1905A) was used to calculate extinction of coefficients during the sampling trips. In addition, a SEATEC transmissometer was attached to the CTD to produce profiles of light transmission.

Bottom Depth

Bottom depth of less than 3m was determined to the nearest 5 cm with the Secchi disk which was lowered until the line went slack. In deeper water, the depth sounder was read in feet and converted to meters.

Chlorophyll a and Phaeopigments

Samples for chlorophyll a and phaeopigments were collected from the surface and bottom sampling bottle in calibrated syringes. The 10 ml samples were filtered in the field, placed in scintillation vials containing 90% acetone and placed on ice in the dark. The samples were transferred to a shipboard freezer as soon as possible for transportation to the laboratory. The method of Holm-Hansen *et al.* (1965) was used to analyze the samples fluorometrically.

Latitude and Longitude

Latitude and longitude of the sampling locations was determined with a Furuno loran model LC-90. The position readings for several sampling trips were compared and averaged for each sampling site. Sampling sites near accurately known land marks were checked to assure accuracy.

FRESHWATER INFLOW

The inflow of the Nueces River into Nueces Bay is normally small and very uniform except during episodes of large amounts of precipitation. The gaged inflow for the years

1984-1987 can be used as a reference of the relative input into the Nueces/Corpus Christi ecosystem although the absolute values are not correct. Two of the four years had low flow while the other two years had increased flows of 20 to 50 times as much water during runoff events (Fig. 38). The year 1987 in particular had large inflows in the Nueces River for the entire month of June with a maximum daily inflow value of $2.89x10^7$ m3 and a daily mean for the entire year of $2.64x10^6$ m3. In comparison the years of 1985 and 1986 had a mean total inflow value of $9.4x10^5$. Not all of the data is available for 1988 at the present time but the first five months had declining amounts (Fig. 38) which permitted Nueces Bay to increase its salinity to as high as 40 ‰ in August.

DISTRIBUTIONS

In the following descriptions, only surface distributions are depicted in figures however near bottom data were collected. In most cases the Nueces/Corpus Christi Bay system was vertically well mixed but if this is not the case, then it will be noted in the following discussion.

Salinity

The distribution of salinity in Nueces/Corpus Christi Bays revealed the small amount of freshwater that enters into the bays over the 12 month study from September 1987 through August 1988. The lowest salinity was measured in the mouth of the Nueces River at 4 ‰, in Nueces Bay at 17.8 ‰ and Corpus Christi Bay at 29.5 ‰. In contrast, the highest salinity was 38.1 ‰ at the mouth of the Nueces River, 41.4 ‰ in Nueces Bay and 39.0 ‰ in Corpus Christi Bay. A station approximately 4 miles up the Nueces River was

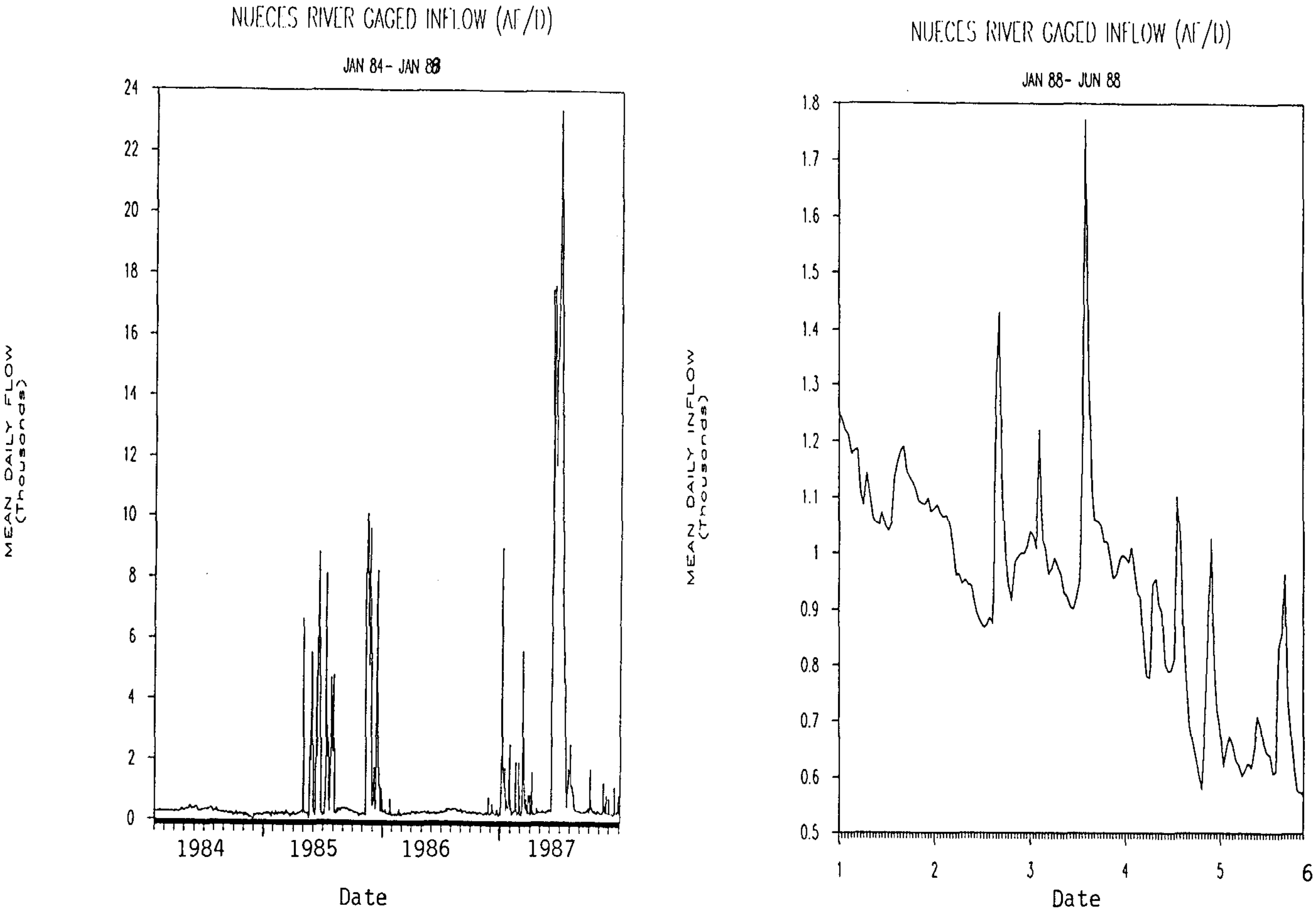


Figure 38. Mean daily gaged Nueces River flow for 1984-1987 and January 1988-June 1988.

sampled on 8 occasions where salinities of 0 to 34.4 ‰ were observed. When all of the monthly distributions of surface salinity are compared (Fig. 39) the general pattern of low salinity (< 30-32 ‰) in Nueces Bay is evident except for July and August when large evaporation losses were occurring. As the sampling started in September, the salinity in the Nueces Bay was increasing from the summer low of 0 ‰ in July 1987 which resulted from heavy precipitation. A variable pattern of higher and lower salinities occurred during the winter and spring until the lack of summer rainfall and high evaporation started. The strongest salinity gradients were always observed in Nueces Bay while Corpus Christi Bay had a change of 2 ‰ or less. No strong evidence of Gulf of Mexico water appeared in any of the 12 sample periods, not even the deeper parts of the ship channel. The salinity gradient in Nueces Bay frequently extended so that the southwest side of Corpus Christi Bay had slightly smaller salinity values.

Nitrate

The distribution of surface nitrate showed no strong gradient from Nueces Bay into Corpus Christi Bay in the autumn and early winter months, however in February through April a considerable gradient (> 20 ug-at/liter) was observed (Fig. 40). During the May through August period Nueces Bay ceased to be a source of nitrate but large concentrations were observed in Corpus Christi Bay. Preliminary findings suggest that nitrification processes ($NH_4 \rightarrow NO_3$) may be oxidizing recycled nitrogen during the summer season. The south and east sides of Corpus Christi Bay is much more conservative in its behavior (few large changes) which is probably an influence of Laguna Madre and due to its remoteness to freshwater inflow. Only a few samplings indicate that Oso Bay exerts any influence in

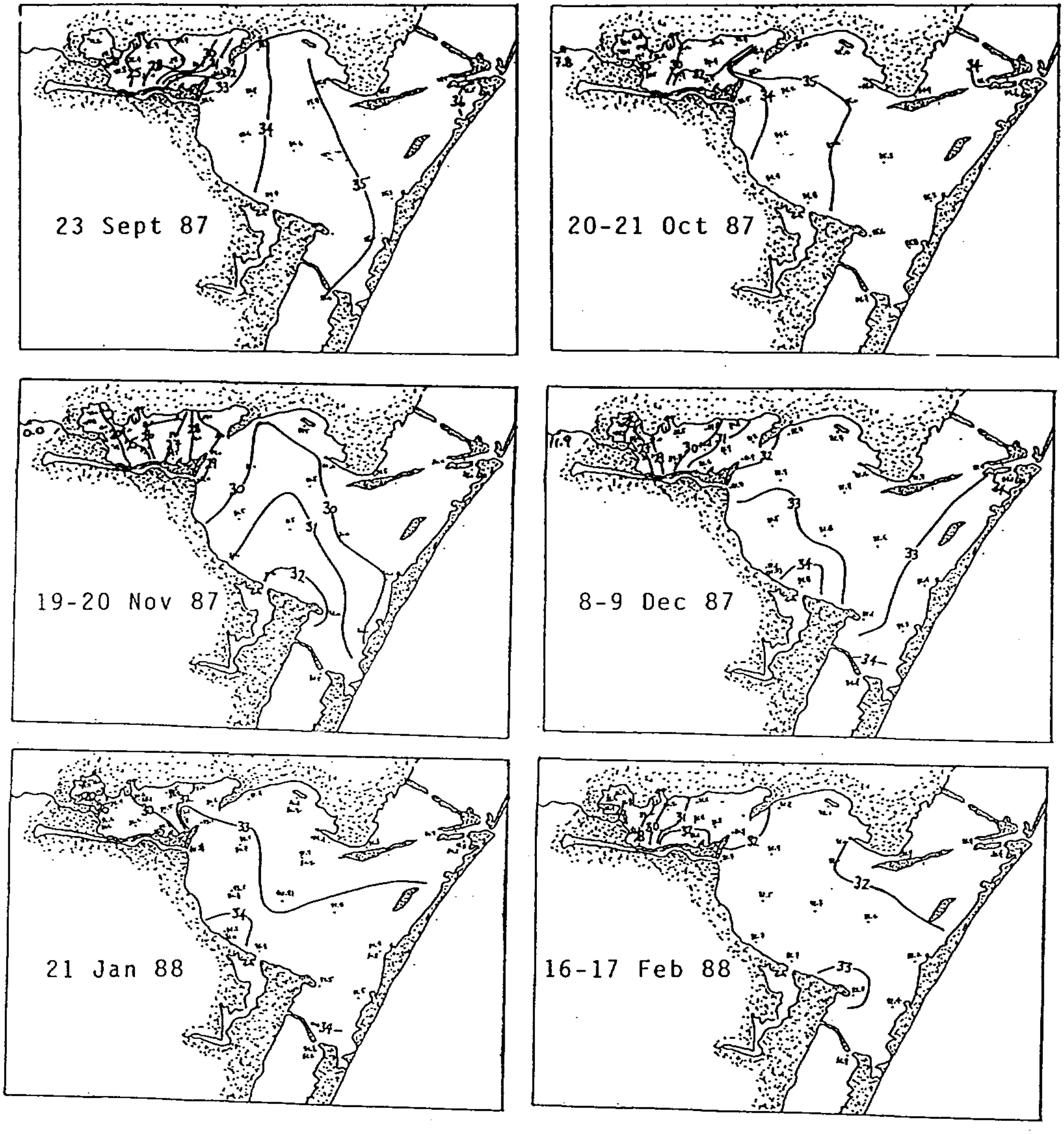


Figure 39. Surface salinity (o/oo) in Nueces/Corpus Christi bay.

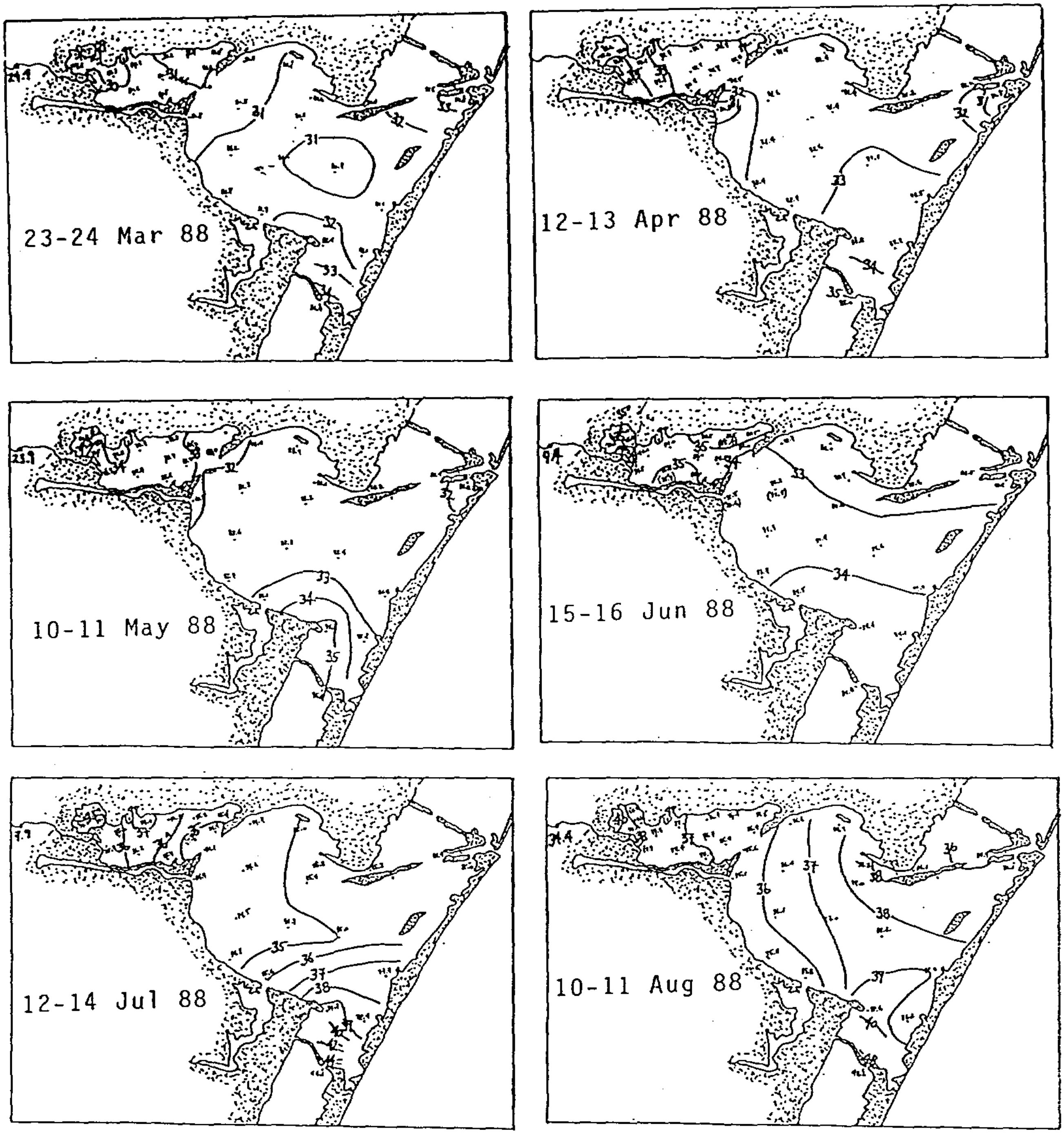


Figure 39 continued. Surface salinity (o/oo) in Nueces/Corpus Christi bay.

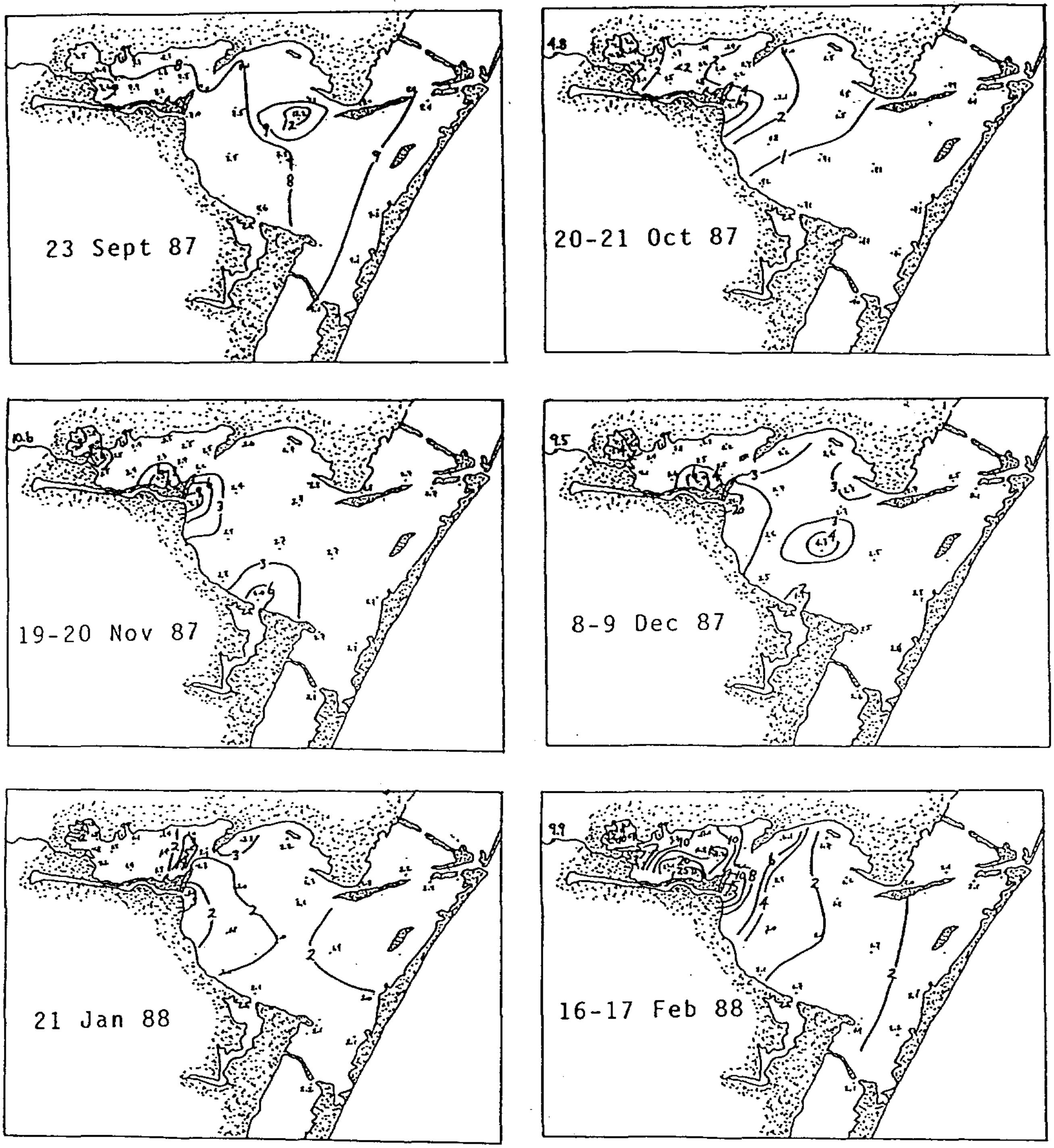


Figure 40. Surface nitrate (umole/l) in Nueces/Corpus Christi bay.

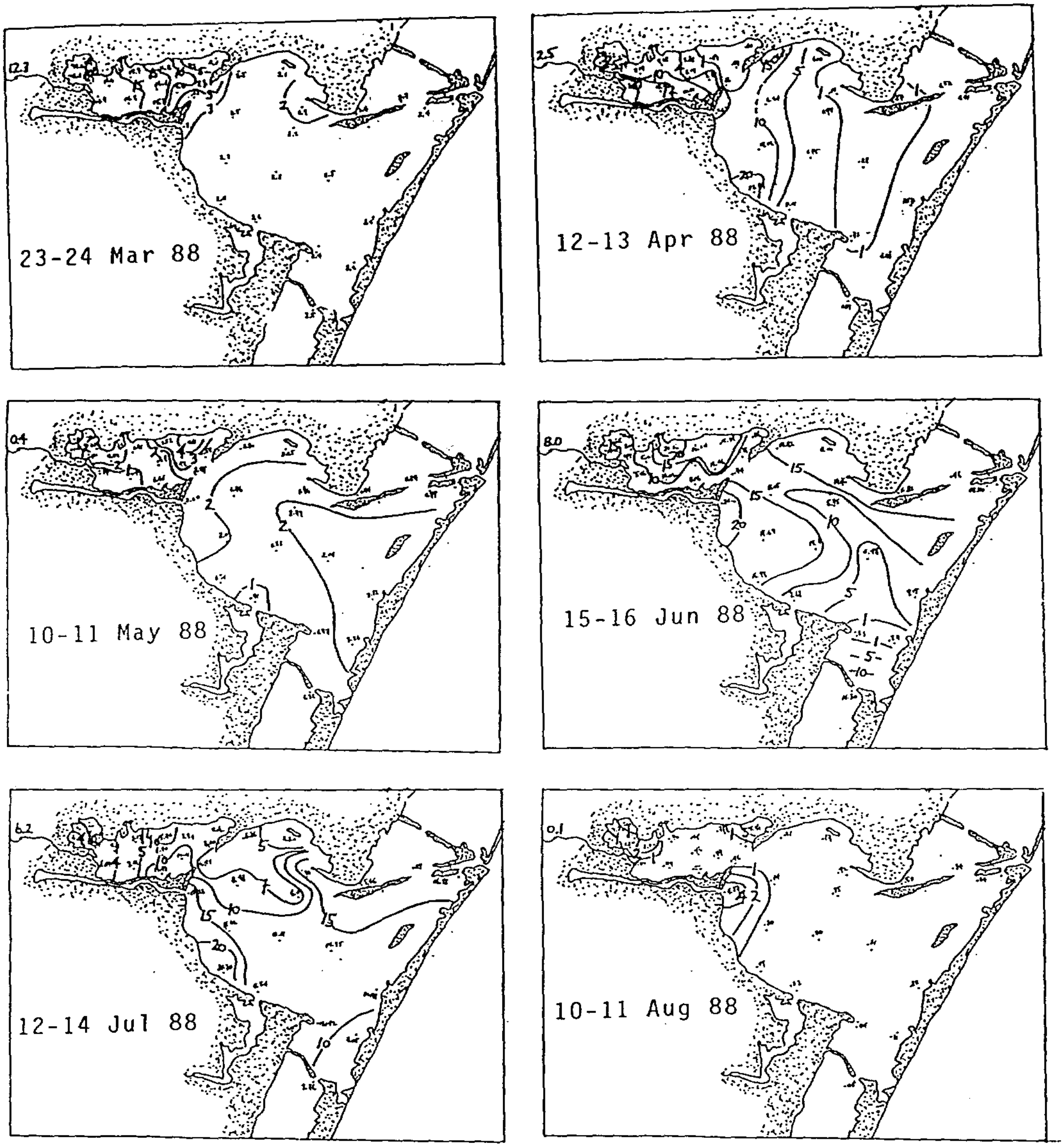


Figure 40 Surface nitrate (umole/l) in Nueces/Corpus Christi bay. continued.

even a small region of Corpus Christi Bay. Likewise no important influence on Gulf of Mexico water was observed in the data sets. Nitrate concentrations in the Nueces River ranged from 0.1 to 12.3 ug-at/liter.

Secchi Depth

Secchi depth was determined to quantify the water clarity for the possible light effects on chlorophyll distributions and primary productivity. The most obvious conclusion was that Nueces Bay with a mean depth of about 0.5 m was always more turbid than Corpus Christi Bay which usually had Secchi depths of 1-1.5m (Fig. 41). Smaller Secchi depths tended to be observed along the south side of Nueces Bay where Nueces River inflow should appear but water clarity in the river was occasionally higher so this is probably very weather dependent. Water in upper Laguna Madre always had a relatively high clarity even under varying weather conditions.

Chlorophyll a

The surface distribution of chlorophyll a ranged quite widely in the Nueces/Corpus Christi Bay system during all months of the year. Large chlorophyll a concentrations (> 10 μg/liter) were observed in Nueces Bay or in the nearby region of Corpus Christi Bay (Fig. 42). The concentrations of chlorophyll a in the Nueces River ranged from 15.5 to 174 μg/liter so the river was the site of intense primary production before entering Nueces Bay. The relatively small continuous flow of the Nueces River is much like the outflow of a chemostat which produces particulate matter (phytoplankton) for the populations in Nueces Bay to consume. The greater part of Corpus Christi Bay had lower and more uniform

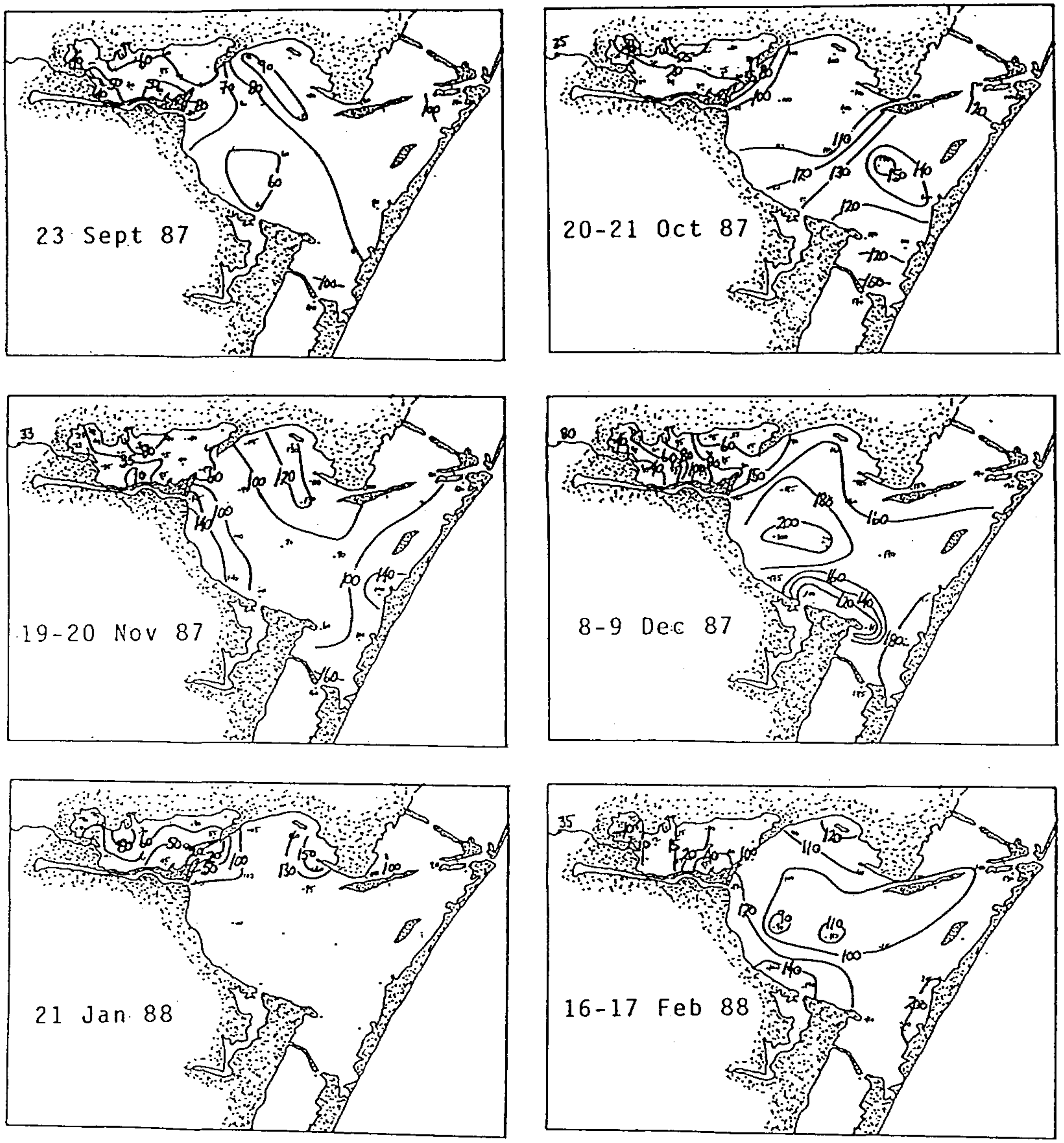


Figure 41. Secchi depth (cm) in Nueces/Corpus Christi bay.

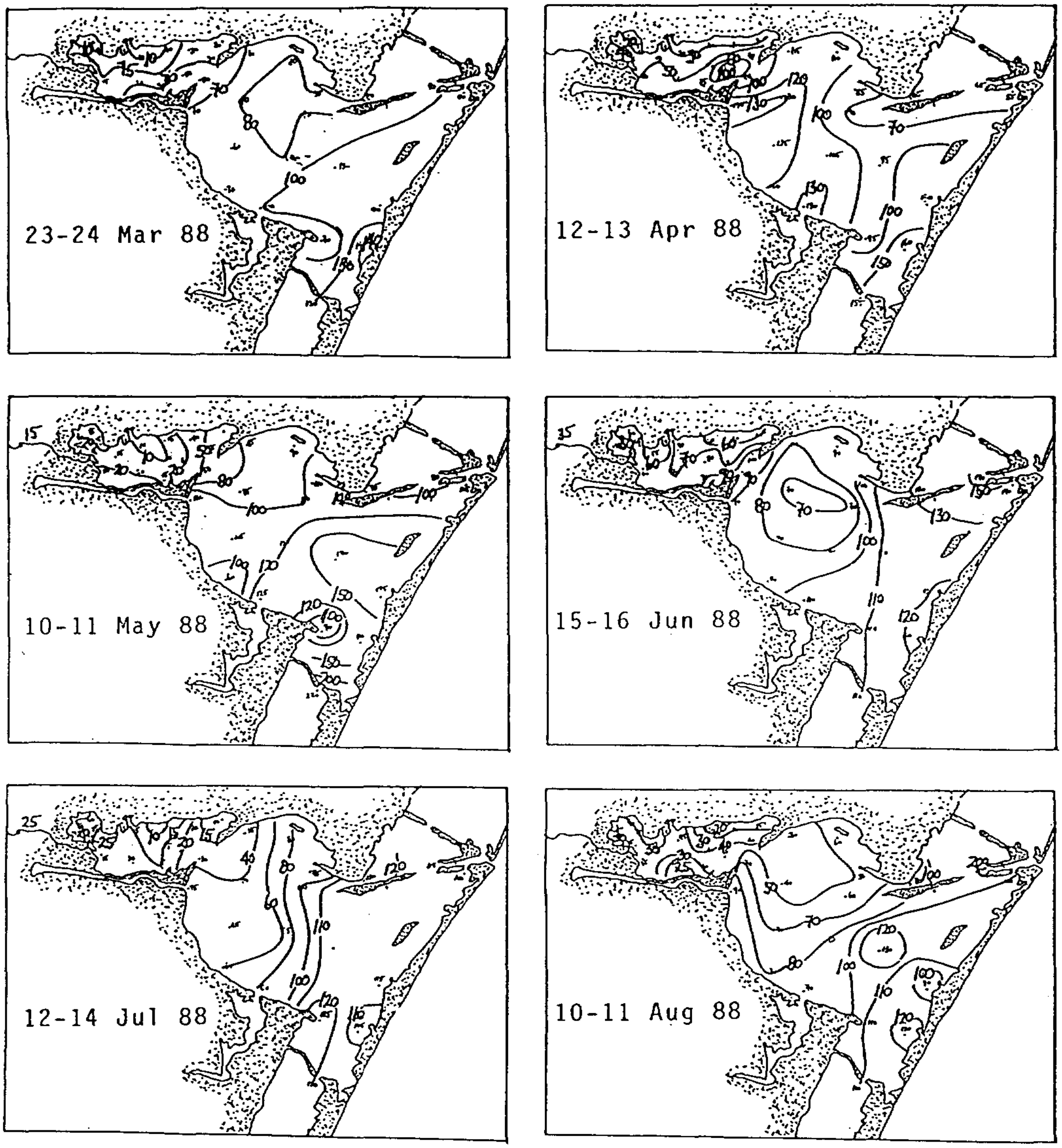


Figure 41 Secchi depth (cm) in Nueces/Corpus Christi bay. continued.

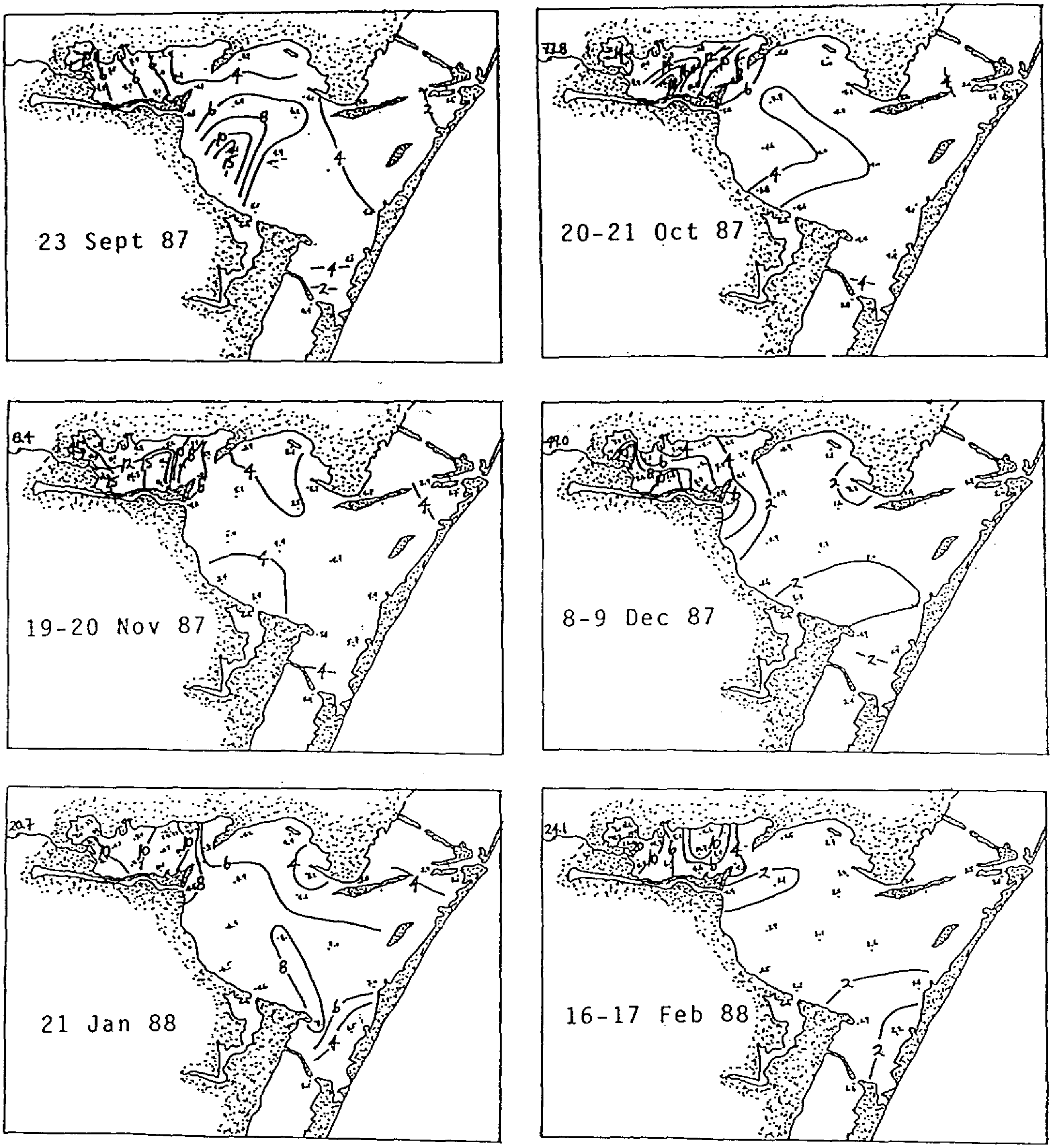


Figure 42. Surface chlorophyll a (ug/l) in Nueces/Corpus Christi bay.

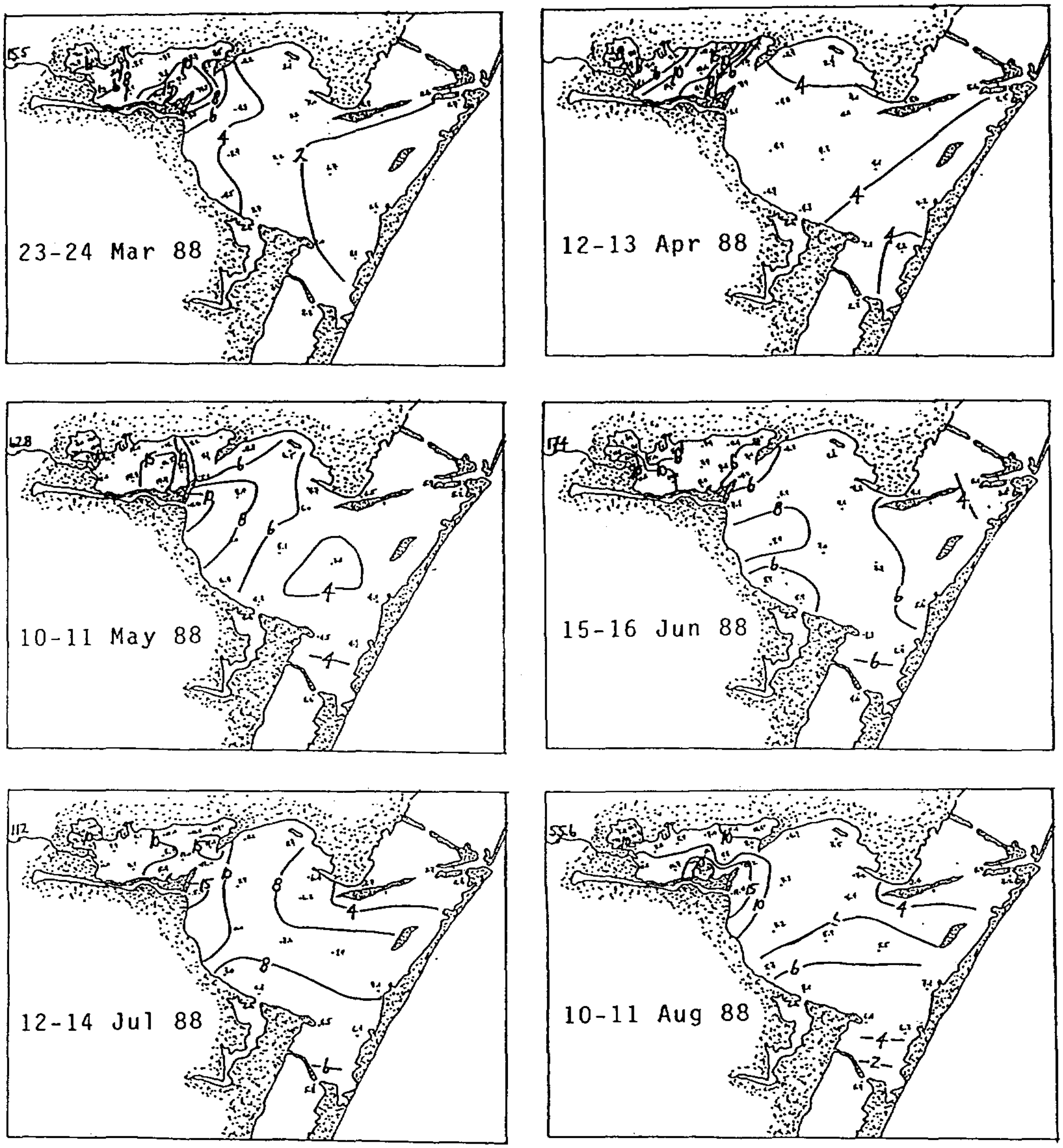


Figure 42 Surface chlorophyll a (ug/l) in Nueces/Corpus Christi bay. continued.

chlorophyll concentrations than Nueces Bay and there was no noticeable effect from the Gulf of Mexico. The Laguna Madre stations nearly always contained the smallest concentrations of chlorophyll a in the bay system.

Ammonium

The concentration of ammonium in the surface waters of Nueces/Corpus Christi Bays was very significant in relation to possible utilization by phytoplankton. Both Nueces and Corpus Christi Bay contained large concentrations (> 25 ug-at/liter) occasionally at different times (Fig. 43). The range of ammonium in the Nueces River was 1.5 to 44.2 ug-at/liter but the mean was 5.4 ug-at/liter when a single high value was omitted. The region of largest concentrations was often on the southwest side of Corpus Christi Bay which may be partially derived from municipal and industrial discharges. A more thorough discussion of this possibility will be undertaken in another section. The large concentrations of ammonium observed are highly significant to the phytoplankton ecology of the bay system.

TEMPORAL TRENDS

The repeated sampling of a set of fixed stations allows for an analysis of local changes that occur over the time period sampled. This analysis is possible for all the survey stations but it is most useful at the experimental sites A, B, C and D (Fig. 37) where the rate processes were determined by all the components of the study. In essence, this shows some of the behavior of the ecosystem during the study time and gives the background conditions for the experimental sites throughout the sampling period. Local changes that

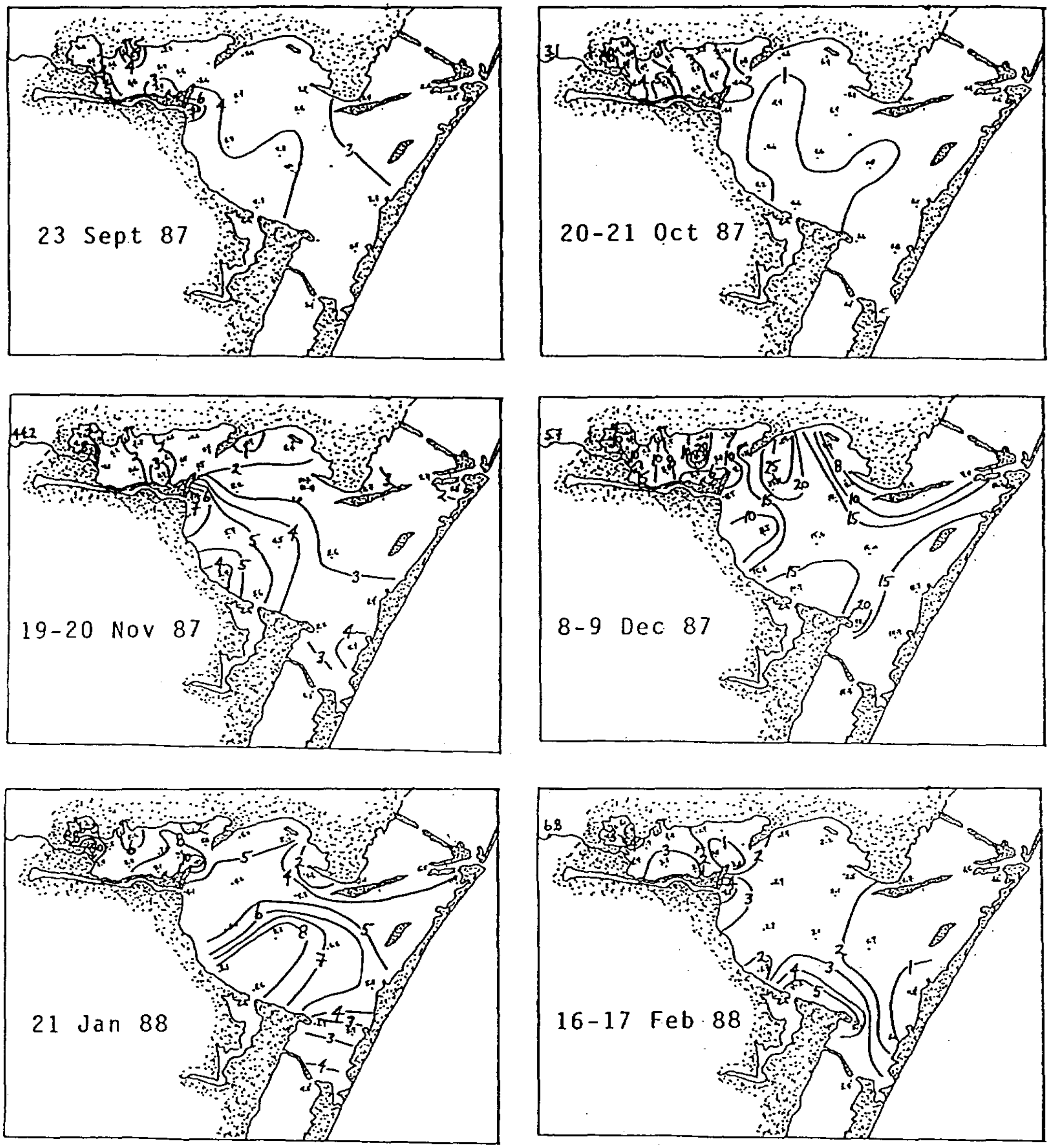


Figure 43. Surface ammonium (umole/l) in Nueces/Corpus Christi bay.

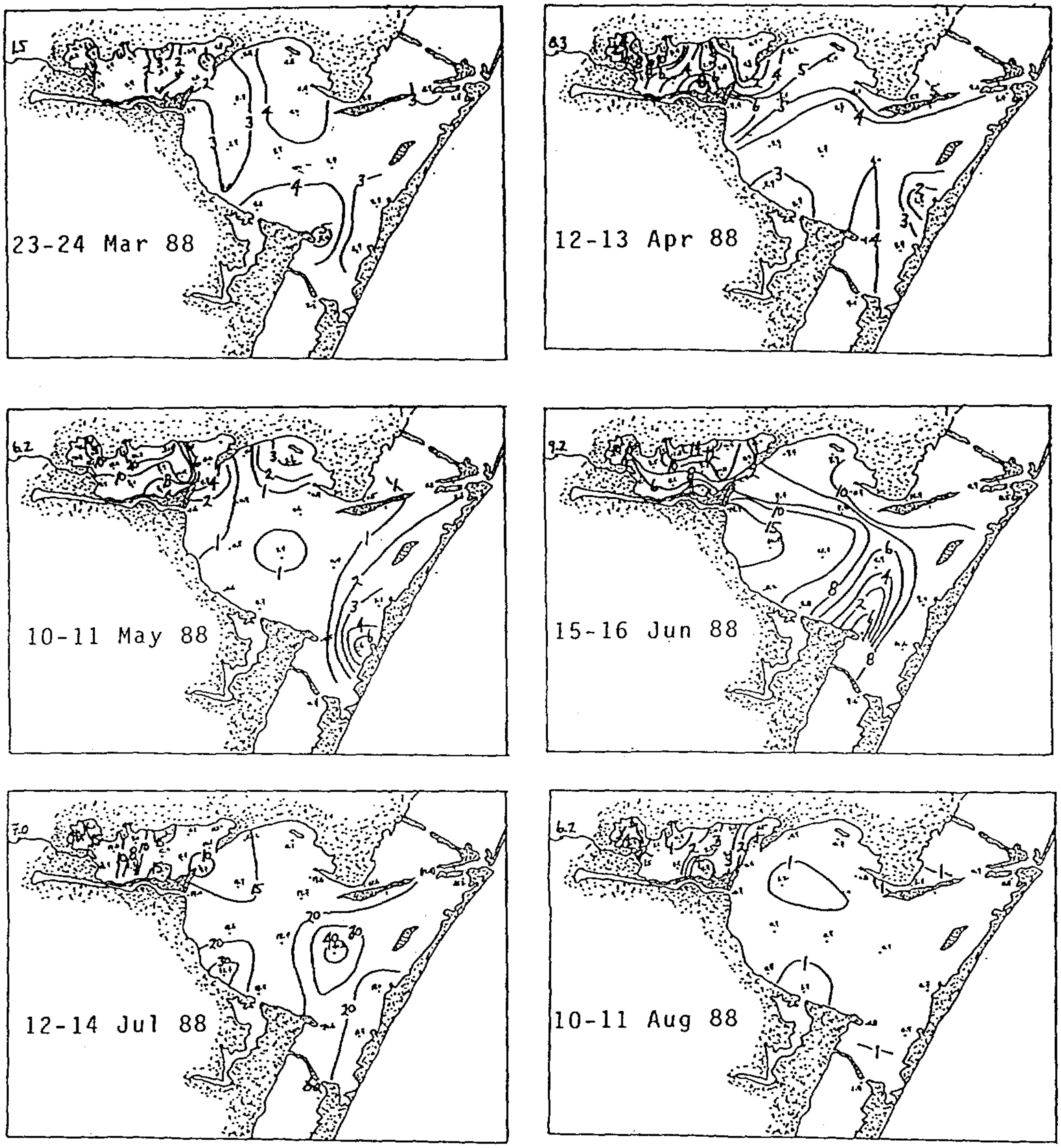


Figure 43 Surface ammonium (umole/l) in Nueces/Corpus Christi bay. continued.

occur during a single sampling period are also interesting and are important in defining the small scale variability in the bay ecosystem. These diurnal time series measurements include both the variability of physical forcing such as winds and tides but also biological variability such as light dependent nutrient uptake or vertical migrations of zooplankton.

Long Term Trends - Stations A and B

The long term trends in Nueces Bay (Fig. 37), the site of the principal freshwater inflow into the Corpus Christi ecosystem, are available from both hydrosonde data (temperature, salinity, pH and dissolved oxygen) and regular hydrographic sampling (salinity, temperature, nutrients and chlorophyll) from experimental sites A and B which were located about 8 km apart.

Nueces River Inflow

The temperature record from the hydrosonde in Nueces Bay covers a continuous period of 20 months with nearly continuous records every 1 - 1-1/2 hours. The location of the hydrosonde corresponds to station 11 (Fig. 37) along the power lines in the center of the bay and the experimental sample sites A and B lie on either side of its implacement. The period of record starts in December 1986, 9 months before the first hydrographic or experimental sample was collected but this allows some prior knowledge of freshwater inflow and weather patterns in the bays. In general the temperature record of the hydrosonde shows several "northers" in both winters which rapidly cooled the bay waters to almost 7°C on occasions (Fig. 44). The number of winter storms was more frequent but a

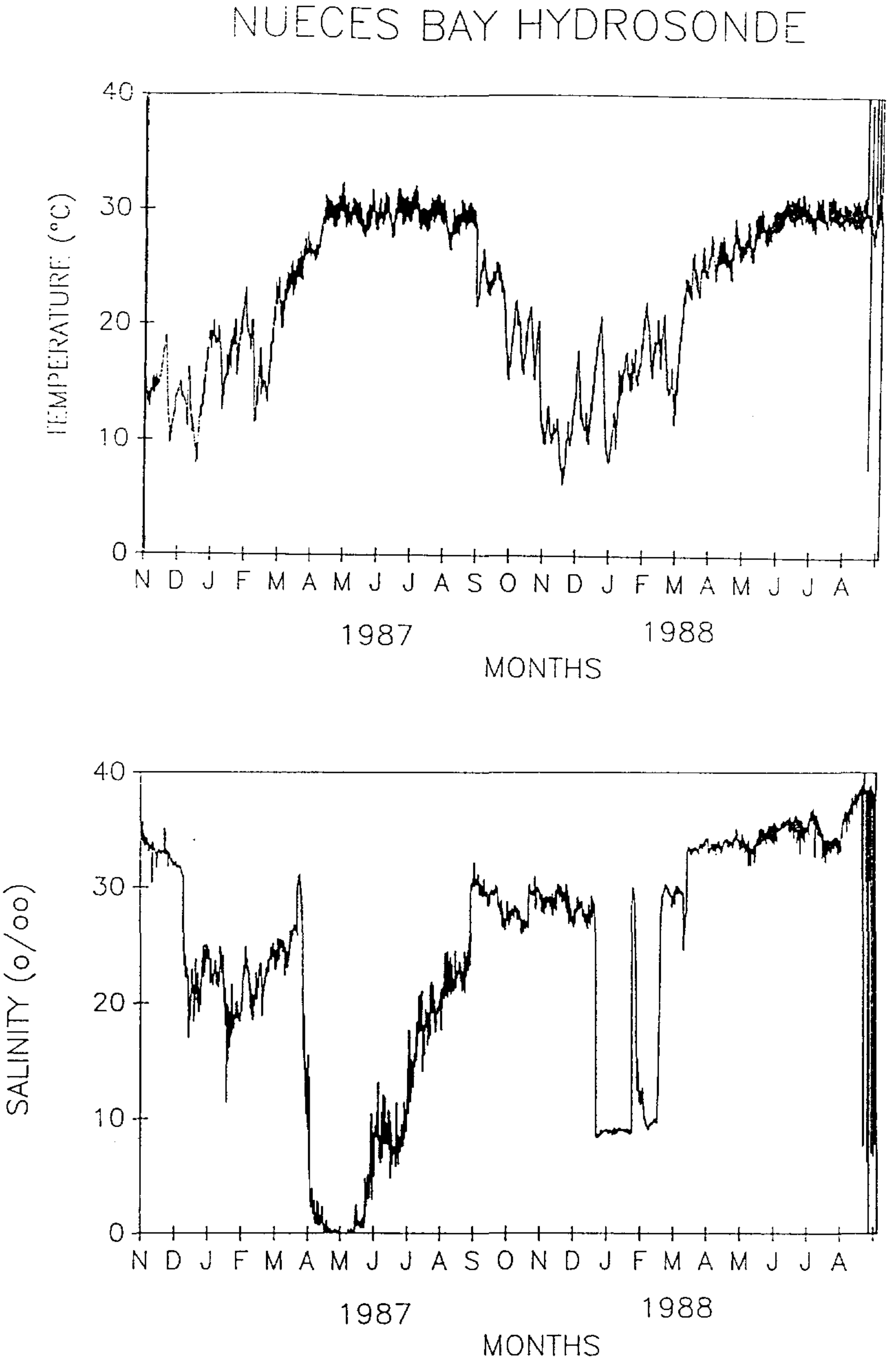
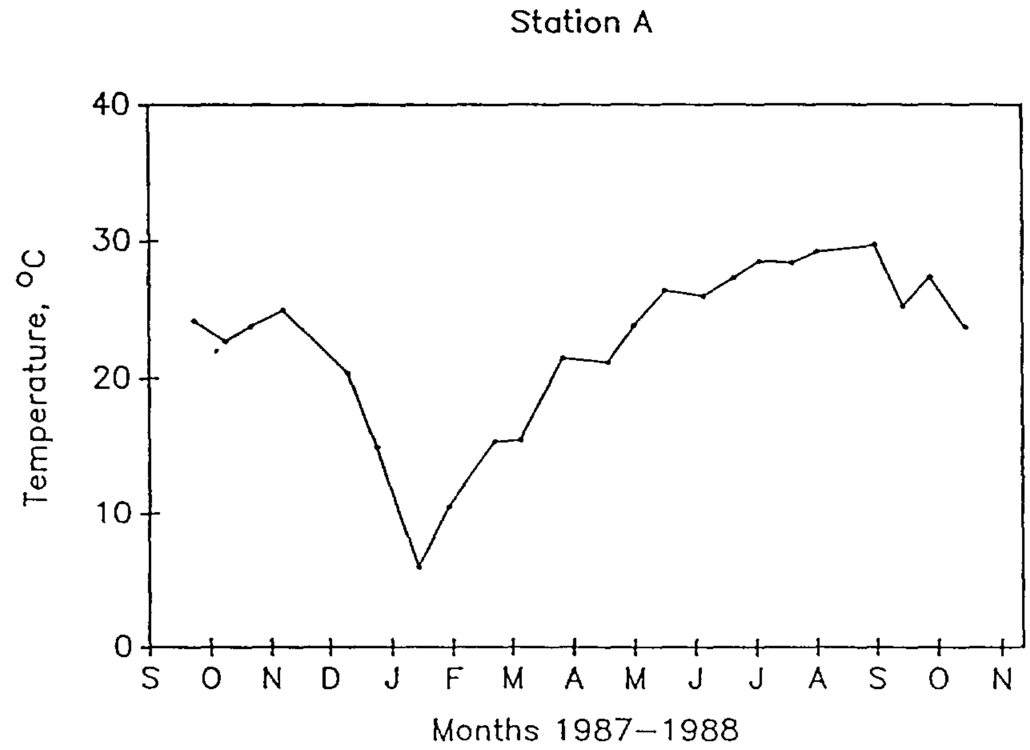


Figure 44. Temperature (upper) and salinity (lower) measured by an in situ recorder in mid Nueces Bay every three hours from November 1986-August 1988.

shorter duration in 1988 compared to 1987. As spring and summer approached the storm events decreased but diurnal heating and cooling increased with summer maximum water temperatures of greater than 30°C. Biweekly temperature readings from hydrographic sampling accurately display the same seasons temperature trend for both station A and B (Fig. 45). The only information not realistically shown by the hydrographic data is the high frequency changes caused by storms and diurnal cooling.

Salinity records from the hydrosonde are especially interesting because a freshwater inflow event of nearly 6 weeks was measured from June into August 1987 (Fig. 44). The salinity in Nueces Bay remained above 20 ‰ in 1988 in both the hydrosonde and hydrographic sampling (Fig. 46). There were some minor fluctuations in salinity of 2 to 3 ‰ which are likely associated with local precipitation. The trend of salinity for 1988 was increasing from around 25 ‰ in March 1988 to about 38 ‰ in August 1988. This increasing trend may be due to the decline of the previous freshwater event and strong evaporation during the windy dry summer. The hydrographic samples for salinity at stations A and B are virtually identical except for a single point which is probably an error.

Hydrosonde records for pH and dissolved oxygen display no strong effects during the freshwater inflow event in 1987 but pH became less variable during the low flow period in 1988 and dissolved oxygen declined to less than 5 mg/liter (3.5 ml/l) with a few values below 4 mg/liter (2.8 ml/l) (Fig. 47). This oxygen decline may be related to the warm temperatures and high recycling of organic matter. Nitrate on stations A and B varied from low concentrations of 2-3 μg-at/liter during the winter to extreme high and lows of 15 and 4 μg-at/liter during the spring with low values in the summer (Fig. 48). The concentrations of nitrate at the two stations varied by as much as 8 μg-at/liter between the surface



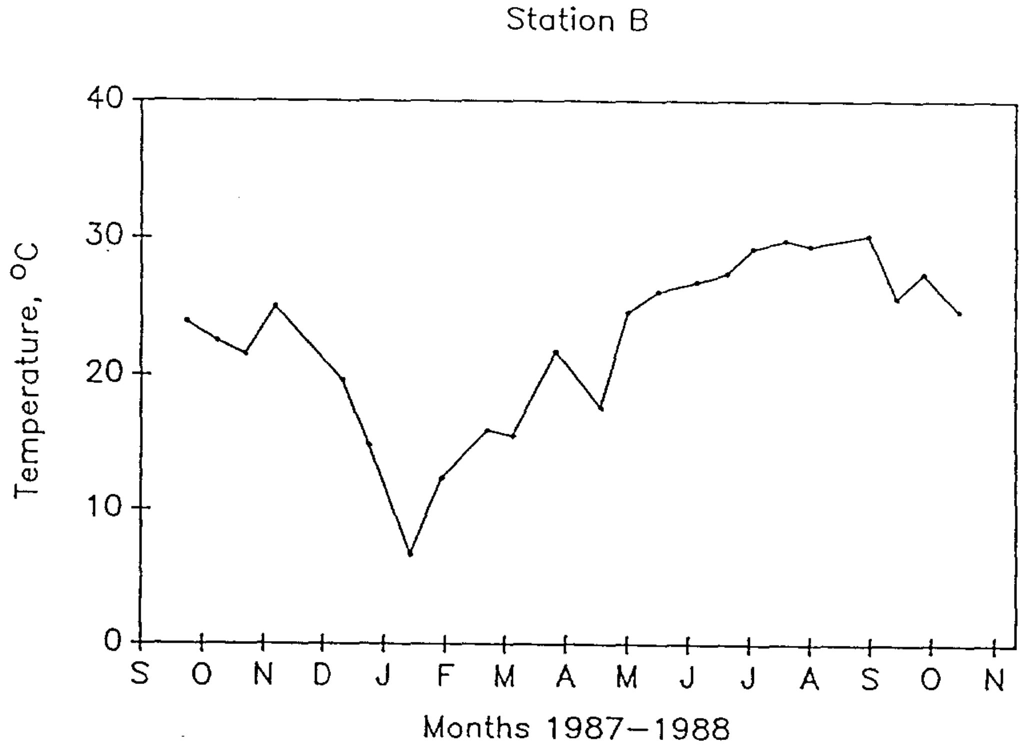


Figure 45. Temperature measured at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

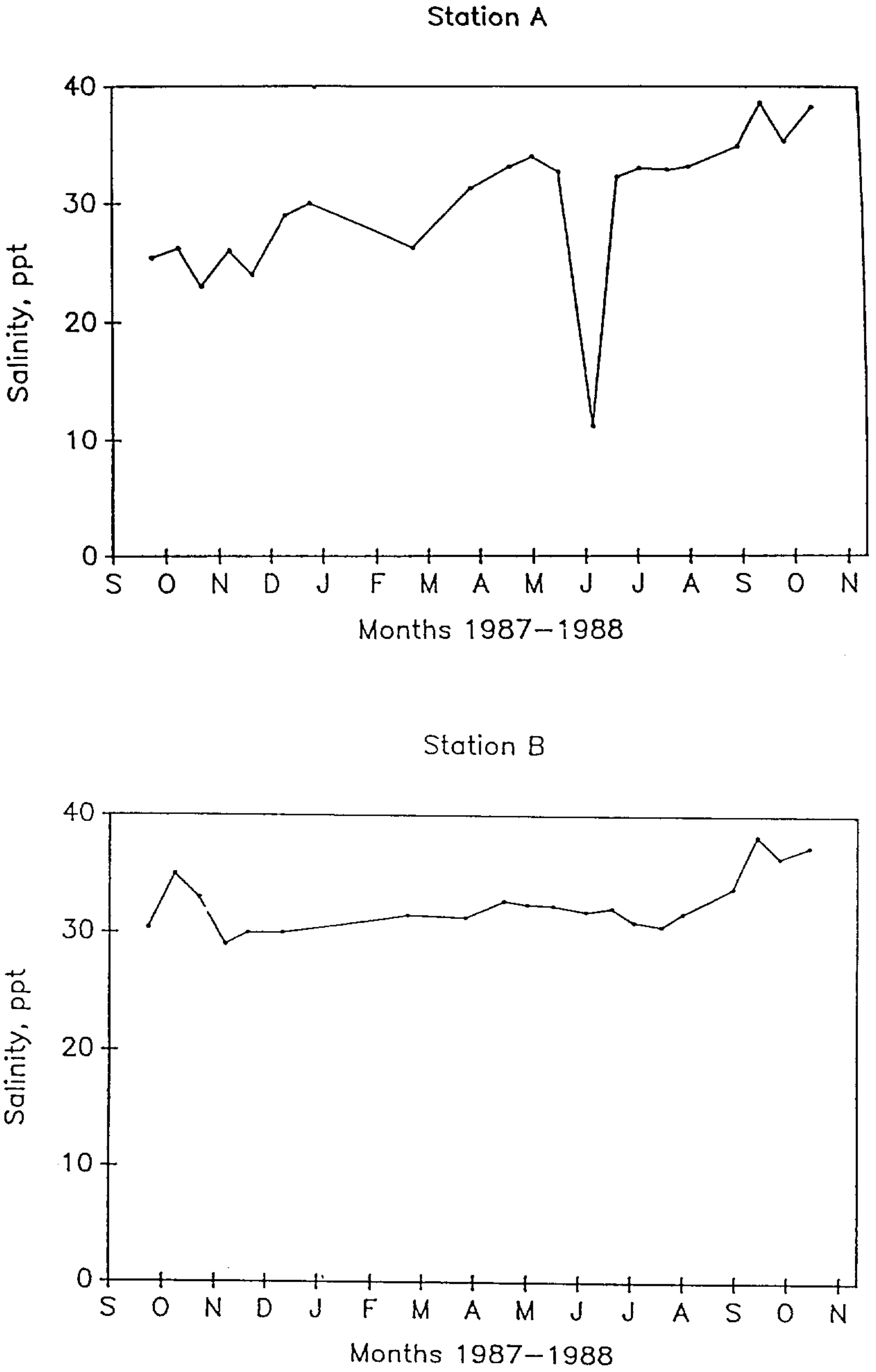


Figure 46. Salinity measured at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

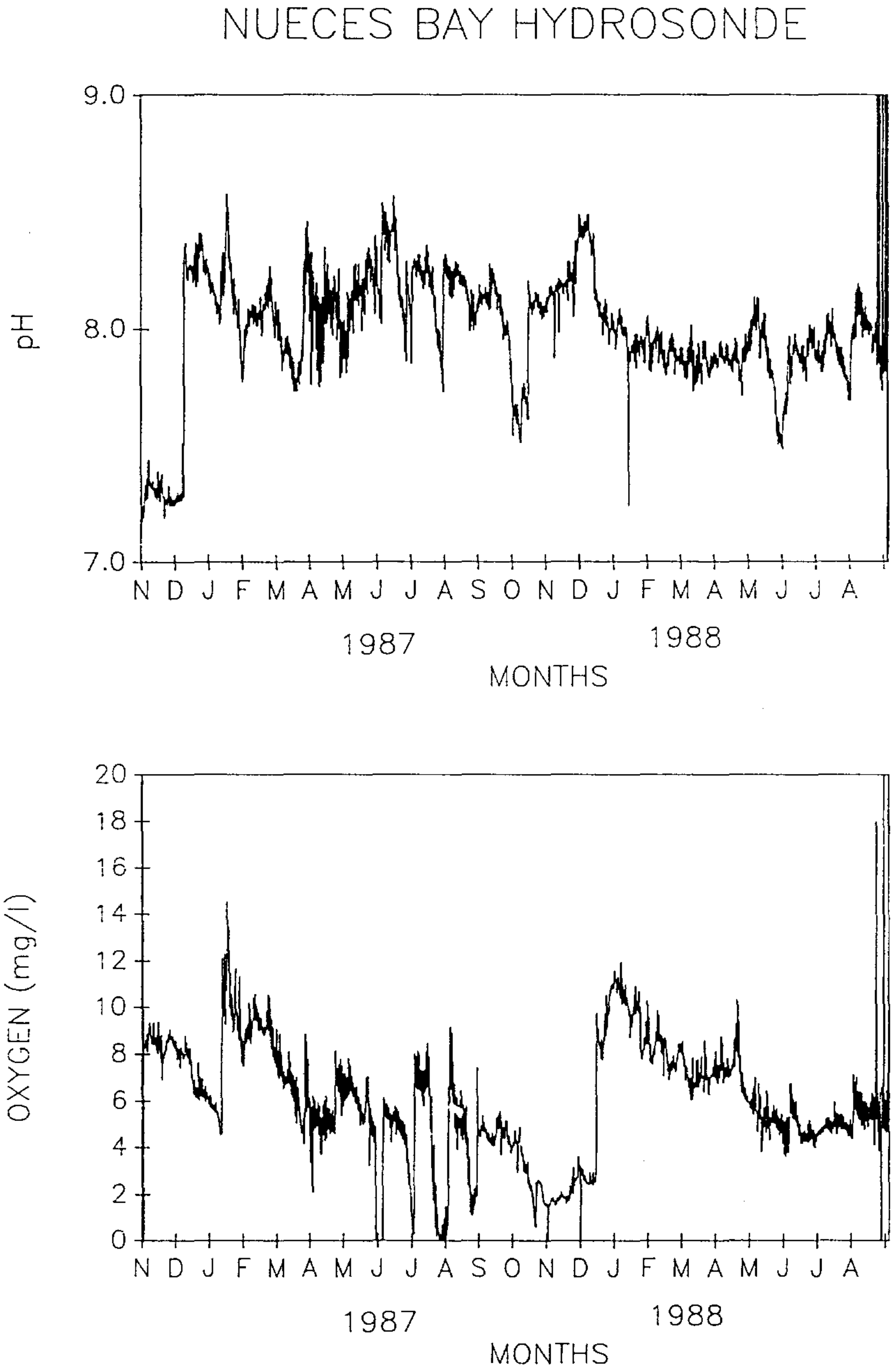


Figure 47. pH (upper) and dissolved oxygen (lower) measured by an in situ recorder in mid-Nueces Bay every three hours from November 1986-August 1988.

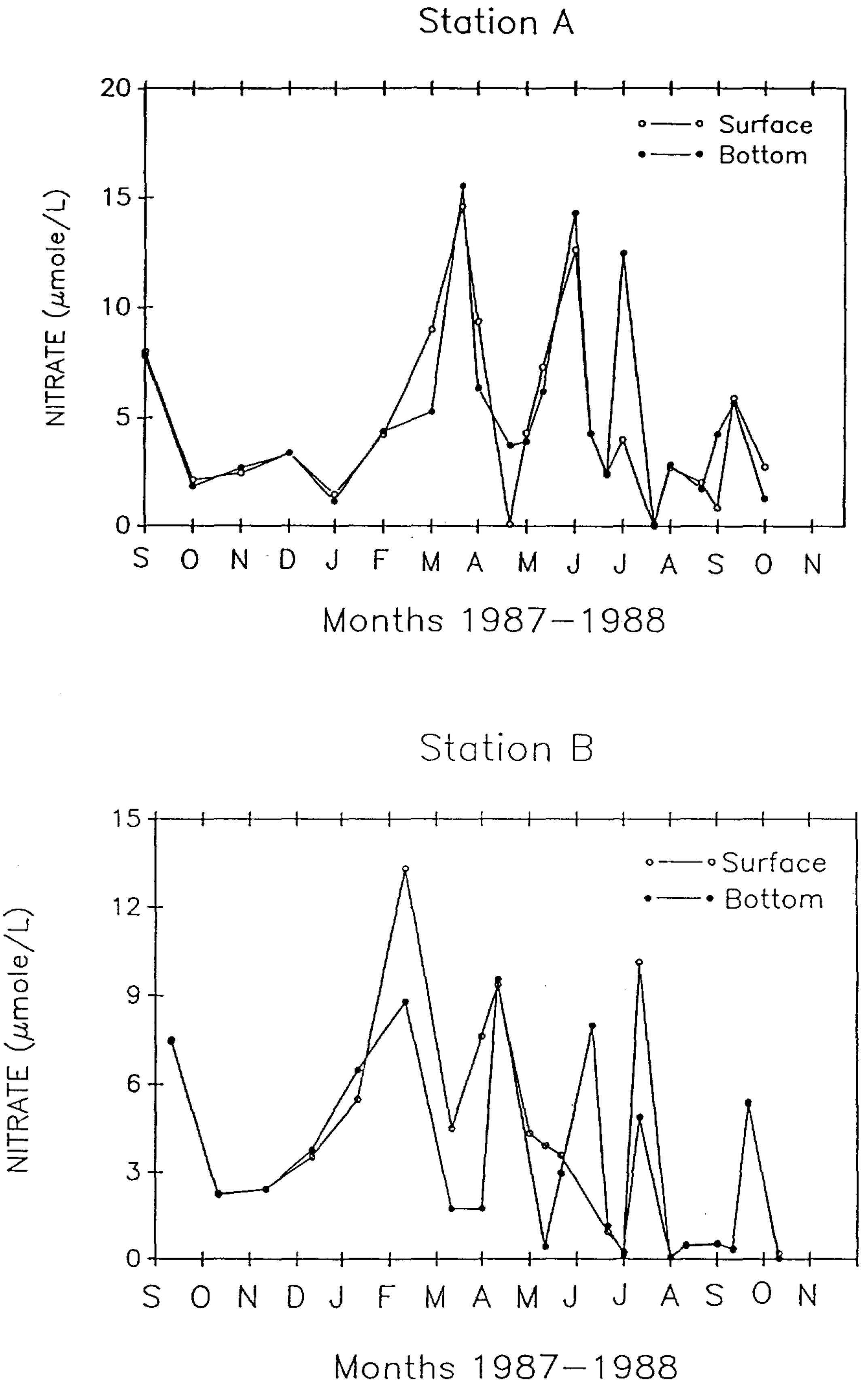


Figure 48. Nitrate measured at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

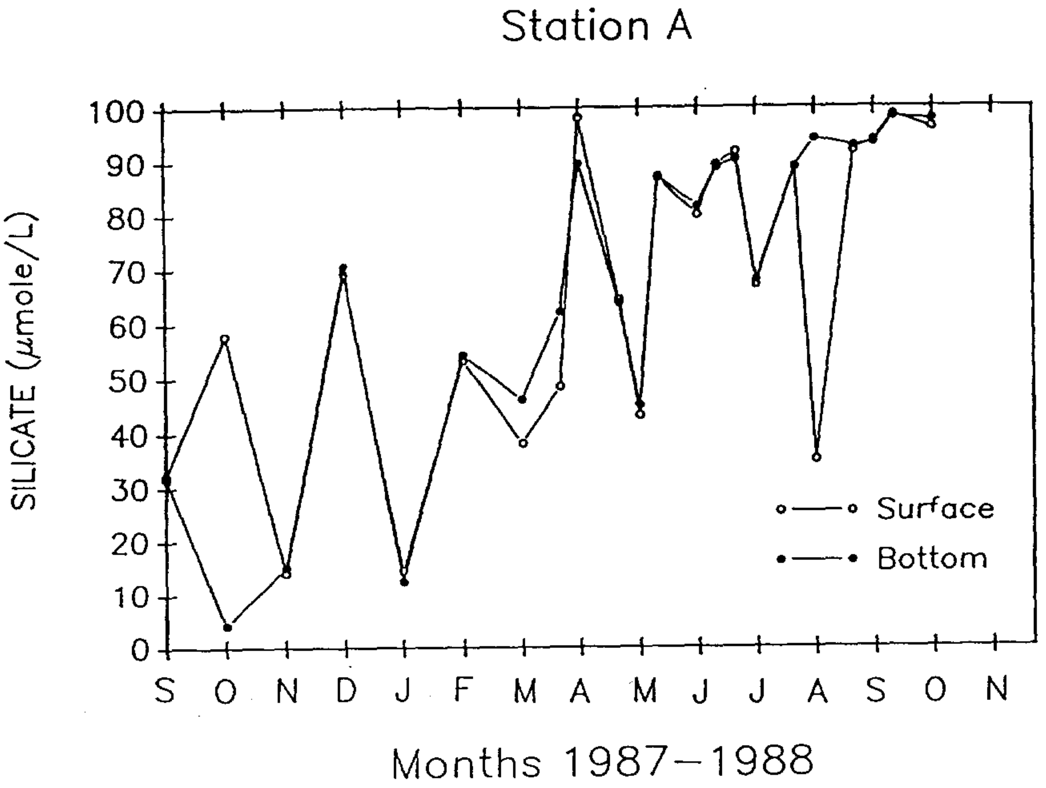
samples. It is interesting to note that the slightly larger nitrate concentrations occurred in the bottom sample at station A while the surface values were usually larger at station B.

Silicate also had a variable pattern with fluctuating high and low concentrations but stations A and B were synchronous. Silicate concentrations ranged from 4 to 98 μg-at/liter (Fig. 49) with the highest concentrations occurring during the summer of 1988 during low inflow. Recycling of biogenic silica is a possible reason for this increase. Station B had the lowest silicate concentrations during the period of maximum total pigments.

Orthophosphate concentrations ranged from less than 1 to 4 μg-at/liter during the entire year at station B (Fig. 50). One surface sample contained > 10 μg-at/liter but an isolated high value probably represents a bad sample.

Chlorophyll a and total phytoplankton pigments at stations A and B in surface waters were present in substantial quantities throughout the entire year (Fig. 51) with no real differences between the two locations. The chlorophyll concentrations ranged from about 4 to 15 μg/liter while phaeopigments were present from 2-15 μg/liter. The largest chlorophyll corresponds to a concurrent maximum in nitrate at station B. The appearance of high concentrations of phaeopigments must be related to wind mixing and bottom sediment resuspension that had large quantities of degraded pigments. The Secchi disk values in Nueces were as low as 10 cm at that time in February. About half of the total pigment was chlorophyll a while the remaining phaeopigments may be the result of zooplankton grazing under weaker wind conditions.

Ammonium concentrations at stations A and B were also quite variable but the coherance between the stations at high concentrations was quite strong. Relatively low values were observed during the fall, spring and summer but impressively large values were



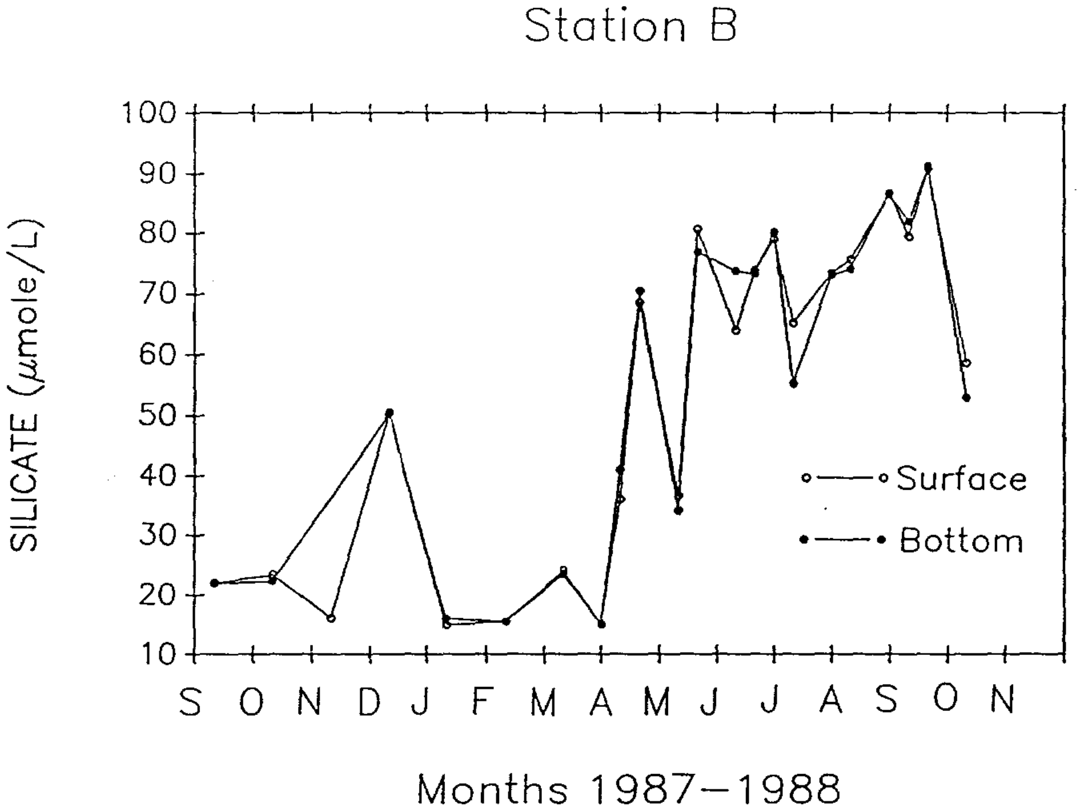


Figure 49. Silicate measured at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

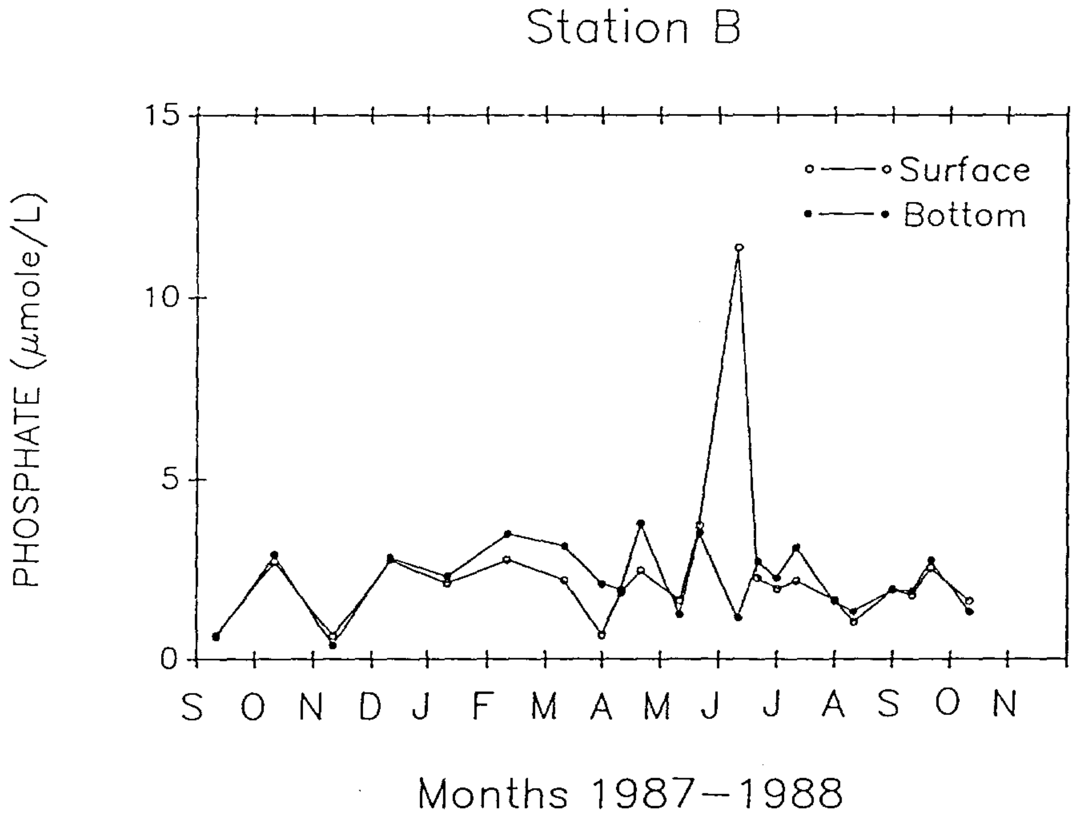


Figure 50. Orthophosphate measured at station B during biweekly surveys from September 1987-October 1988.

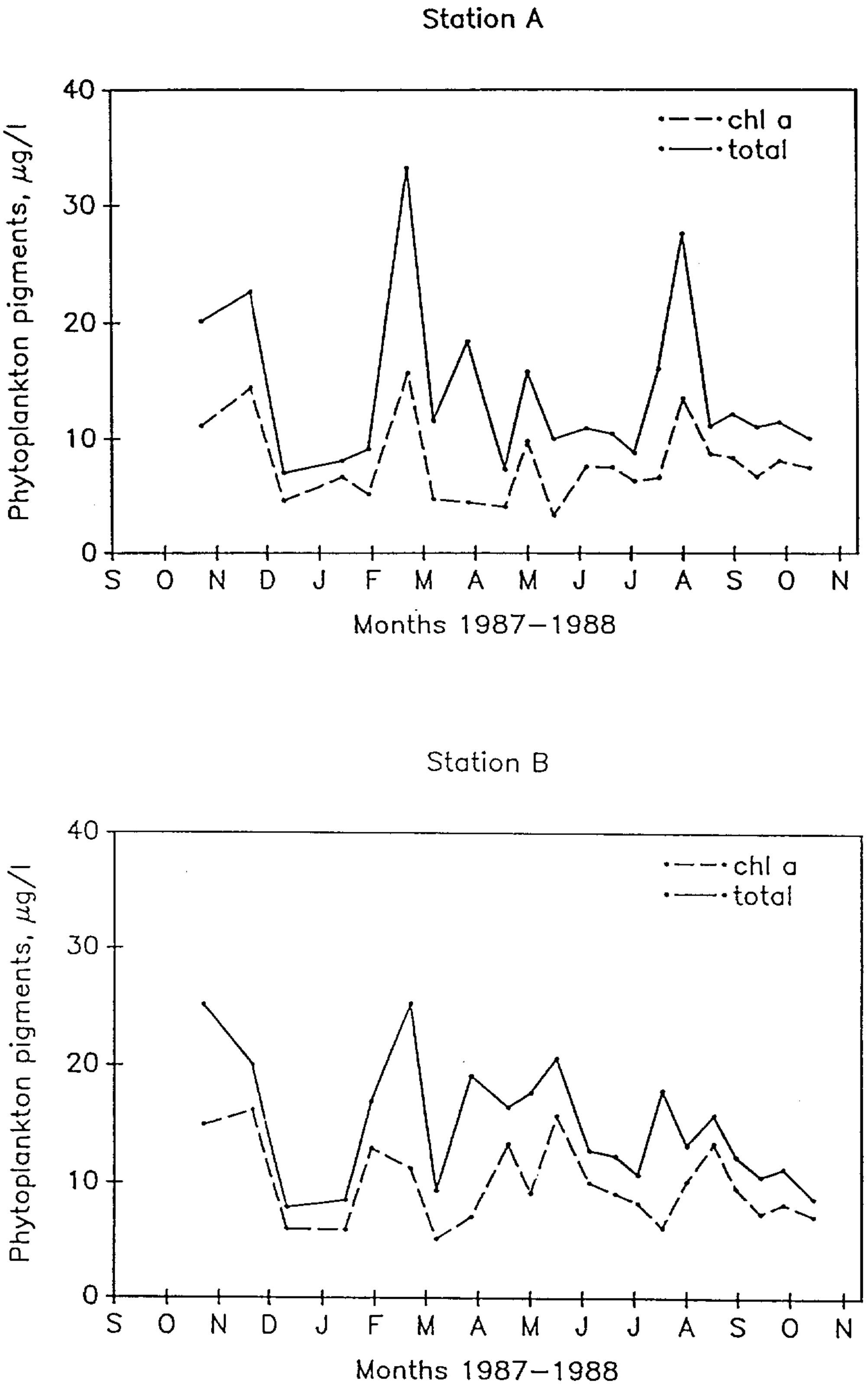


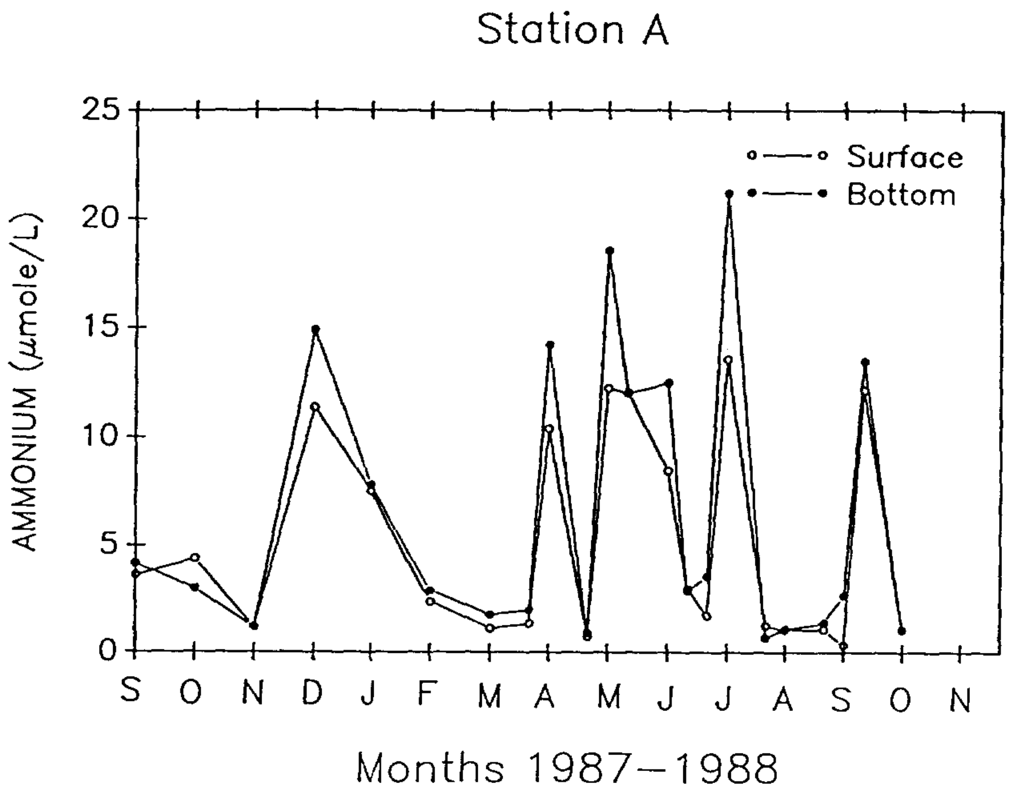
Figure 51. Phytoplankton pigments at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

found on about 30% of the sampling times (Fig. 52). The ammonium concentrations >10 μg-at/liter is very significant indication of magnitude of decomposition processes and/or chemical transformations between nitrogen species. It is especially interesting to note that maximum concentrations of ammonium were collected near the bottom on station A while maximum concentrations were at the surface on station B, similar to the behavior of nitrate.

Nitrite concentrations at stations A and B reinforce the supposition that transformations of ammonium are occurring in Nueces Bay. The very high nitrite concentrations of almost 4 μg-at/liter occurred in February through April when ammonium was in low abundance (Fig. 53). This maximum in nitrite concentration occurred only during the spring when phytoplankton growth was relatively large. There are some literature sources that have observed nitrite production by phytoplankton during high growth periods in marine waters.

Hourly Time Series - Stations A and B

Hourly measurements of temperature, salinity, nutrients and pigments were collected over a 24 hour period in order to ascertain the short term variations that were occurring in these parameters. The variability observed in these parameters is produced by both physical and biological processes but very useful information may be gained about the time response of the ecosystem to a physical change such as a weather front. All of these hourly time series measurements are detailed in time series plots in the appendix and are listed in the data tables. An example will be discussed here to describe the most interesting results.



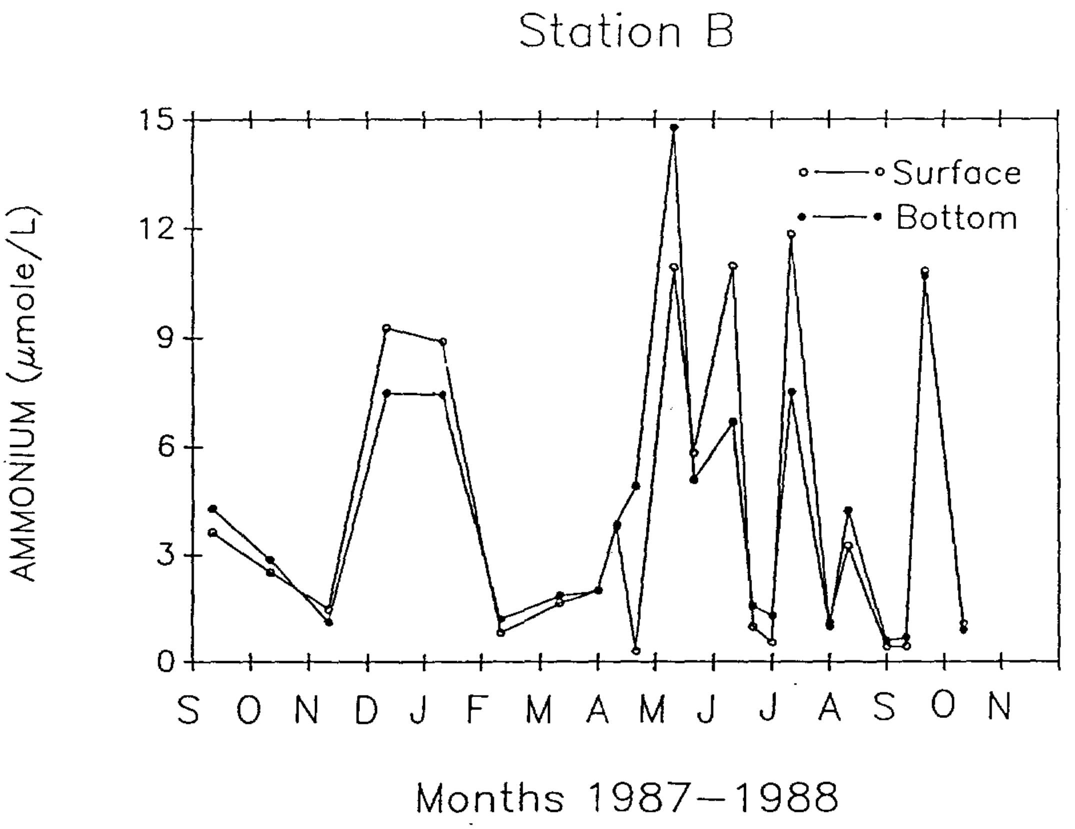
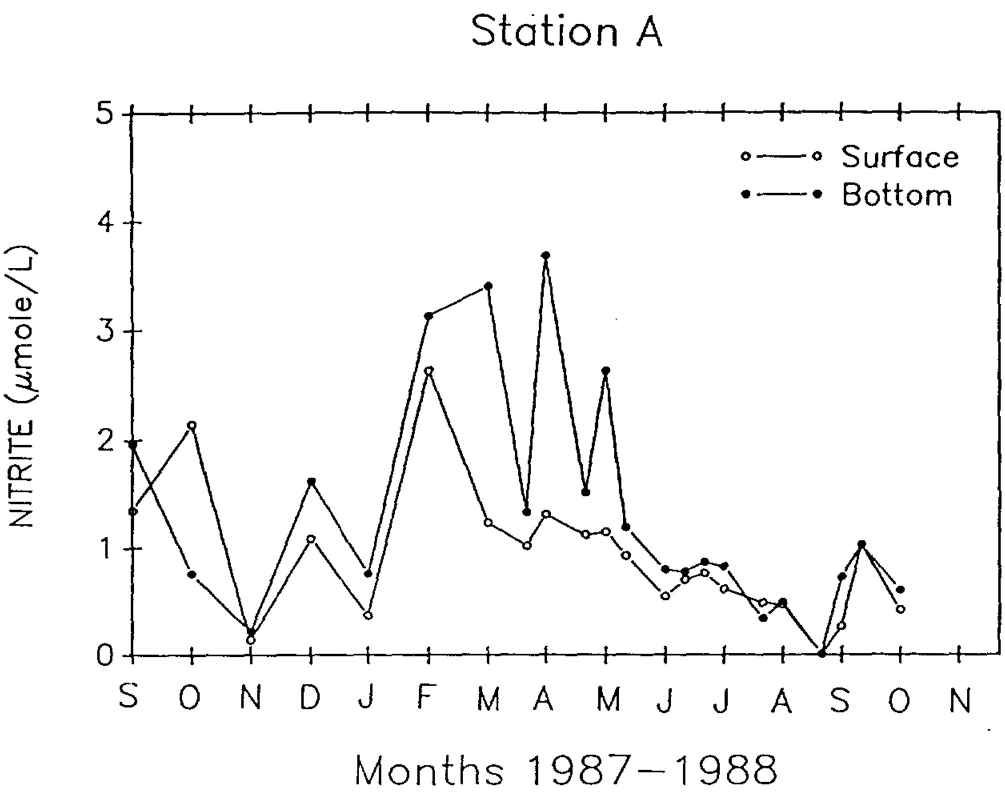


Figure 52. Ammonium at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.



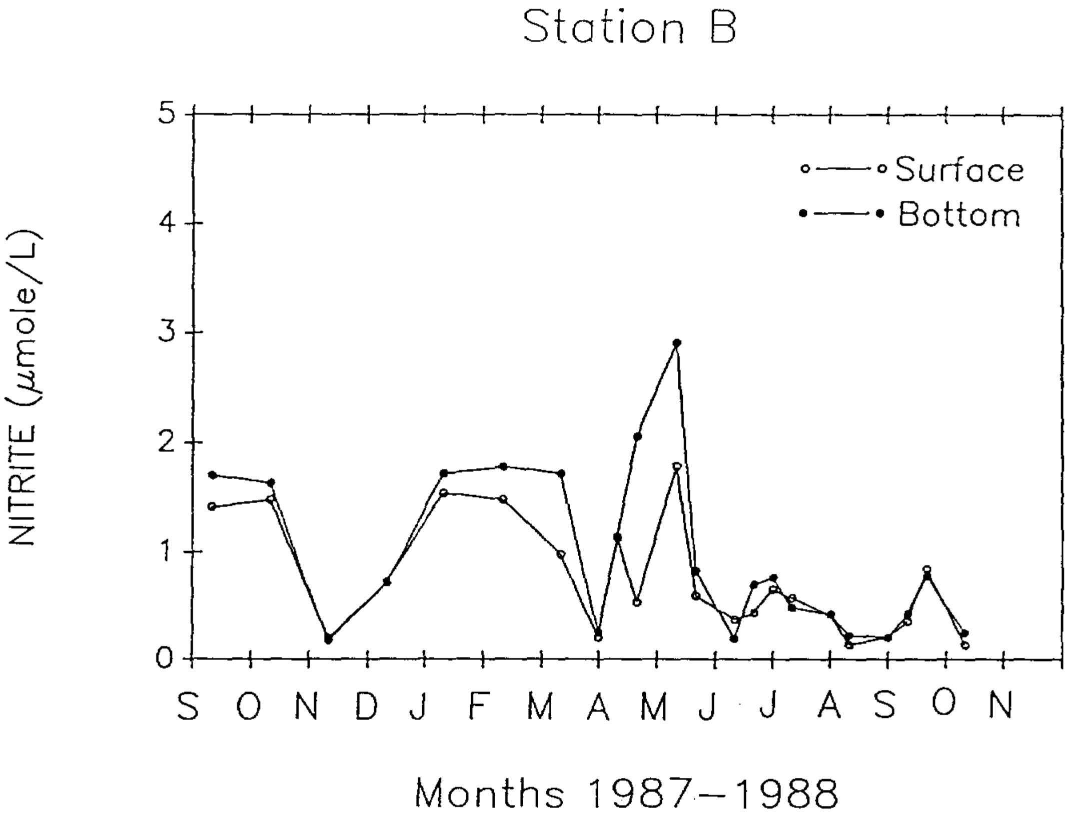


Figure 53. Nitrite at station A (upper) and station B (lower) during biweekly surveys from September 1987-October 1988.

The July 1988 time series at stations A and B occurred when gradients of salinity were small but other parameters were actively variable. Both stations A and B displayed a diurnal variations of temperature of about 1.8°C and these temperature changes occurred in both surface and near bottom layers equally (Figs. 54 and 55). The highest temperatures occurred at 1700 and the low temperatures at 0700. In contrast salinity at station A remained relatively constant at 35 to 35.5 ‰ while station B had an increase from 33.8 to 35.2‰ over the 24 hour period.

The nitrate concentrations at stations A and B were initially low during daylight hours but increased from 0.3 and 1.7 respectively to nearly 5 μg-at/liter during the night. It is tempting to speculate that this reflects phytoplankton uptake because the changes observed are a reasonable size. Silicate on station A increased from 80 to 95 μg-at/liter but the change at station B went from 75 to 120 μg-at/liter and phosphate at both stations changed in the same fashion.

Chlorophyll a concentrations were scattered between 7 and 10 μg/liter at station A but at station B the chlorophyll increased from 10 μg/liter to a maximum of 21 μg/liter at 2300 and thence declined. Dissolved oxygen, an indicator of both primary production and respiration remained quite steady at 6 to 6.5 mg/l so no phytoplankton growth was likely to have occurred locally to explain the change in chlorophyll. Perhaps tidal flow or wind driven advection pushed a chlorophyll front past station B.

Ammonium was uniformly high at station A with concentrations of between 12 and 15 μg-at/liter. Station B, however, initially started at 1 to 2 μg-at/liter but increased to nearly 15 μmole/liter after 24 hours. In a similar way, phaeopigments were uniformly high (~ 10 to 15 μg/liter) at station A and station B increased from 5 to 15 μg/liter. The

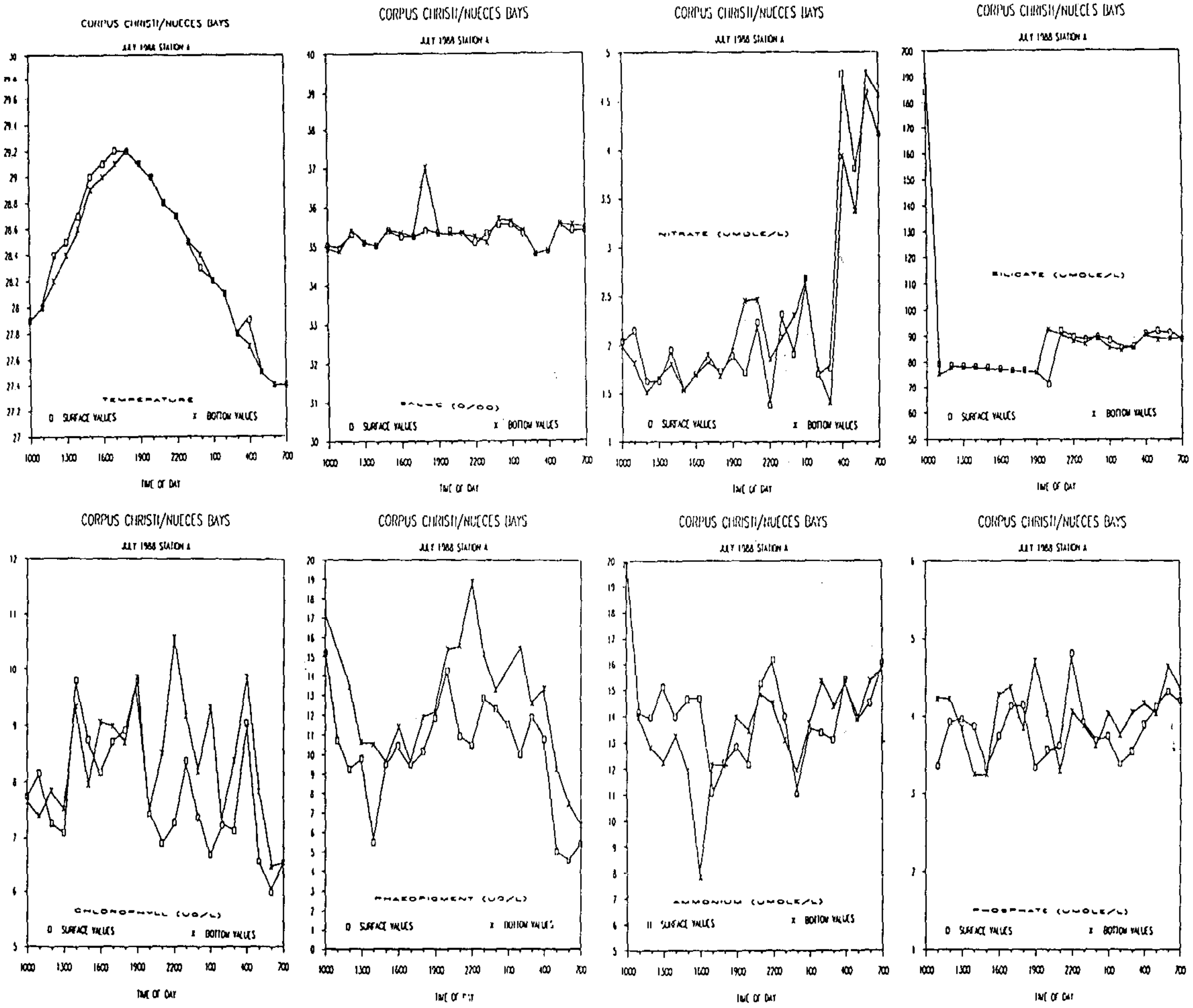


Figure 54. Hourly time series measurements of temperature, salinity, nitrate and silicate (upper) and chlorophyll, phaeopigment, ammonium and phosphate (lower) at station A in Nueces Bay on 11-12 July 1988.

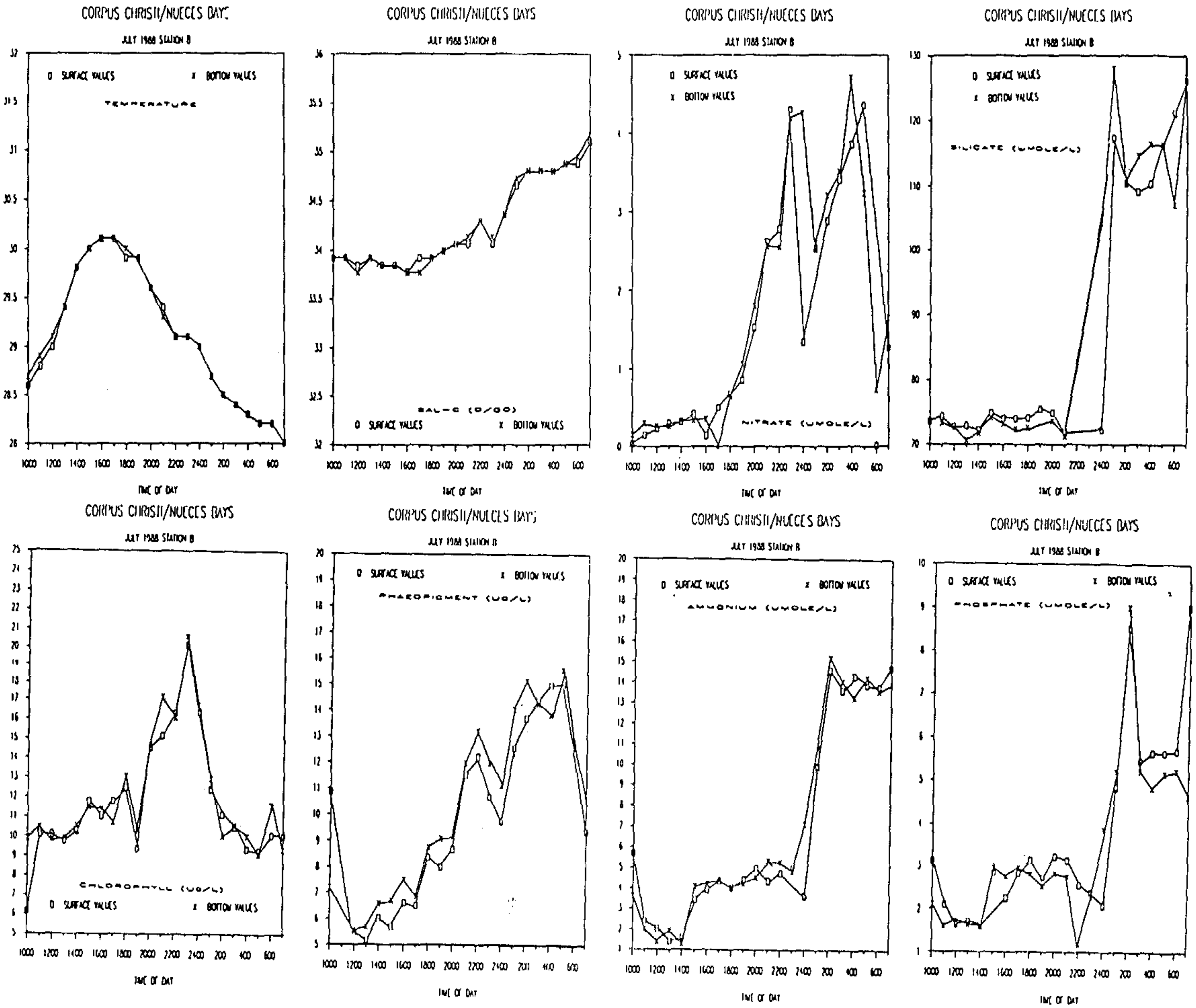


Figure 55. Hourly time series measurements of temperature, salinity, nitrate and silicate (upper) and chlorophyll, phaeopigment, ammonium and phosphate (lower) at station B in Nueces Bay on 10-11 July 1988.

changes in both of these degradation products indicate a water movement from station A to B during the 24 hour period perhaps by a combination of winds and tides.

Long Term Trends - Station C and D

The long term trends in Corpus Christi Bay (Fig. 37), were determined not far from the junction of the two bays. The Corpus Christi hydrosonde was located on the south side of the spoil island near station 26 where continuous measurements of temperature, salinity, pH and dissolved oxygen were recorded. Hydrographic samples (temperature, salinity, nutrients and plant pigments) were collected at experimental sites C (located about 7 km from station B) and D (located across Corpus Christi Bay about 20 km from station C).

The temperature record in Corpus Christi Bay from the hydrosonde instrument was very similar to that in Nueces Bay with the minor exception that the lowest temperatures were only about 10 to 12°C during the winters rather than 7 to 8°C (Fig. 56). Most of the storm events were identical with regard to cooling intensity and duration. The hydrographic samples collected at stations C and D reflected an accurate representation of the hydrosonde temperature record with regard to the general heating and cooling trend but not the storm events or diurnal fluctuations (Fig. 57).

The hydrosonde salinity records in Corpus Christi Bay are interesting because the freshwater inflow period in August 1987 was present at approximately the same time as in Nueces Bay however the salinity never went below 20 ‰ (Fig. 56). The variations of salinity indicate that high frequency variations (tides or winds) were strong. The salinity in Corpus Christi Bay did decline to 26 ‰ for about a month. During the study period the salinity ranged between 30 and 33 ‰ except for a short period in March 1988 when salinity

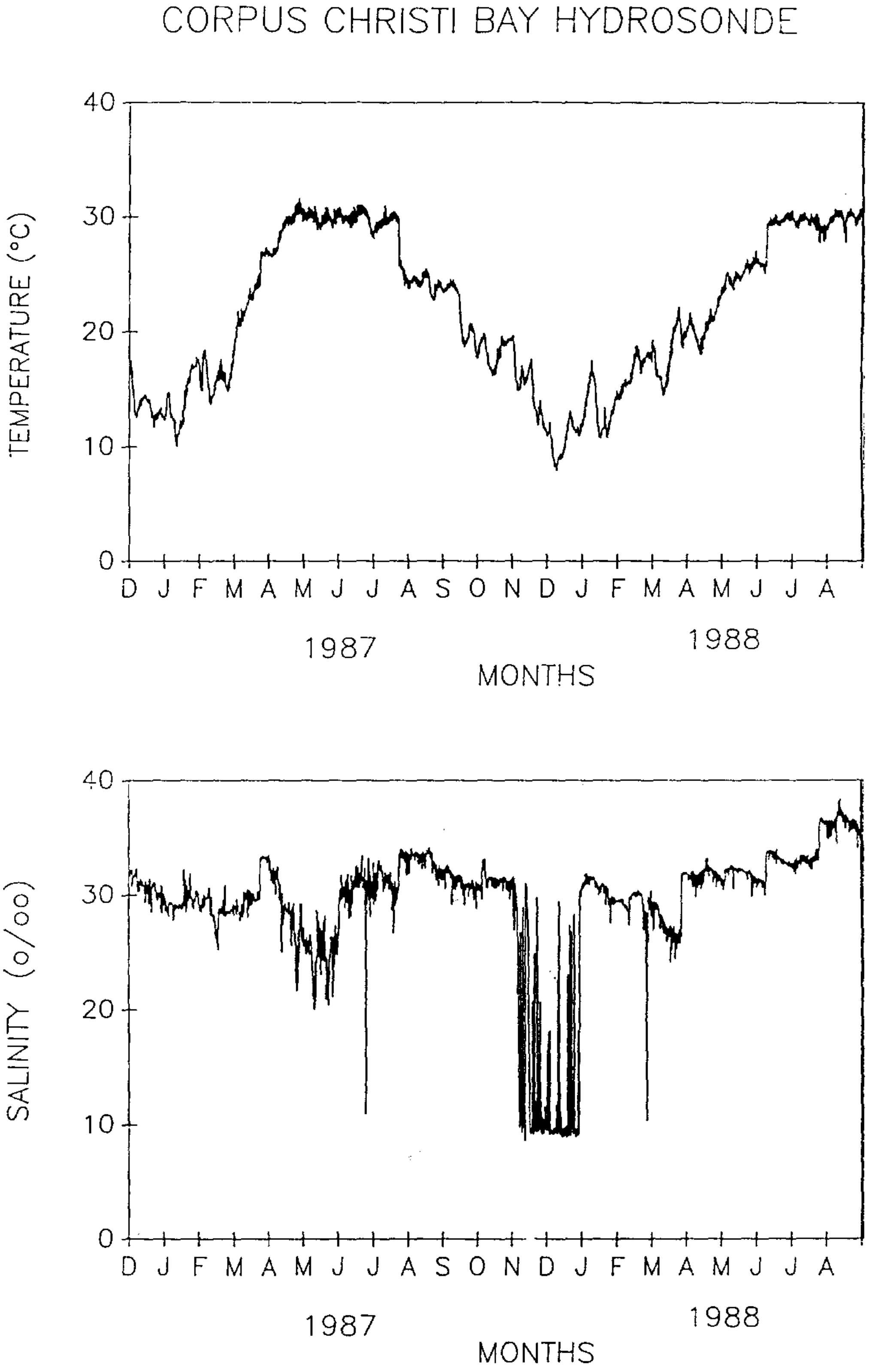


Figure 56. Temperature (upper) and salinity (lower) measured by an in situ recorder in Corpus Christi Bay near Ingleside, Texas every three hours from December 1986-August 1988.

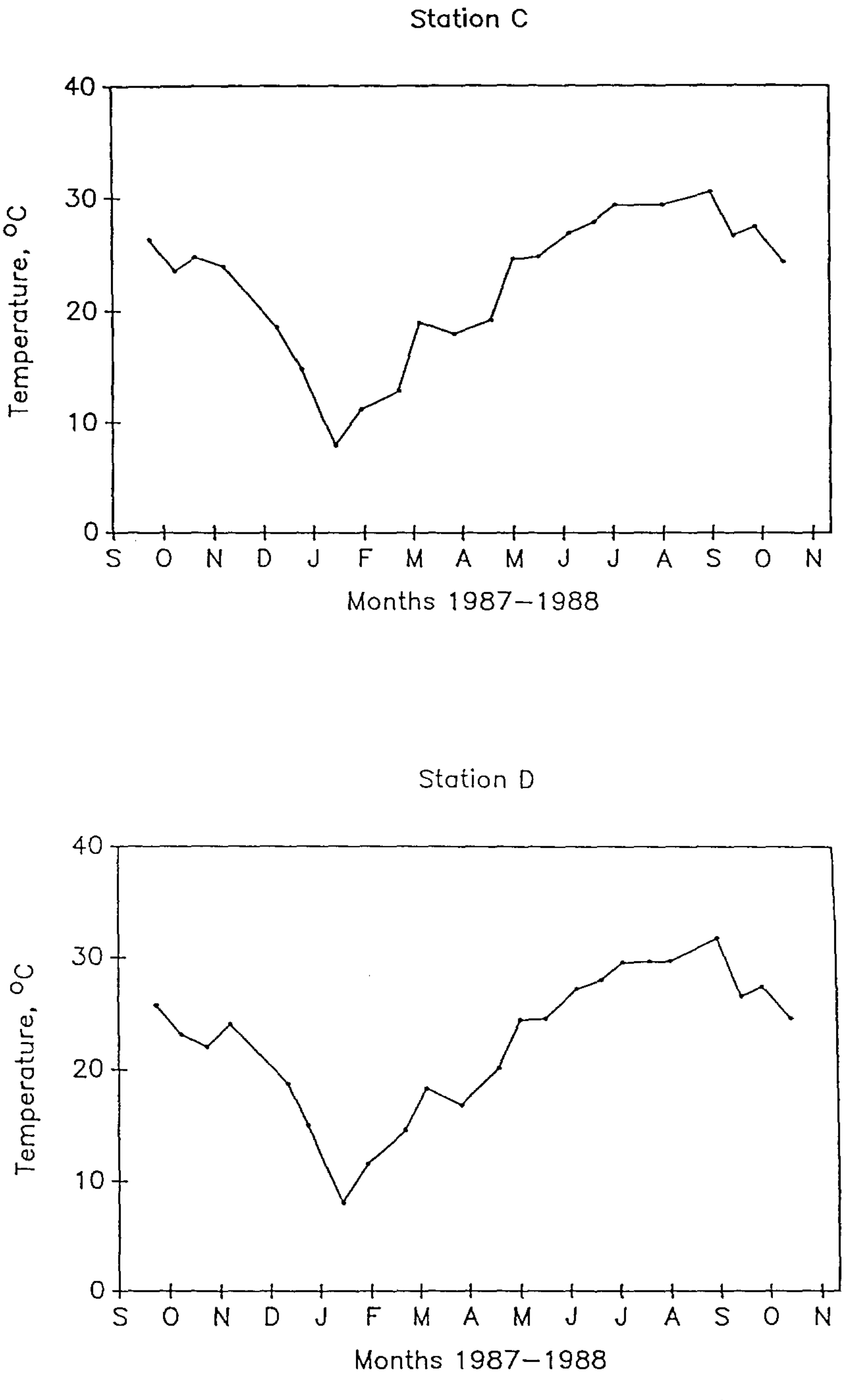


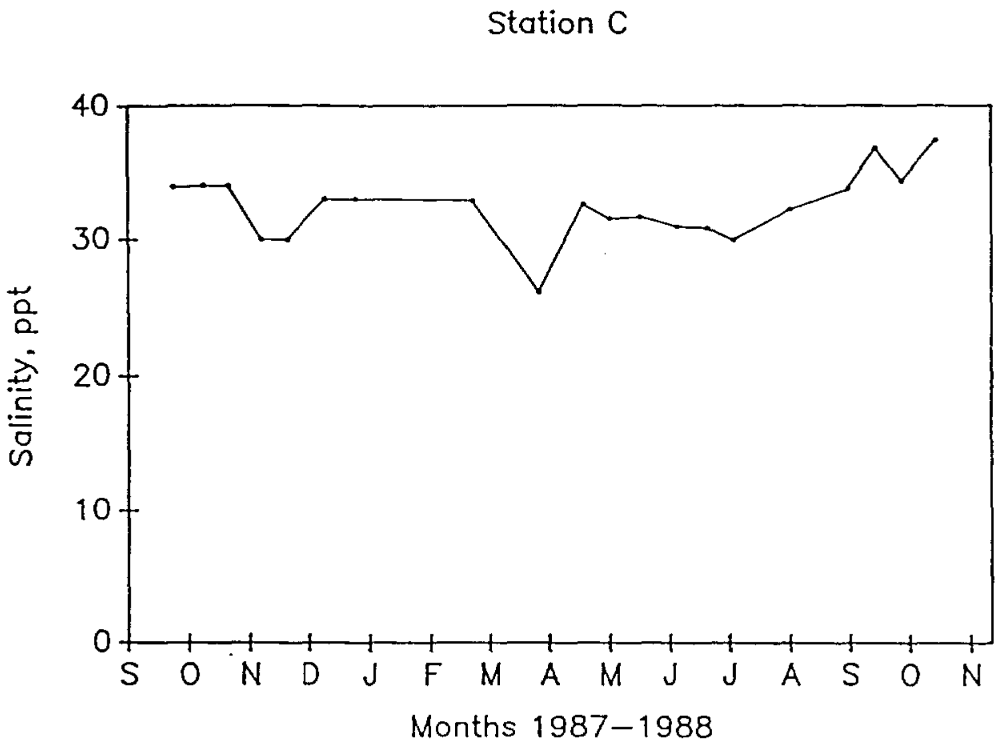
Figure 57. Temperature measured at station C (upper) and station D during biweekly surveys from September 1987-October 1988.

decreased to 27 ‰ for about 2 weeks. Hydrographic sampling at station C observed the same decrease in salinity in March so the two measurements confirm each other (Fig. 58). The experimental sites presented no other events however the increase in salinity from July through October 1988 was interesting. Salinities nearly to 40 o/oo were observed at the surface at Station D.

The Corpus Christi hydrosonde data for pH and dissolved oxygen underwent frequent variations of ± 0.2 pH units and 2 mg 0_2/liter. pH displayed very little response to changes in salinity and fouling of the oxygen sensor appeared to be a problem (Figs. 59).

Nitrate concentrations at experimental stations C and D were rather large at the first sampling in September at 8 to 10 μg-at/liter but concentrations declined to about 2 μg-at/liter during the winter months (Fig. 60). Nitrate concentrations increased in March and April at station C while D remained at winter concentrations. This increase at station C coincides with the lower salinity water so it is likely to be derived from Nueces Bay. Later during June and July nitrate concentrations rose very high first at the bottom and later at the surface which argues for near bottom nitrification processes being very important in the available form of nitrogen available to phytoplankton populations.

Silicate concentrations had very similar behavior patterns on stations C and D. Silicate exhibited high concentrations in the winter, declined to very low levels during February through April and finally increased monotonically to very high levels during the summer (Fig. 61). The large winter concentrations could be a lack of biological uptake and the low concentrations in the spring are almost certainly caused by phytoplankton uptake. The steady increase of silicate during the summer is mostly like to be recycling of biogenic silica as described by Nelson and Goering (1978) and Nelson *et al.* (1981).



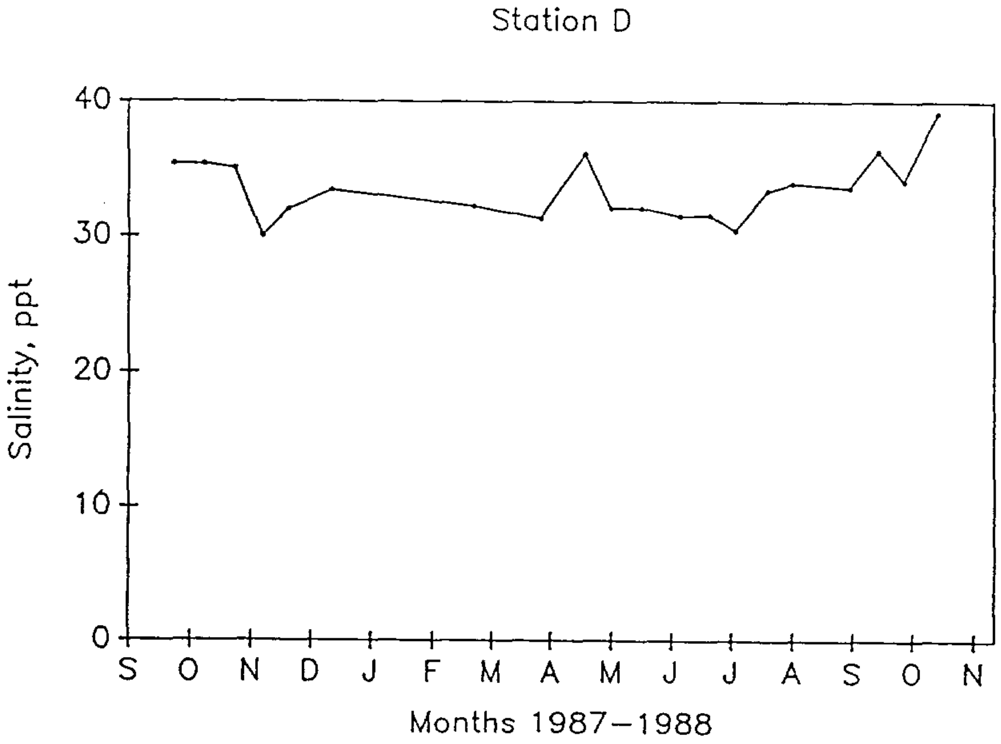


Figure 58. Salinity measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.

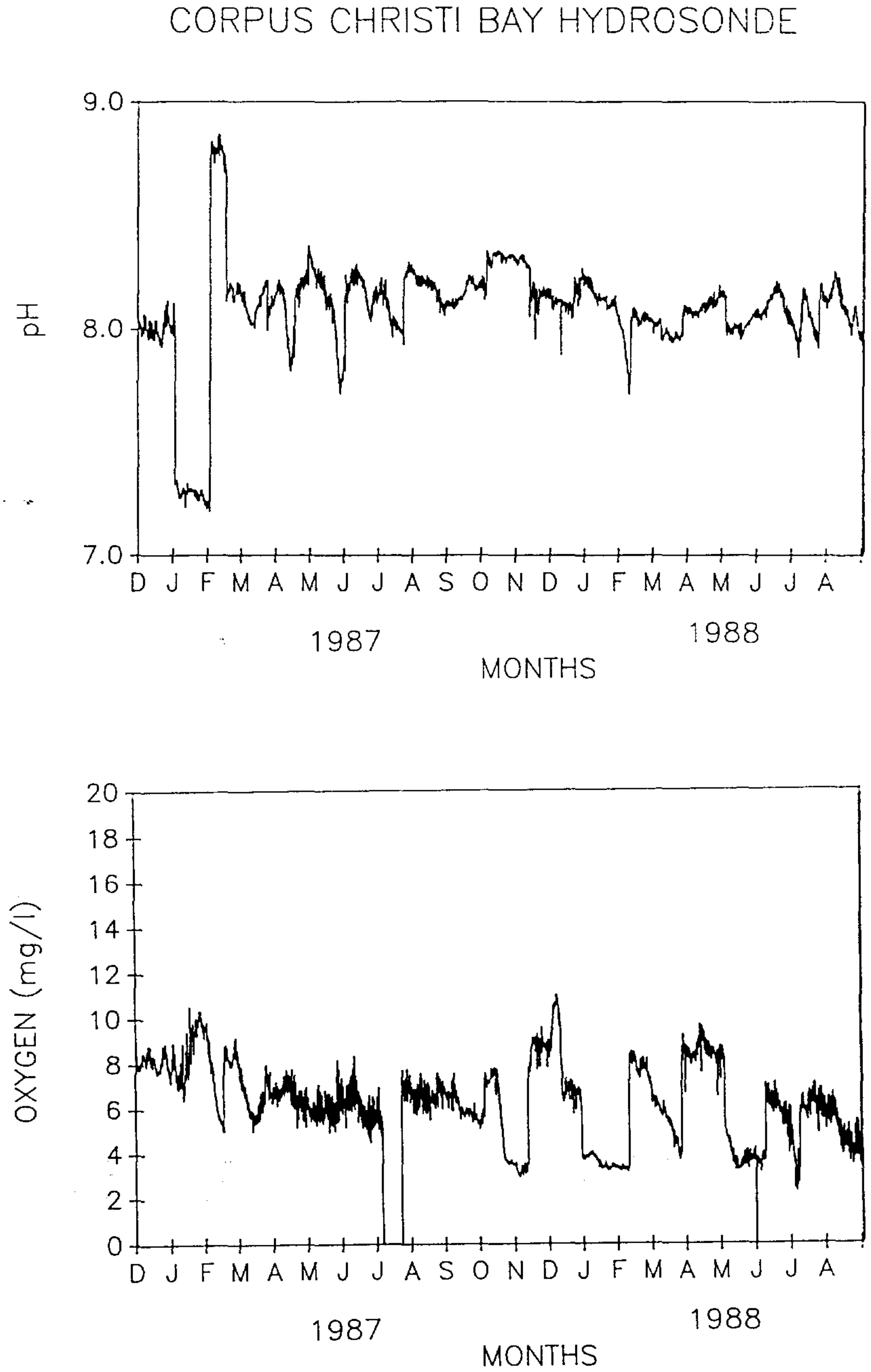
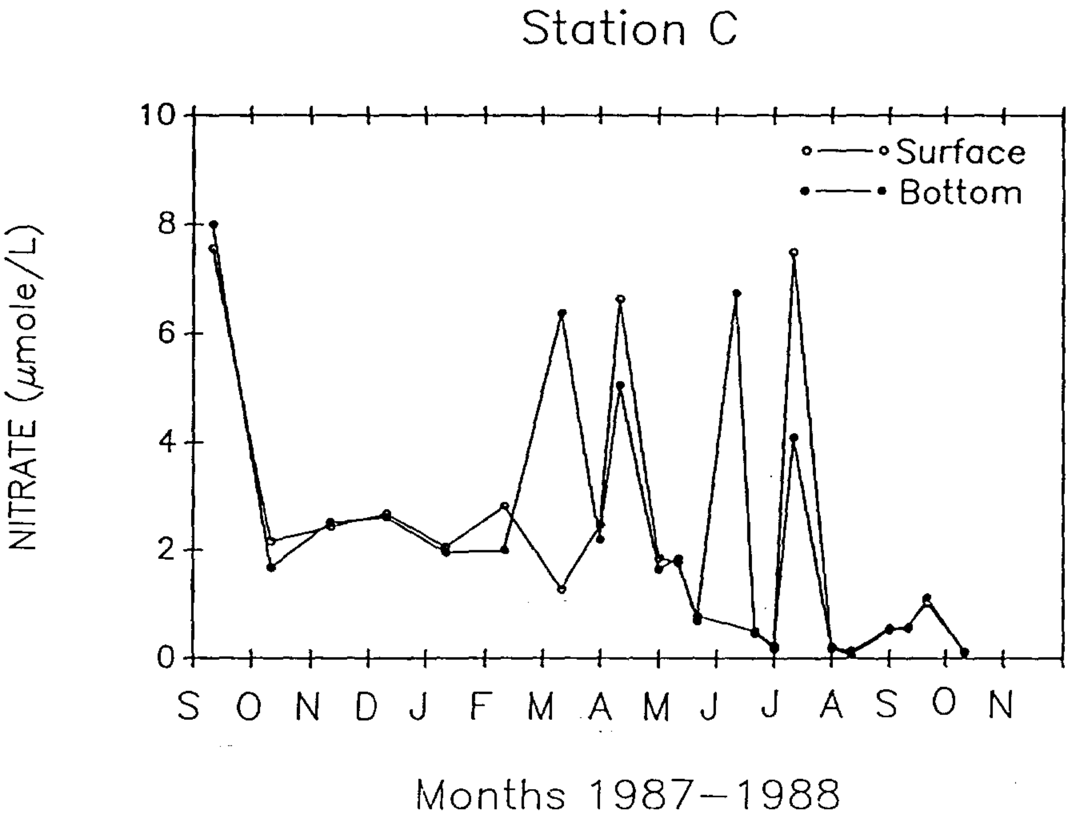


Figure 59. pH (upper) and dissolved oxygen (lower) measured by an in situ recorder in Corpus Christi Bay near Ingleside, Texas every three hours from December 1986-August 1988.



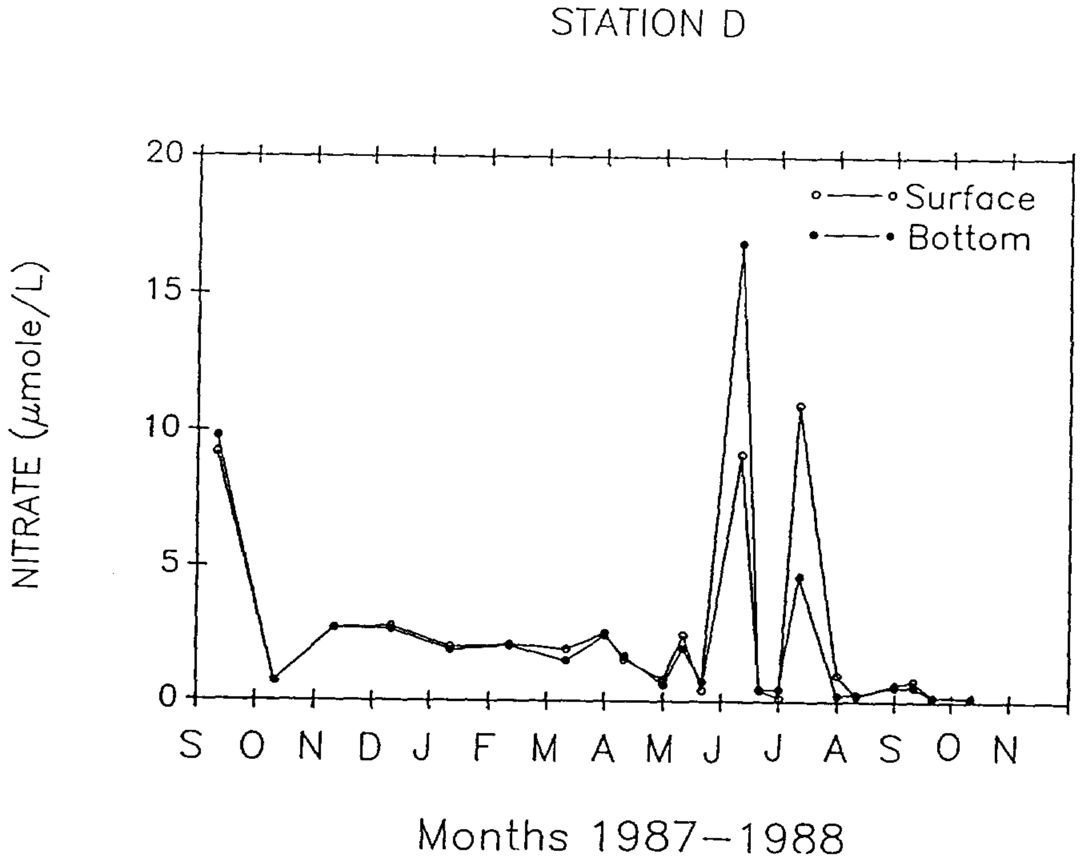
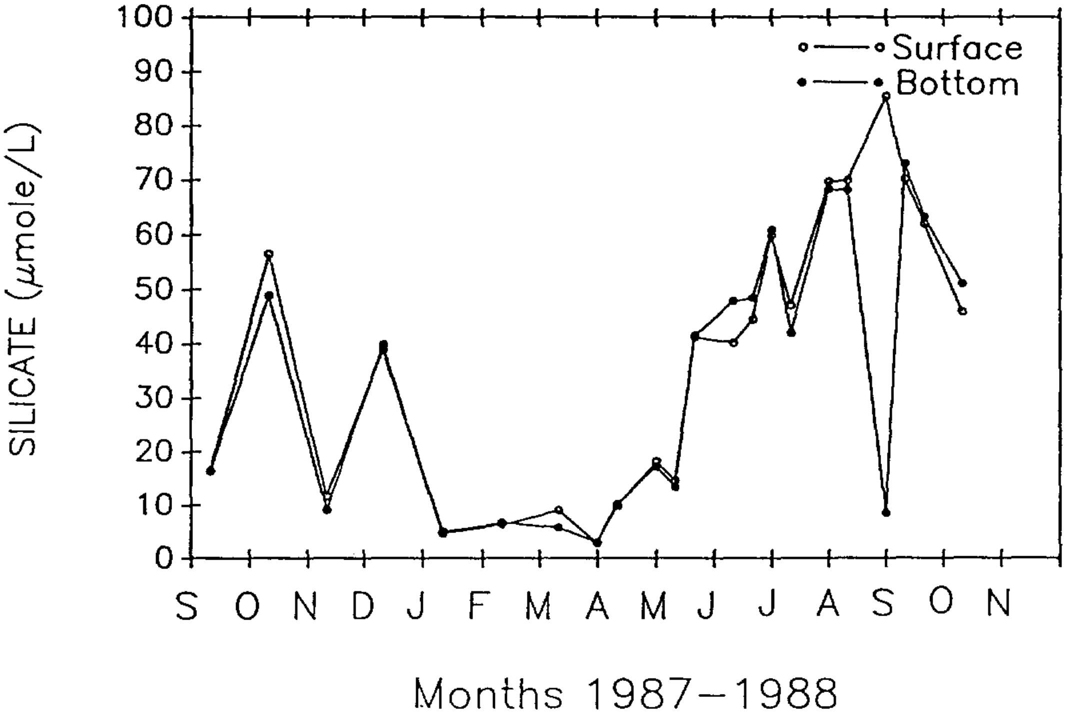


Figure 60. Nitrate measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.


Station C

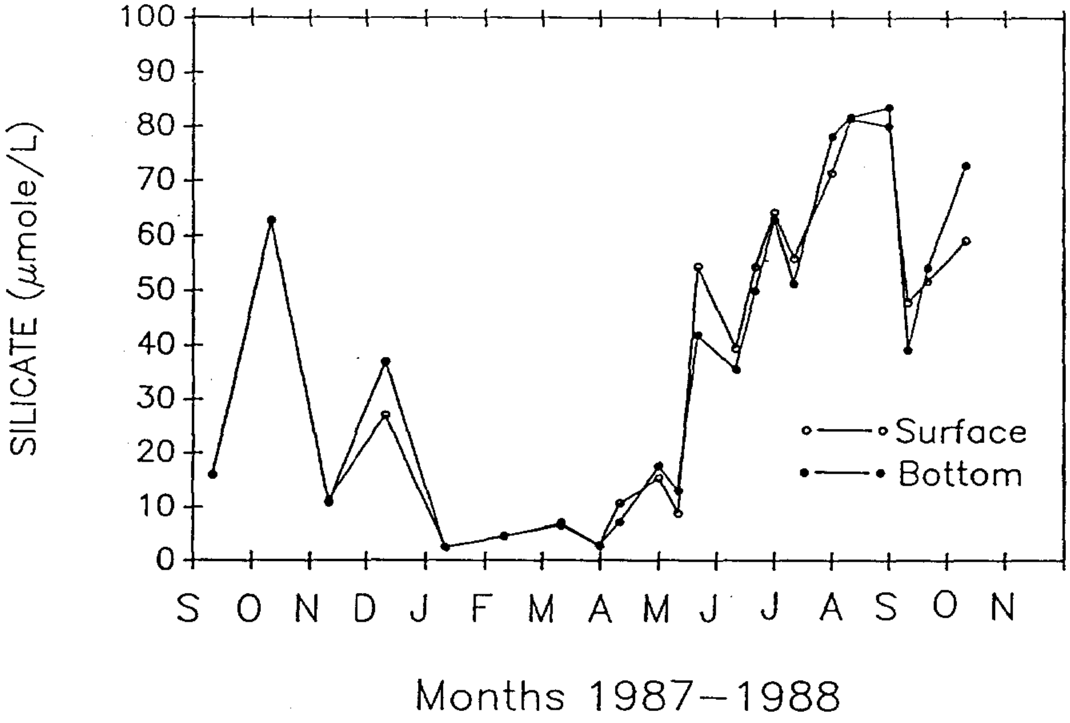

STATION D

Figure 61. Silicate measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.

Orthophosphate concentration at stations C and D were similar to values at experimental sites A and B although minimum values were very low on 1 or 2 samplings (Fig. 62). Phosphate concentrations were so low on those occasions that primary production rates may have been affected.

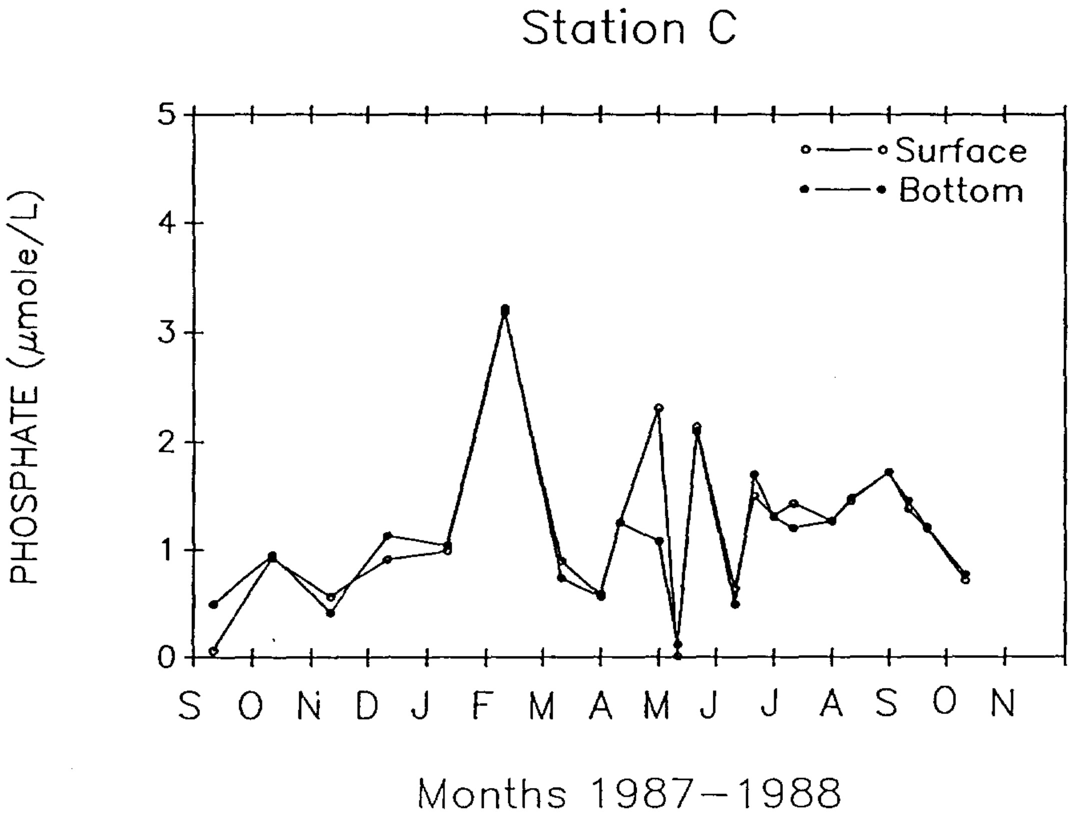
Surface chlorophyll and total phytoplankton pigments at stations C and D were relatively uniform with no high peaks throughout the 4 month period. Concentrations of chlorophyll a ranged from about 5 to 10 μg/liter at both stations however there was a trend of increased concentration in late summer especially at site D (Fig. 63). Phaeopigment concentrations were small (~ 2 μg/liter) with only a few larger values.

Ammonium concentrations were bimodal with large concentrations in winter and summer with low values in the spring (Fig. 64). There was no clear pattern of surface and bottom concentrations so ammonium production may result from several sources seasonally throughout the bay system. The largest concentrations (> 25 μg-at/liter) is extremely high and rarely observed at this distance from discharges or other point sources. Since the pattern was observed at all experimental sites A through D and the concentrations were similar, then the most obvious cause is a general biological process like nutrient recycling.

Nitrite concentrations at station C and D were smaller than sites A and B in Nueces Bay. The bottom sample usually had larger concentrations of nitrite than the surface and may be remotely related to observed ammonium fluctuations (Fig. 65).

Hourly Time Series - Stations C and D

Hourly measurements of temperature, salinity, nutrients and pigments were collected over a 24 hour period in order to ascertain the short term variations that were occurring



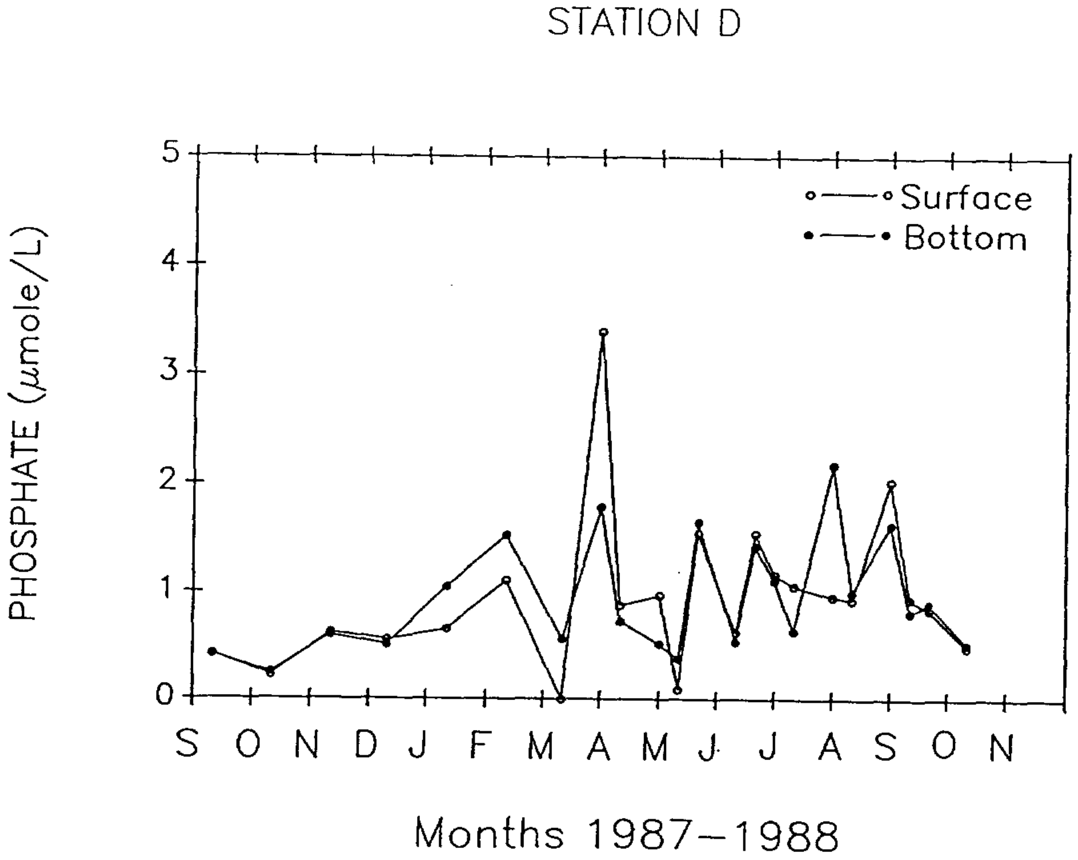
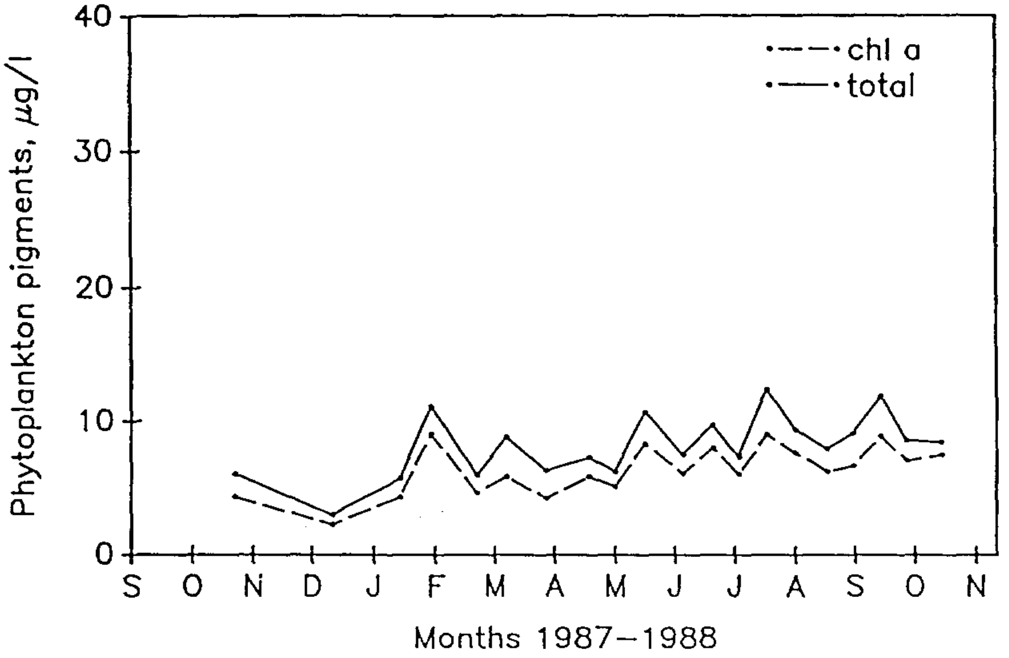


Figure 62. Orthophosphate measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.

Station C



Station D

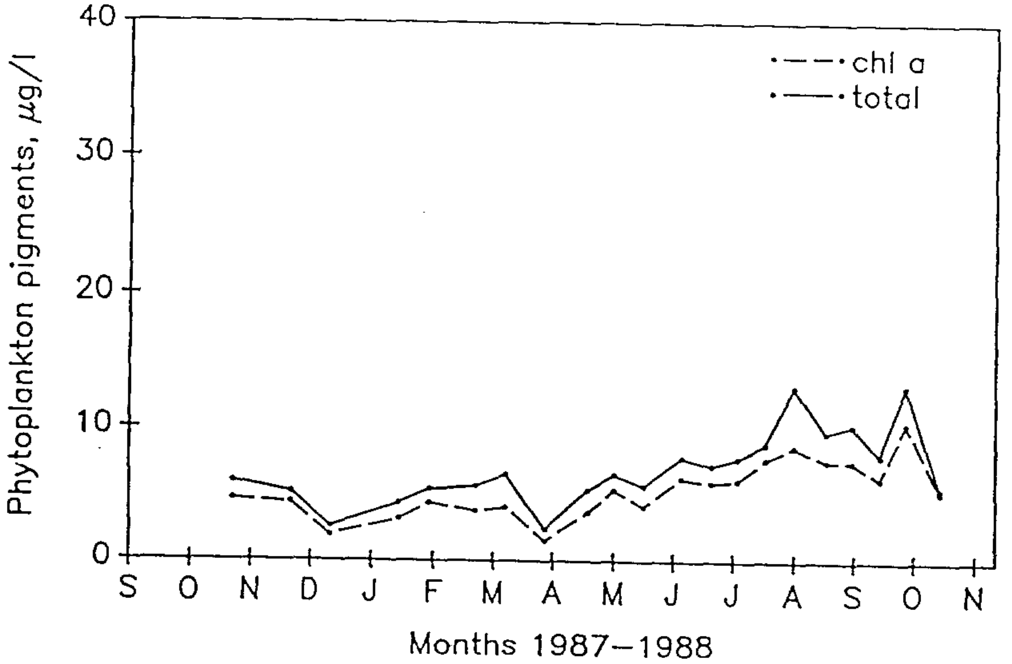


Figure 63. Phytoplankton pigments measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.

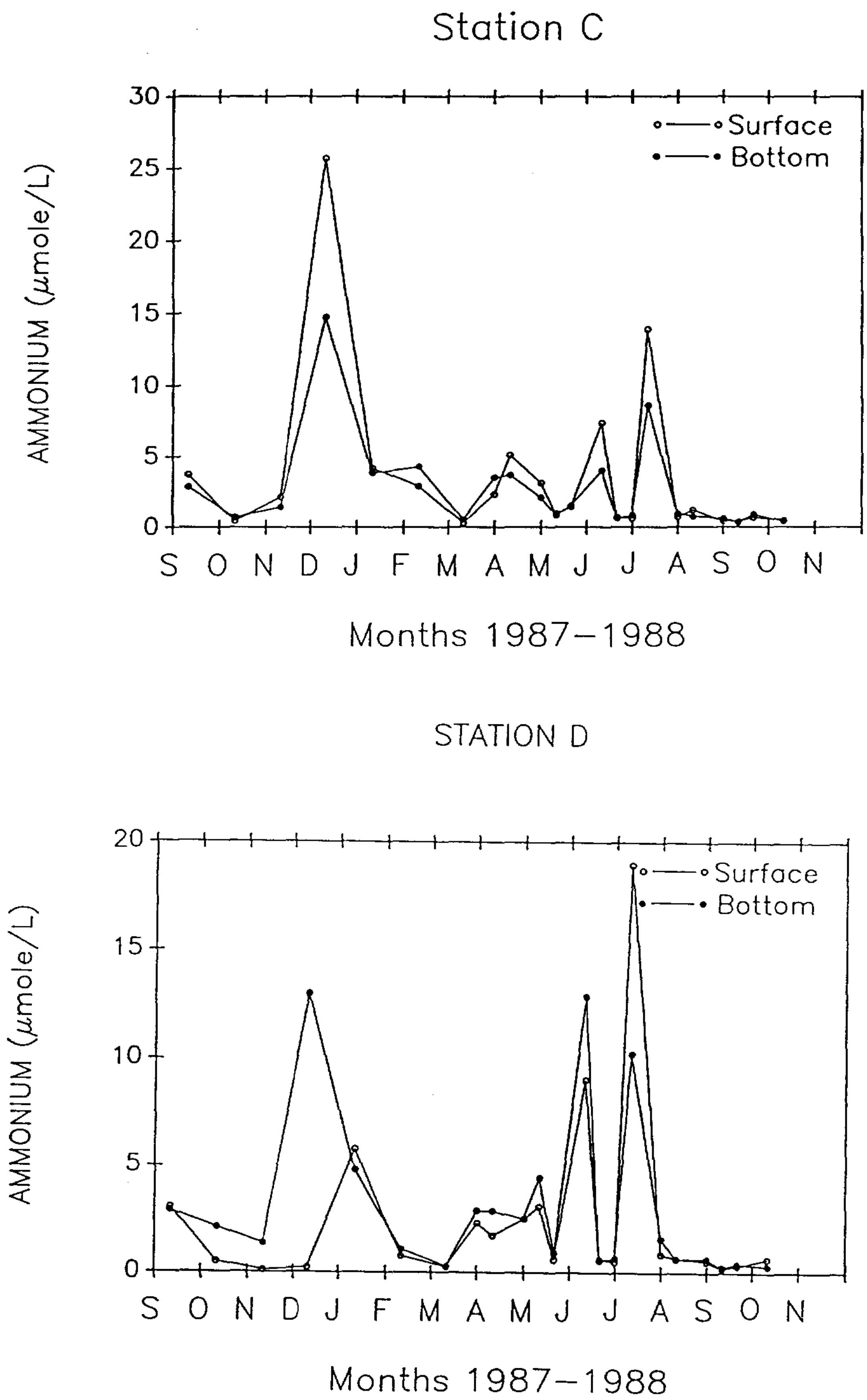
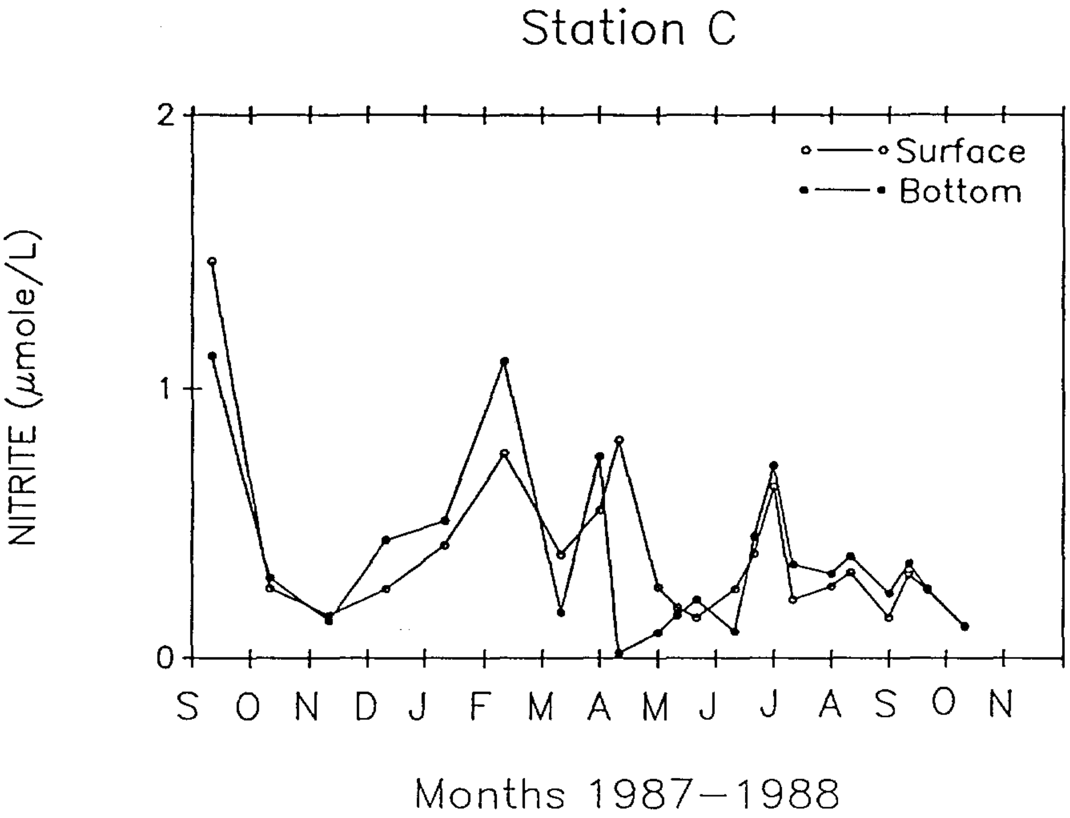


Figure 64. Ammonium measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.



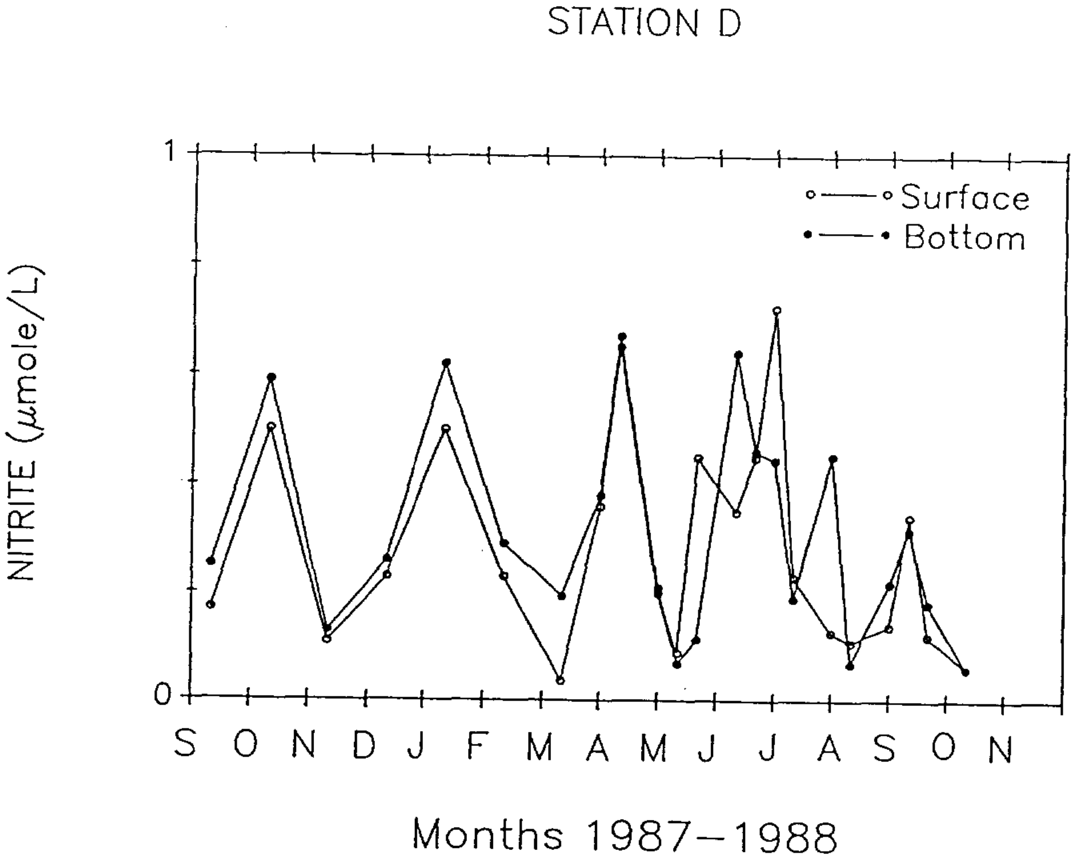


Figure 65. Nitrate measured at station C (upper) and station D (lower) during biweekly surveys from September 1987-October 1988.

in these parameters. The variability observed in these parameters is produced by both physical and biological processes but very useful information may be gained about the time response of the ecosystem to a physical change such as a weather front. All of these hourly time series measurements are detailed in the appendix in time series plots and data tables. An example will be discussed here to describe the most interesting results.

Both station C and D were located in the more uniform Corpus Christi Bay compared to stations A and B in lower salinity waters of Nueces Bay however the following examples show some of the range of diurnal variations that can occur in Corpus Christi Bay.

A set of time series measurements at station C in February 1988 exhibited a mid-day increase of temperature at the time of relatively lower salinity (Fig. 66). Nitrate concentration was very high initially in the morning but declined steadily during the next 20 hours. In contrast, silicate increased at the surface and bottom during the entire day. Chlorophyll and phaeopigments displayed an unusual simultaneous increase along with ammonium and phosphate. Closer examination to this set of measurements indicates that the wind increased about 1600 hours when small decreases in bottom temperature, salinity and nitrate were recorded while the other parameters (silicate, chlorophyll a, phaeopigments, ammonium and phosphate) displayed sharp increases. Since station C is located in relatively deep water in Corpus Christi Bay, this demonstrates the dramatic response of vertical mixing that can occur.

Hourly time series measurements at station D in July 1988 illustrates the advection of higher salinity bottom water past the study site while surface salinity did not vary. (Note: surface water could be advected also but with no salinity gradient) (Fig. 67). The high salinity bottom water which probably originated in Laguna Madre also contained elevated

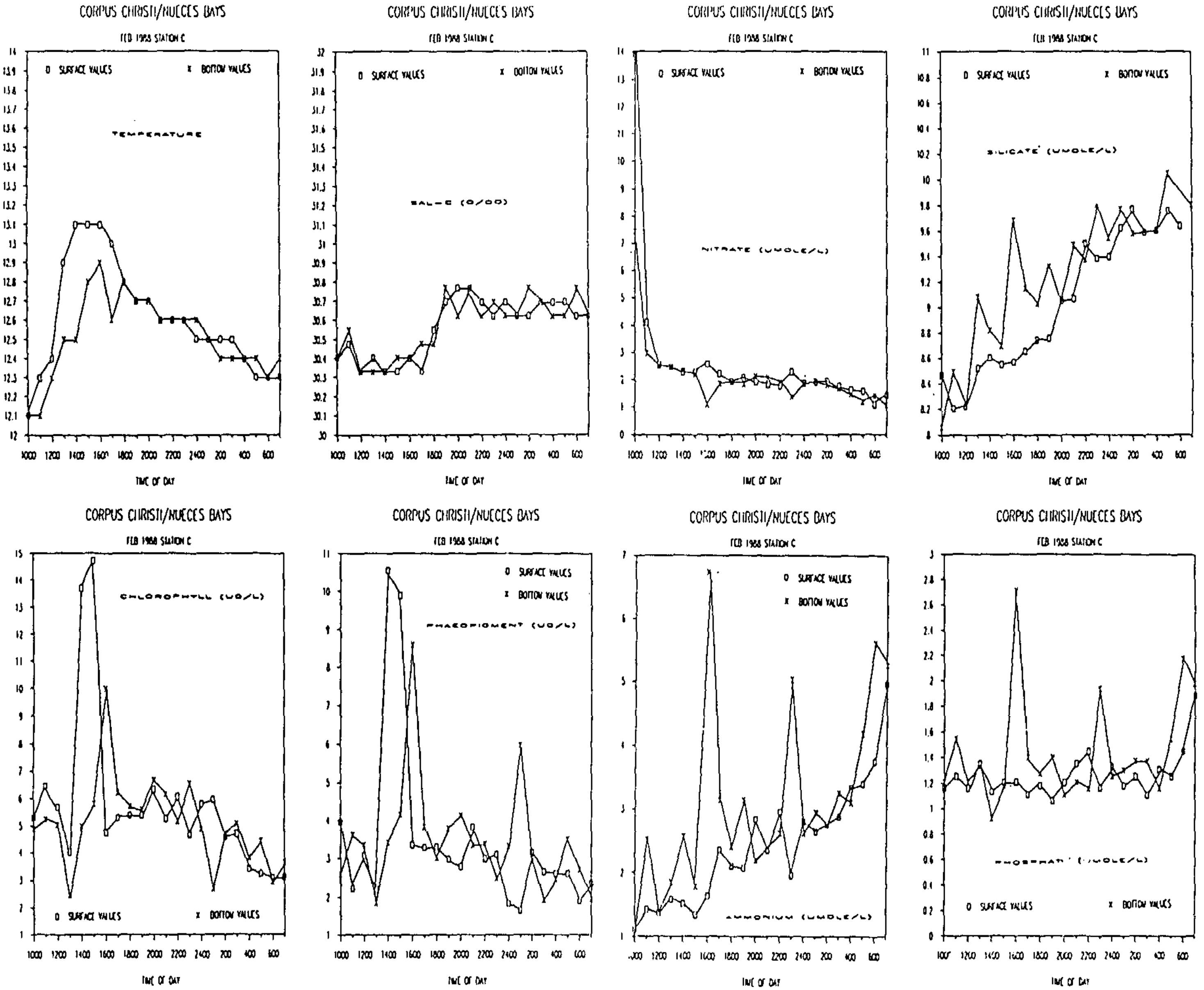


Figure 66. Hourly time series measurements of temperature, salinity, nitrate and silicate (upper) and chlorophyll, phaeopigments, ammonium and phosphate (lower) at station C in Corpus Christi Bay on 15-16 Febuary 1988.

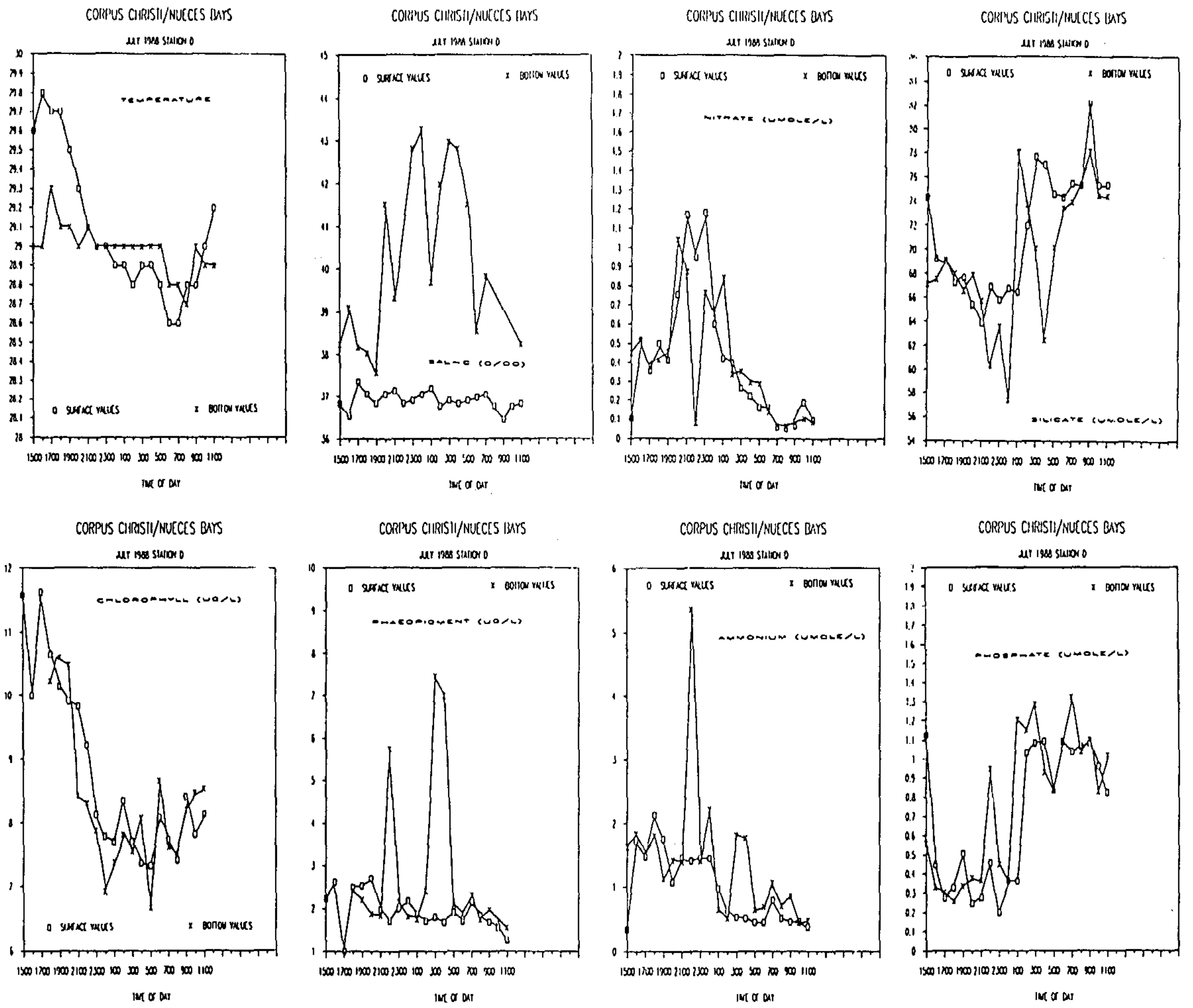


Figure 67. Hourly time series measurement of temperature, salinity, nitrate and silicate (upper) and chlorophyll, phaeopigment, ammonium and phosphate (lower) at station D in Corpus Christi Bay on 13-14 July 1988.

concentrations of nitrate (surface and bottom), phaeopigments (bottom only) and ammonium (bottom only). Chlorophyll a decreased through the sampling period while silicate and phosphate decreased mutually but then increased. The large bottom phaeopigment concentration corresponds to maximum salinity and ammonium near the bottom so this suggests that the bottom water was isolated from surface by a strong pycnocline. The advection of water past station D therefore flowed as a layer with little vertical mixing.

DISCUSSION

Nutrient Inflow

The study duration from September 1987 through August 1988 started shortly after a period of increased freshwater inflow into Nueces Bay in June 1987 (Table 14). The 35 year mean freshwater inflow was 1575 acre-ft/day and the mean for water year 1987 was 2138 acre-ft/day, an increase of 36%. The duration of the high discharge was one month (USGS Water Resource Data, Texas Water Year 1987) in contrast to San Antonio Bay which had high freshwater inflow rates for about 6 months. The total gaged inflows for 1985 and 1986 were 272,100 and 285,800 acre-ft while 1987 was 780,400 which is about a factor of three variation. The annual mean volume for the years 1941 to 1976 was 575,000 acre-ft so 1987 was substantially larger. The monthly discharge rates, especially, indicate the unusual discharge rate in June 1987 (Table 14).

There were no nutrient or chlorophyll data found in the USGS data reviewed for the Nueces River. Two river stations were sampled in this study, one located at the river mouth (station 4) and another located approximately four miles up the Nueces River

Table 14. Monthly total discharge of Nueces River (ft^3/sec) near Mathis, Texas

	1984	1985	1986	1987	1988
January		3132	3315	10005	
February		2940	2783	9663	
March		3145	3827	12958	
April		10206	4104	4312	
May		50407	3889	8746	
June		25783	3882	246120	
July		24405	5723	59514	
August		5633	5145	8305	
September		4001	4245	6425	
October	2286	40876	3789		
November	2269	57920	4236		
December	2983	8364	19397		

Water Year (Oct-Sept) Summaries	ft^3/sec	Acre-ft	Acre-ft/day	m^3/day
1985	376	272,100	745	9.19×10^5
1986	395	285,800	783	9.65×10^5
1987	1078	780,400	2138	2.64×10^6
1988				
35 year mean (1941-1976)	794	575,000	1575	1.94×10^6

From: USGS Water Resource Data, Texas, Water Year 1987 (station 4A) (Figure 37). The low flow rate of the Nueces River allowed the river mouth station to be very saline so all discussion of river parameters will utilize station 4A data only.

The oxidized forms of nitrogen (nitrate) are normally predominate in freshwater systems while more reduced forms are observed more often in estuarine and marine environments. The Nueces River has the dissolved inorganic nitrogen (DIN) about equally divided between nitrate and ammonium (Table 15) in terms of mean values for the entire year. However, winter and spring seasons had larger nitrate concentrations than ammonium and the reverse was true in the summer and early fall. The total DIN loading of the Nueces River is much smaller than the Guadalupe River because of the much smaller discharge rates and the prolonged residence time in Corpus Christi and Choke Canyon reservoirs. The yearly mean DIN concentration for the Guadalupe River was about 81 ug-at/liter while the Nueces River mean was about 19 ug-at/liter, a factor of 4 difference. The saline content of the Nueces River was often large enough to suggest that Nueces Bay or oil production waters were being mixed into the Nueces River somewhere above the sampling location. Since the flow rates of the Nueces River were small during the entire study period, only the mean conditions will be addressed in budget calculations. Seasonal effects were more prominent in the data than gaged river discharge rates. The mean nitrate plus nitrite concentration for the study period was 9.03 ug-at/liter while ammonium was 9.82 ug-at/liter. The concentration range of mean DIN for the year was about eight fold while nitrate plus nitrite was 23 and ammonium was 29. The rather uniform and low gaged flow that resulted from the low precipitation produced the rather narrow range of observed DIN concentration through the seasons.

Table 15. Dissolved nutrient concentrations (ug-at/liter) approximately 4 miles up the Nueces River from mouth[2].

Date	Nitrate plus Nitrite	Ammonium	Dissolved Inorganic Nitrogen	Chl	Phosphate	Dissolved Silicon
21 Oct 1987	8.02	3.06	11.08	73.8	10.96	150.7
20 Nov 1987	12.12	44.24	56.36	8.4	6.11	63.58
9 Dec 1987	11.67	5.72	22.41	49.0	13.40	271.3
16 Feb 1988	13.10	6.82	19.92	24.1	10.49	126.5
24 Mar 1988	12.44	1.50	13.94	15.5	4.00	77.78
13 Apr 1988	10.06	8.34	18.40	-	4.95	171.4
11 May 1988	1.89	6.25	8.14	62.8	5.88	80.04
16 June 1988	8.66	9.17	17.83	173.9	8.99	81.09
12 July 1988	6.55	6.98	13.53	111.8	3.46	96.22
11 Aug 1988	0.73	6.16	6.89	55.6	4.18	97.65
Mean	8.52	9.82	18.85	63.88	7.24	121.13

Dissolved silicon concentrations ranged from 80 to 270 ug-at/liter, a range of about 3.3 times. As with nitrate plus nitrite, silicate was at continuing low concentrations in the river during the summer which was probably governed by diatom uptake. The mean silicate value for the Nueces was 121 ug-at/liter which is 17% lower than the mean for the Guadalupe River.

Orthophosphate concentrations ranged from 3.5 to 13.4 ug-at/liter, a factor of 3.8 times. The seasonal concentration changes of phosphate occur in concert with nitrate and silicate which indicates that all three nutrients are abundant in the river water while ammonium is a produced nutrient from shorter time scale processes. The Nueces River overall phosphate mean for the entire year was 7.2 ug-at/liter, a value that is 29% smaller than the NIPS measurements in the Guadalupe River.

During the mean freshwater inflow conditions about 510 Kg N/day enters Nueces Bay from gaged flow. This compares to about 15 Kg N/day under low inflow conditions and 6700 Kg N/day under the high inflow conditions of June 1987 (Table 16). Since the gaged flow is monitored continuously, the water chemistry analyses is the weak point in this calculation of nutrient flux although other inflows like ungaged and return flows in combination with direct precipitation and their respective nutrient loads are also not well documented. The increased nitrogen inflow during June 1987 was more than 13 times the mean conditions while during low inflow conditions the introduction of nitrogen may fall to less than 10% of normal. This range of nitrogen inflow is more pronounced than that of the Guadalupe River especially under low inflow conditions and probably reflects the

Table 16. Characteristics of Nueces/Corpus Christi Bay during 1987-1988.

	Units	June 1987 High Flow	Nov. 1984 Low Flow	Mean Flow
Inflow of Nueces River	AF/D	$11.16x10^3$	$4.0x10^1$	$1.6x10^3$
Inflow of Nueces River	m^3/day	$2.7x10^7$	$4.9x10^4$	$1.94x10^6$
Residence Time (Nueces Bay)[1]	days	2.1	1124	28.4
Residence Time (Corpus Christi/Nueces Bay)[2]	days	42.5	23,408	591
Nitrate in Nueces River	ug-at/l	8.66	16.69	9.03
Nitrate Inflow	ug-at/day	$2.3x10^8$	$8.2x10^5$	$1.7x10^7$
Nitrate Inflow	kg/day	$3.27x10^3$	$1.1x10^1$	$2.4x10^2$
DIN in Nueces River	ug-at/l	17.83	22.41	18.88
DIN Inflow	ug-at/day	$4.8x10^8$	$1.1x10^6$	$1.7x10^7$
DIN Inflow	kg/day	$6.7x10^3$	$1.5x10^1$	$5.1x10^2$
DIN Outflow (Nueces Bay)	mg-at/day	$1.8x10^8$	$3.3x10^5$	$1.3x10^7$
DIN Outflow (Nueces Bay	kg/day	$2.6x10^3$	$4.6x10^0$	$1.8x10^2$
DIN Outflow (Corpus Christi/Nueces Bay)	mg-at/day	$1.4x10^8$	$2.6x10^5$	$1.0x10^7$
DIN Outflow (Corpus Christi/Nueces Bay)	kg/day	$2.0x10^3$	$3.6x10^0$	$1.42x10^2$
DIN Inflow-Outflow (Nueces Bay)	kg/day	$4.1x10^3$	$10.4x10^0$	$3.3x10^2$
DIN Inflow-Outflow (Corpus Christi/Nueces Bay)	kg/day	$4.7x10^3$	$4.6x10^0$	$3.7x10^2$
Industrial Discharge (Nueces Bay)	401 kg/day = 0.364 umole/m^2/day			
DIN Inflow Discharge-Outflow (Nueces Bay)	kg/day	$4.50x10^3$		

[1] Volume of Nueces Bay = .0551 km^3 = $5.51x10^7$ m^3 (Collier and Hedgpeth, 1950)

[2] Volume of Nueces/Corpus Christi Bay = 1.147 km^3 = $1.147x10^9$ m^3 (Armstrong, 1987)

Mean depth of Nueces Bay = 0.7m

Mean depth of Nuecs/Corpus Christi Bay = 2.4m (Armstrong, 1987) water used by the City of Corpus Christi. The major change in these conditions is not the concentration of ambient nitrogen but the actual quantity of water flowing in the river.

Bulk Nutrient Inventory

The bulk nutrient inventory increases somewhat in Nueces Bay during a year of large freshwater inflow because more nutrients are entering but low concentrations continually exit from the bay. The greatest difference therefore occurs in the central regions of the bay. During normal inflow about 510 kg N/day enters the bay while not more than 180 Kg N/day leaves Nueces Bay and 142 Kg N/day from the combined Nueces/Corpus Christi Bays. These losses were calculated from ambient nitrogen concentrations at stations 16 under the Nueces Causeway and station 27 in south central Corpus Christi Bay. The mean concentrations in the bay (Table 17) were not used in these calculations because it is felt that they didn't represent the losses. At high gaged inflow rates a net increase of 4100 Kg N/day accumulates in Nueces Bay and 4700 Kg N/day is utilized in Nueces/Corpus Christi Bays. At periods of low inflow about 10 Kg N/day and 4.6 Kg N/day are lost in Nueces and Nueces/Corpus Christi Bays. These values show the extreme lack of influence of the Nueces River alone on its related bay system. Discharges and other anthropogenic influences would completely dominate the nutrient influxes. This analysis is a first approximation because the other inputs and losses have not been considered. In the year of 1987 the increased freshwater inflow into Nueces Bay over 8 months of unusually high inflow increased the bulk nitrogen loading in the bay ecosystem by 2.4×10^4 Kg DIN which is about a 30% increase over the mean inflow estimates.

Table 17. Mean values measured in Nueces/Corpus Christi Bay during NIPS surveys, September 1987-August 1988.

Parameter	Units	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	June	July	Aug	Mean(S.D.)
Temperature	°C	25.61	23.34	17.09	19.54	12.01	14.93	19.68	19.75	26.20	28.03	29.10	29.78	22.09(5.80)
Salinity	‰	31.53	31.39	31.86	30.67	29.04	31.17	28.64	32.66	32.61	32.77	35.43	37.91	32.14 (2.54)
Nitrate	ug-at/liter	7.98	1.51	3.83	3.86	2.07	6.37	6.49	5.08	3.23	11.29	8.54	0.72	5.08 (3.16)
Nitrite	ug-at/liter	1.46	1.33	0.38	0.77	0.80	1.53	0.74	1.15	0.82	0.45	0.50	0.27	0.85 (0.43)
Ammonium	ug-at/liter	4.37	2.29	4.14	12.35	7.08	3.03	2.95	4.46	6.45	9.42	16.11	1.67	6.19 (4.41)
DIN	ug-at/lite	13.81	5.13	8.35	16.98	9.95	10.93	10.18	10.69	10.50	21.16	25.15	2.66	12.12 (6.36)
Phosphate	ug-at/liter	0.58	2.32	1.16	2.68	2.03	4.62	2.02	2.25	1.28	1.31	1.84	1.73	1.99(1.01)
Silicate	ug-at/liter	21.11	52.78	16.77	60.84	10.49	21.85	25.25	40.61	28.68	49.89	54.50	75.27	38.17(20.34)
Chlorophyll	ug/liter	5.31	10.16	7.82	5.26	8.40	7.66	5.96	6.27	10.26	12.31	11.25	9.66	8.36 (2.38)
Phaeopigments	ug/liter	4.36	5.37	2.95	1.85	3.20	7.64	5.37	2.06	5.12	3.40	6.00	2.83	4.18 (1.75)
Secchi depth	m	0.70	0.60	0.77	1.18	0.76	0.77	0.58	0.80	0.70	0.85	0.51	0.62	0.74 (0.17)

Atmospheric Nitrogen Input

The direct precipitation falling directly on the bay contains a variety of substances including nitrogen nutrients in both oxidized and reduced forms such as nitrate and ammonium. Precipitation data were obtained from Victoria, Beeville and Attwater Prairie Chicken, Texas from the National Atmospheric Deposition Program and several rainwater samples were collected from the meteorological station at the Marine Science Institute and analyzed for nutrient content (Table 5). The quantity of various constituents varies a great deal for unknown reasons. It is known that periodic sampling during a precipitation event will show a decline in concentration of most constituents with time. These samples are composites of the entire event but the duration of collection obviously varied with the particular storm or time between storms. It is possible that the concentrations observed in the composite samples are somewhat related to the amount of precipitation and the origin or direction of the storm. Dry deposition is an additional input but there is currently no known data for the region.

The concentrations of ammonium and nitrate were very similar from all three collection sites at Victoria, Beeville and Attwater Prairie Chicken with mean values ranging from 8.8 to 12.7 and 10.9 to 12.9 ug-at/liter respectively. The total DIN averaged from 19.7 to 25.7 ug-at/liter. The quantities of nitrate and ammonium in rainwater at Port Aransas were similar over the duration of collection in 1988-1989 but were much larger than the other reporting stations. The differences may be due to sample contamination to this data was not used in subsequent flux calculations.. Nitrite concentrations were very small so the resulting DIN for rain was found to be 99./9 ug-at/liter of rainfall. Orthophosphate and silicate had mean concentrations of 3.6 and 2.9 ug-at/liter in the rainwater. The only nearby source of these nutrients would be sea spray.

Using an average rainfall for the Nueces/Corpus Christi region of about 29.2 inches of rainfall/year (equivalent to 74.2 cm/yr) (Armstrong,1987), the direct annual addition totals about $5.8x10^7$ m^3 and $3.3x10^8$ m^3 of rainfall in Nueces and Nueces/Corpus Christi Bays respectively. The annual DIN of the rainwater represents $1.9x10^4$ Kg N for Nueces Bay and $1.1x10^5$ Kg N for the combined Nueces/Corpus Christi Bay. For comparison, the Nueces River has a mean input of $5.1x10^2$ Kg N/day so the Nueces Bay rainfall alone amounts to 9.3 percent of the DIN introduced by gaged inflow and direct precipitation. When the larger area of Nueces/Corpus Christi is considered, 37 percent of the total is derived from direct precipitation. During a wet year the percentage will remain high because the direct precipitation and gaged inflow are both caused by the same rainfall since the watershed is rather small and dams are used to store some of the water.

Ergoclines (Fronts and Pycnoclines)

The presence of interfaces between different water types either in horizontal or vertical directions and the water-benthic interface are locations where biological and physical processes are often enhanced and therefore increased production can occur (Legendre, 1986). The increased physical mixing that occurs at a discontinuity has the units of work hence the term ergocline arises. Although no specific measurements were targeted toward surface fronts, the gradient of nitrate in Nueces Bay generally corresponded with relative distributions of surface salinity, turbidity (Secchi depth) and chlorophyll *a* concentrations. The presence of a front indicates that very little physical mixing is occurring across the frontal zone but several recent investigations have found lateral transport in opposite directions (shear) along a frontal zone. These differential flows create small scale turbulence and thus lateral mixing. A phytoplankton cell at the frontal interface can therefore be mixed with small amounts of water along or across a front and as a result be located at the boundary of sufficient nutrients and available light.

The freshwater gradient throughout the Nueces estuary was small due to the lack of rainfall. The gradients were most pronounced in Nueces Bay however they were still smaller than San Antonio Bay. The salinity gradients ranged from 0.04 to 0.94 ‰/km except for November 1987 when a gradient of 2.12 ‰/km was observed (Table 18). This November gradient was equivalent to San Antonio Bay in July 1988. Nitrate concentrations across the fronts ranged from negligible to 1.04 μg-at/liter/km. Only three values were greater than 0.5 μg-at/liter/km and those were February, March and June 1988 from the upper reaches to middle Nueces Bay. The chlorophyll gradients were maximal in January and February 1988 with values of 1.25 and 1.34 μg/liter/km. Other chlorophyll gradients ranged from 0.02 to 0.58 μg/liter/km. These strong chlorophyll gradients occurred at the time when integrated chlorophyll concentrations started to rise for the spring bloom (see Stockwell report).

It should be mentioned here that even though small scale gradients in Nueces/Corpus Christi Bay were not especially strong, the gradients over the entire system were often pronounced, for example, surface salinity differences of greater than 12 ‰ in November 1987 and surface nitrate differences of greater than 20 μg-at/liter in April 1988. These differences were not associated with frontal processes but they represented a significant gradient across the estuary system.

Table 18. Small scale surface gradients of salinity, nitrate and chlorophyll in Nueces Bay, Texas.

Date	Distance km	Salinity ‰/km	Nitrate umole/l/km	Chlorophyll ug/liter/km	Locations Compared
Sept. 1987	11.1	0.56	0.001	0.22	Sta. 16-7
Oct. 1987	13.7	0.74	0.02	0.23	Sta. 16-5
Nov. 1987	11.8	2.12	0.30	0.58	Sta. 16-4
Dec. 1987	14.4	0.41	0.002	0.02	Sta. 16-3
Jan. 1988	11.8	0.94	0.34	1.34	Sta. 13-3
Feb. 1988	10.4	0.55	0.97	1.25	Sta. 11-2
Mar. 1988	9.1	0.43	0.58	0.02	Sta. 11-3
Apr. 1988	10.4	0.12	0.06	0.42	Sta. 11-2
May 1988	15.2	0.19	0.17	0.51	Sta. 16-1
June 1988	12.4	0.04	1.04	0.15	Sta. 13-1
July 1988	7.6	0.38	0.43	0.72	Sta. 16-8
Aug. 1988	9.6	0.38	0.14	0.14	Sta. 11-1

Observations that could be related to vertical stratification and pycnoclines were collected with a high precision CTD during May, June and July 1988. The data tables and figures (see Amos' report) show the lack of vertical structure on most stations without regard to depth with some exceptions. Most notable was station 29 at the Kennedy Causeway in upper Laguna Madre. Vertical salinity gradients between surface and bottom waters of 3.5 ‰ and sigma-t differences of 3 provide insight on the exchange of water between these two bay systems. Other examples are scattered throughout the 3 months of data. The processes relevant to vertical stratification were not sampled well but on a few stations some interesting features were observed (e.g. the surface maximum in light transmission between 7 and 10m depth on station 26 in the July 1988 survey which was accompanied by a small but perceptible decrease in temperature).

Temporal Variability

The long term temporal variations show the seasonal and/or annual cycle of processes and help define the range limits on the ecosystem over the time scale of weeks or months (Table 19). It is tempting to consider the variability for the year long record as "normal" but without similar records from other years no certainty could be proclaimed. The 3 months previous to data collection contained a freshwater inflow event that was distinctly shown by the Nueces Bay hydrosonde (Figure 44). Since no surveys occurred before September 1987 the extent of the effects of freshwater inflow are not directly known however some differences in the September 1987 and September 1988 samples will be discussed in relation to possible effects.

Table 19. Range of values for parameters measured in Nueces/Corpus Christi Bay surveys September 1987-August 1988.

Parameters	Units	Max.	Min.	Range
Temperature	°C	31.67	11.0	20.67
Salinity	‰	48.67	7.1	41.57
Nitrate	µg-at/liter	32.24	0	32.24
Nitrite	µg-at/liter	7.80	0.01	7.79
Ammonium	µg-at/liter	86.13	0.18	85.95
Phosphate	µg-at/liter	22.86	0.01	22.85
Silicate	µg-at/liter	271.3	0.25	271.05
Chlorophyll *a*	ug/liter	173.9	0.4	173.5
Phaeopigments	ug/liter	60.9	0.22	60.68
Secchi depth	m	2.2	0.08	2.12

Water temperatures at stations A and B in 1987 were about 5°C cooler than September 1988 but this same effect was observed at stations C and D so it is most likely a general trend for the entire area. Salinity values for stations A and B were about 12 and 8 ‰ lower respectively in September 1987 compared to September 1988 but the September values at stations C and D were the same both years. In concert with the salinity changes, nitrate concentrations were 4 and 6 μg-at/liter higher respectively in September 1987 at stations A and B and chlorophyll concentrations (October) were likewise higher by 5-10 μg/liter. Unfortunately stations C and D changed with respect to nitrate between the two years so a precise analysis would be unjustified. The continuity of possible freshwater effects continues with ammonium and nitrite at stations A and B to give the entire range of variables circumstantially supporting the idea. Other factors related to the nitrogen cycle confuses the picture in Corpus Christi Bay proper.

The short term variability was assessed on the four experimental sites principally to place station data in the context of diel changes that were occurring. The range of variations differed markedly with the parameters in different seasons. The examples shown in Figures 54, 55, 66 and 67 were some of the most well behaved and yet demonstrated a trend of change. Space and time are closely coupled in small scale features, so a successful mathematical model of a bay ecosystem would need to simulate these scales and incorporate them into a large scale version.

The relative amount of short term variability was rather small in Nueces/Corpus Christi Bay due to the lack of strong surface gradients. The diel changes observed were mainly related to cycles of wind, and incident radiation. Strong biological signals were not apparent compared to physical processes. The change of phaeopigments resuspended by the winds were larger than changes in the chlorophyll *a*. Stations B exhibited some stronger variations of parameters than station A, an observation that has no clear explanation. All parameters, especially salinity, seemed to change more at the surface and bottom on station B in July 1988. The salinity increase was proceeded at a very uniform rate unlike some of the nutrient parameters. The short term changes at station C were small foremost of the parameters but plant pigments and ammonium had some large variations. Station D sampled different water types in July 1988 so that surface samples represented Corpus Christi Bay water while bottom water was from Laguna Madre.

Circulation and Conservative Properties

The subject of circulation will not be exhaustively treated here but more details can be obtained from the Amos report (Component 9). In general, current meters were placed at three locations to follow the year long circulation at Aransas Pass, the Nueces Bay entrance channel and the Kennedy Causeway channel. Using these Eulerian measurements, it was determined that (1) the net flow each month was Gulfward from the Corpus Christi and/or Aransas Bays with a monthly mean ranging from 100 to 470 m^3/sec for August 1988 through February 1989. (2) The net flow was out of Nueces Bay into Corpus Christi Bay with a monthly mean that ranged from 1 to 20 m^3/sec for July 1988 through February 1989. And (3) the net flow for 6 out of 8 months was out of Corpus Christi Bay into Laguna Madre with a monthly mean rate ranging from 2 to 9 m^3/sec for August through February with the exception of July and November 1988 when the mean flow was 1-2 m^3/sec into Corpus Christi Bay. Extrapolation of these Eulerian measurements indicates that Aransas Bay is probably responsible for much of the water going out through Aransas Pass while the water leaving Nueces Bay may be a combination of Nueces River and surface water (sheet flow) from Corpus Christi Bay.

The general distribution of salinity in Nueces Bay has a gradient that would be compatible with flow out of Nueces Bay and the south shoreline salinity was usually lower than the north and/or east. The relatively high salinity water (except June-August) could have a source in Laguna Madre and/or Aransas Pass. Higher salinities from Laguna Madre were almost always observed in the south part of the bay. The ship channel did not dominate the distribution of salinity in Corpus Christi Bay. Evidence of flow through the center of Corpus Christi Bay to the northwest and a northern and southern shoreline return flows were not observed.

Nutrient Uptake Processes

Nutrients are utilized in the water column by both autotrophic and heterotrophic processes. Experiments were performed by two groups in an effort to better quantify the amount of nitrogen used by microbiological and phytoplankton populations. The details of the microbiological investigation are discussed in Nitrogen Cycling and Bacterial Production by Drs. Benner and Yoon (Component 7) and the Carbon Productivity of Phytoplankton by Dr. Stockwell (Component 2).

The particulate nitrogen (PN) and particulate carbon (PC) concentrations at stations A, C and D were determined in May 1988 when primary production was reasonably high (Table 20). The mean PN and PC concentrations were larger at stations C and D in Corpus Christi Bay than at station A in Nueces Bay. The PC/PN ratio was the same for all three locations so the increased particulate concentrations were possibly related to the

Table 20. Phytoplankton nitrogen and carbon composition at stations A, C and D in Nueces/Corpus Christi Bay.

Station	Date	PN(ug-at/liter)	PC(ug-at/liter)	PC/PN (at/at)
A	10 May 1988	7.87	46.2	5.87
A	10 May 1988	1.59	9.9	6.23
A	10 May 1988	9.23	100.9	10.93
A	10 May 1988	1.67	10.2	6.11
A	10 May 1988	7.56	71.8	9.50
A	10 May 1988	6.82	67.5	9.90
A	10 May 1988	4.45	82.7	18.58
Mean (S.D.)		5.60 (3.07)	55.60 (35.19)	9.59(4.47)
C	9 May 1988	6.98	79.0	11.32
C	9 May 1988	4.07	50.2	12.33
C	9 May 1988	6.20	64.4	10.39
C	9 May 1988	14.28	72.0	5.04
Mean (S.D.)		7.88 (4.44)	66.40 (12.34)	9.77 (3.25)
D	12 May 1988	15.2	62.8	4.13
D	12 May 1988	1.12	11.4	10.18
D	12 May 1988	2.57	27.4	10.66
D	12 May 1988	8.98	80.7	8.99
D	12 May 1988	6.45	42.1	6.53
D	12 May 1988	10.01	93.6	9.35
D	12 May 1988	12.45	106.3	8.54
D	12 May 1988	5.14	53.2	10.35
D	12 May 1988	9.53	105.9	11.11
D	12 May 1988	7.95	81.3	10.23
Mean (S.D.)		7.94 (4.30)	66.47 (32.73)	9.01 (2.16)

relatively large amounts of ammonium at the time in Corpus Christi Bay. The PN and PC concentrations at station A in San Antonio Bay were about two times those in Nueces/Corpus Christi Bays while the PC/PN ratios were about the same.

The ^{14}C-primary production measurements at the four experimental sites for each of the five experimental sampling trips were converted to nitrogen uptake using a PC/PN ratio for phytoplankton. While this is a first approximation of actual nitrogen uptake, this procedure has produced relatively good results compared to direct measurements of carbon and nitrogen uptake (Whitledge, Reeburgh and Walsh, 1986). The range of carbon primary productivity was 105 to 6015 mg C/m^2/day with an overall mean of 1225 mg C/m^2/day (Table 21). When converted to nitrogen productivity, the range was 1.26 to 71.92 mg-at/m^2/day with an overall mean of 14.65 mg-at/m^2/day. These values represent estimated total nitrogen uptake therefore all inorganic nitrogen (nitrate, nitrite and ammonium) and organic nitrogen (urea and amino acids) uptakes are included but no specific nitrogen species uptake rates are available.

The primary production measurements during a slow growth period (December 1987) compared to a relatively fast growth period (July 1988) indicates more than 5.8 times slower carbon uptake rate but only a factor of 3 higher chlorophyll biomass (Table 22). The calculated December nitrogen uptake was 5.7 mg-at/m^2/day which is a typical rate for a bay or continental shelf station. The July nitrogen uptake rate of 33.5 mg-at/m^2/day was very large, the chlorophyll biomass was high and the ammonium concentrations in the bay at that time were extremely high (15-40 μg-at/liter) (Figure 43). The carbon productivity was found to be 93-96 % in the nanoplankton size class (< 20 μ) which tend to thrive in high ammonium environments (Stockwell, Component 2).

Table 21. Phytoplankton productivity estimates for experimental sites in Nueces/Corpus Christi Bays for October 1987-July 1988.

Station	Date	^{14}C Production mg C/m^2/day	Calculated N Production mg-at/m^2/day
A	20 Oct 1987	105	1.26
A	8 Dec 1987	260	3.11
A	12 Apr 1988	998	11.93
A	10 May 1988	840	10.04
A	12 July 1988	455	5.44
B	21 Oct 1987	629	7.52
B	9 Dec 1987	198	2.37
B	13 Apr 1988	823	9.84
B	11 May 1988	2357	28.18
B	11 July 1988	702	8.39
C	19 Oct 1987	335	4.01
C	7 Dec 1987	1068	12.77
C	11 Apr 1988	632	7.56
C	9 May 1988	1436	17.17
C	13 Jul 1988	6015	71.92
D	22 Oct 1987	1379	16.49
D	19 Dec 1987	382	4.57
D	14 Apr 1988	484	5.79
D	12 May 1988	1345	16.08
D	13 Jul 1988	4053	48.46
Mean (S.D.)		1225 (1443)	14.65 (17.25)

Table 22. Phytoplankton productivity estimates for December 1987 and July 1988 in Nueces/Corpus Christi Bay.

	^{14}C Prod (mgC/m^2/day)		Chl (mg/m^2)		Calculated[1] N Prod. (mg-at/m^2/day)	
Sta	Dec 1987	July 1988	Dec 1987	July 1988	Dec 1987	July 1988
A	260	455	3.2	9.2	3.11	5.44
B	198	702	5.5	10.7	2.37	8.39
C	1068	6015	13.6	33.0	12.77	71.92
D	382	4053	4.7	27.9	4.57	48.46
Mean	477	2806	6.75	20.20	5.71	33.55

[1] Calculated using a C/N of 6.97 for Redfield *et al.* (1963)

The loss of ^{15}N-labeled specific uptake velocities (μg-at N uptake/μg-at PN/time) does not allow for a direct comparison of nitrate and ammonium uptake by the phytoplankton. If the uptake constants of nitrate and ammonium are assumed to be equal then an approximation of the uptake rates can be calculated from the observed relative nitrogen concentrations and the primary production rates (Table 23). This is a reasonable approach because Benner and Yoon found that ammonium uptake was strongly correlated with ammonium concentrations in both San Antonio and Nueces/Corpus Christi estuaries. The calculated ammonium uptakes are much larger than nitrate for all stations in the two time periods, December 1987 and July 1988. This is in contrast to San Antonio Bay where nitrate was more important than ammonium.

The calculated ammonium uptake values are lower than the direct ammonium uptake rates by Benner and Yoon for stations A and B where they measured 6.52 and 7.04 mg-at/m^2/day. But the calculated rates of ammonium uptake are higher than the measurements at stations C and D (12.18 and 4.95 μg-at/m^2/day). The phytoplankton were not so heavily dominated by nanoplankton at station B so a change in species composition may be partially responsible for these differences.

The ammonium utilization by size classes clearly demonstrate that the small size organisms are very important. As much as 85% of ammonium uptake was driven by organism less than 20 μmeter in size and 18% was less than 1.5 μmeter. The nanoplankton are clearly very important during the summer period but the seasonal changes are not known.

Table 23. Ambient nitrogen concentrations and calculated nitrate and ammonium uptake by phytoplankton in Nueces/Corpus Christi Bay.

Date	Station	Nitrate	Ammonium	Nitrate Fraction	PNO_3	PNH_4
Dec 1987	A	3.39	11.35	23	0.7	2.4
	B	3.53	9.27	28	0.7	1.7
	C	2.68	25.74	9	1.1	11.6
	D	2.81	11.27	20	0.9	3.7
	Mean	3.10	14.41	20.0	0.85	4.85
July 1988	A	4.01	13.58	23	1.2	4.2
	B	10.11	11.83	46	3.9	4.5
	C	7.48	13.88	35	25.2	46.7
	D	10.98	18.96	37	17.9	30.5
	Mean	8.14	14.56	35.2	12.05	21.47
Units		g-at/ltr	g-at/ltr	%	mg-at/m^2/day	mg-at/m^2/day

Nutrient Regeneration in the Water Column and Sediments

The regeneration of nitrogen in the water column and from the sediments in the Nueces estuary is described by Benner and Yoon for the summer period of 1988. They found ammonium regeneration rates were 3.9 fold higher in bottom water than in surface and the ammonium utilization rates were higher in bottom water than in surface water for all stations. When water column uptake and production of ammonium are combined with the benthic flux of ammonium, a range of 0.74 to 5.68 mg-at/m^2/day was regenerated. In general, the actual and benthic ammonium flux decreased with distance from the river mouth, while the importance of water column ammonium regeneration increased in deeper water or distance away from the river. The sum of these regeneration rates in the water column and from the sediment also increases with the distance away from the river (7.72 to 10.69 mg-at/m^2/day) which is probably a result of the deeper water. Station A in Nueces Bay does not exactly fit into the above pattern but its location was not ideal in terms of proximity to the river mouth. The final location of station A was determined by accessibility to research vessels. It is worth noting that ammonium utilization in the Nueces estuary was 83-114% of the total ammonium regeneration so the two processes were very close to a balance at the time of the measurements.

Ammonium regeneration in the water column is strongly associated with the small size classes of organisms. About 77% of ammonium regeneration was attributed to organisms less than 20 μmeter which included 22% from the less than 1.5 μmeter size. Both the utilization and regeneration processes need to be studied during the winter and spring seasons to determine if the small organisms are dominant the entire year.

A review of concentrations in Nueces/Corpus Christi Bay for the 12 month period of September 1987 through August 1988 shows the importance of ammonium to the ecosystem. The winter period of February and March had mean concentrations of 3 µg-at/liter for April through July (Table 17). Nitrite did not show the progression of increasing mean concentrations which is a noted difference compared to San Antonio Bay. The appearance of only ammonium indicates that regeneration was the major process for its production. The greater water depth of Corpus Christi compared to San Antonio Bay contributed to enhanced water column regeneration rates per unit area. The observed increase of 13.11 µg-at/liter of ammonium throughout the Nueces/Corpus Christi Bay was equivalent to $2.1\text{x}10^5$ KgN which was equal to the DIN mean inflow from the Nueces River for 413 day. The higher inflow rate measured during June 1987 would introduce that quantity of nitrogen in 31 days. In any event, storage of nitrogen must be occurring somewhere in the ecosystem because freshwater inflow was not introducing that quantity of nitrogen. If an excess of only 0.109 µg-at/liter/day are produced in the water column or released by the sediments, then the observed concentrations of ammonium would result.

Nitrification, Denitrification and Nitrogen Fixation

The process of nitrogen fixation introduces new nitrogen into an estuarine ecosystem while nitrification and denitrification transform nitrogen species for subsequent uptake or even loss from the ecosystem. Benner and Yoon reported that denitrification was occurring at 4.0 to 71.1 ug-at/m^2/hr (0.10 to 1.71 mg-at/m^2/day) with a general inverse relationship with salinity since upper estuary stations had higher denitrification rates than lower estuary stations. The nitrification rates measured were 17.2 to 140.2 ug-at/m^2/hr (0.41 to 3.36 mg-at/m^2/day) with the highest rates in Nueces Bay. This finding is in contrast to San Antonio Bay results but agrees with Billen (1975) who reported maximum nitrification rates at low salinities (2 ‰) and Elkins *et al.* (1981) who observed successive peaks of ammonium, nitrite and nitrate going downstream in the Potomac River.

The appearance of increasing DIN during the summer months (June and July) after staying constant in the spring (January through May) strongly suggests that significant amounts of nitrification and denitrification are occurring in Nueces/Corpus Christi Bay. Nitrite was not observed in high concentrations but a nitrification rate of more than 3 mg-at/m^2/day implies that substrate is being produced without a buildup of the intermediate, nitrite. For comparison purposes, nitrification rates of 0.7 to 2.4 μg-at/liter/day in Chesapeake Bay and 0.24 to 0.96 μg-at/liter/day for the York River have been reported by McCarthy *et al.* (1983). Benner and Yoon summarized denitrification rates for 14 estuaries that bracketed the measurements in San Antonio and Nueces/Corpus Christi Bays. The denitrification in Narragansett Bay utilize 35% of the organic matter (Seitzinger, 1982) and the rate in Fourleague Bay, a shallow bay in Louisiana, was 6.9 to 8.5 μg-at/m^2/hr (0.17 to 0.20 mg-at/m^2/day) which readily confirms that denitrification is a process which must be included when constructing a budget for the shallow bays on the Gulf Coast.

Nitrogen fixation was not measured in the study so no local data are available for conclusions, however most nitrogen fixation occurs where there is a dearth of available nitrogen in the water column. Most of the known data on nitrogen fixation concerns tidal fresh waters with blue-green algae and there are no known measurements to show that nitrogen fixation is of any consequence in estuarine waters (Nixon and Pilson, 1983).

The Nueces/Corpus Christi Bay Model

The utility of a model is to draw all of the principal elements together in such a way to increase the quantitative understanding of the ecosystem, to bring attention to those components where more work is necessary, and to help design a better field program and experimental plan to continue the focus on the most critical elements and then spatial and temporal variations.

The work in the Nitrogen Processes Study (NIPS) has been directed at a better understanding of the Nueces/Corpus Christi Bay ecosystem with respect to the quantity of freshwater inflow and subsequent changes in it biological populations (Figures 68-70). The conceptual model that was developed at the initiation of the NIPS program has been modified for the actual measurements and calculations. These new data have been combined with historical data, where appropriate, to produce an enhanced model for nitrogen processes that conforms to the Conclusions in the following section.

The conceptual model for the mean annual condition in Nueces/Corpus Christi Bay (Fig. 68) utilizes a broad range of measurements collected over a year long sampling program. The biomasses are depicted within each box and have units of μg-at/liter. The external input sources (e.g. river concentrations) are also in units of μg-at/liter. The fluxes between biomasses designated by arrows represent the process rates within the ecosystem and have units of μg-at/liter/day. The only exception to the preceding units occurs with macrophytes and seagrasses which have biomass units of mg-at/m^2 and likewise mg-at/m^2/day for production rates. A description of the biomass and flux calculations for Fig. 68 is presented in Table 24.

The ecosystem model for the mean conditions in Nueces/Corpus Christi Bay represents the simplistic results obtained during the 1987-1988 sampling period (Fig. 68). The Nueces/Corpus Christi Bay ecosystem is much more complicated than the simple diagram infers but some interesting bits of information can be observed.

Under mean conditions only very small amounts of nutrients are brought into the Nueces/Corpus Christi estuary. The predominate form of nitrogen entering the bay is ammonium which along with nitrate provide nitrogen for phytoplankton uptake. The importance of ammonium rather than nitrate is in contrast to San Antonio Bay where nitrate is much more important. The fact that the Nueces River has no natural flow, i.e. it has two dams and released water is its only flow, causes the lakes above the dam to be the receiving waters to the detriment of the downstream estuary. Nueces Bay proper is often quite saline as a result of the small inflow, high temperatures and wind which enhance evaporation. The net effect is that the bay has reduced process rates that are normally enhanced with reduced salinity. A loss of nitrogen by denitrification amounts to about 6% of the water column nitrate per day while nitrification may produce about 12% per day. This nitrification rate is about 50-70% of the rate in upper San Antonio Bay where salinities are lower. The daily uptake of nitrate and ammonium by phytoplankton amounts to about 68% of the DIN pool and the daily ammonium regeneration rate contributes 55 percent of the ammonium pool. These data indicate that the production of regenerated nitrogen is about 30% of the San Antonio rates and the resulting phytoplankton biomass is about 50% lower. It is interesting that the regenerated nitrogen supplies only 62% of the ammonium uptake by phytoplankton. Regeneration is very important to maintaining primary production processes in Nueces and Corpus Christi Bay but the direct effects of low riverine

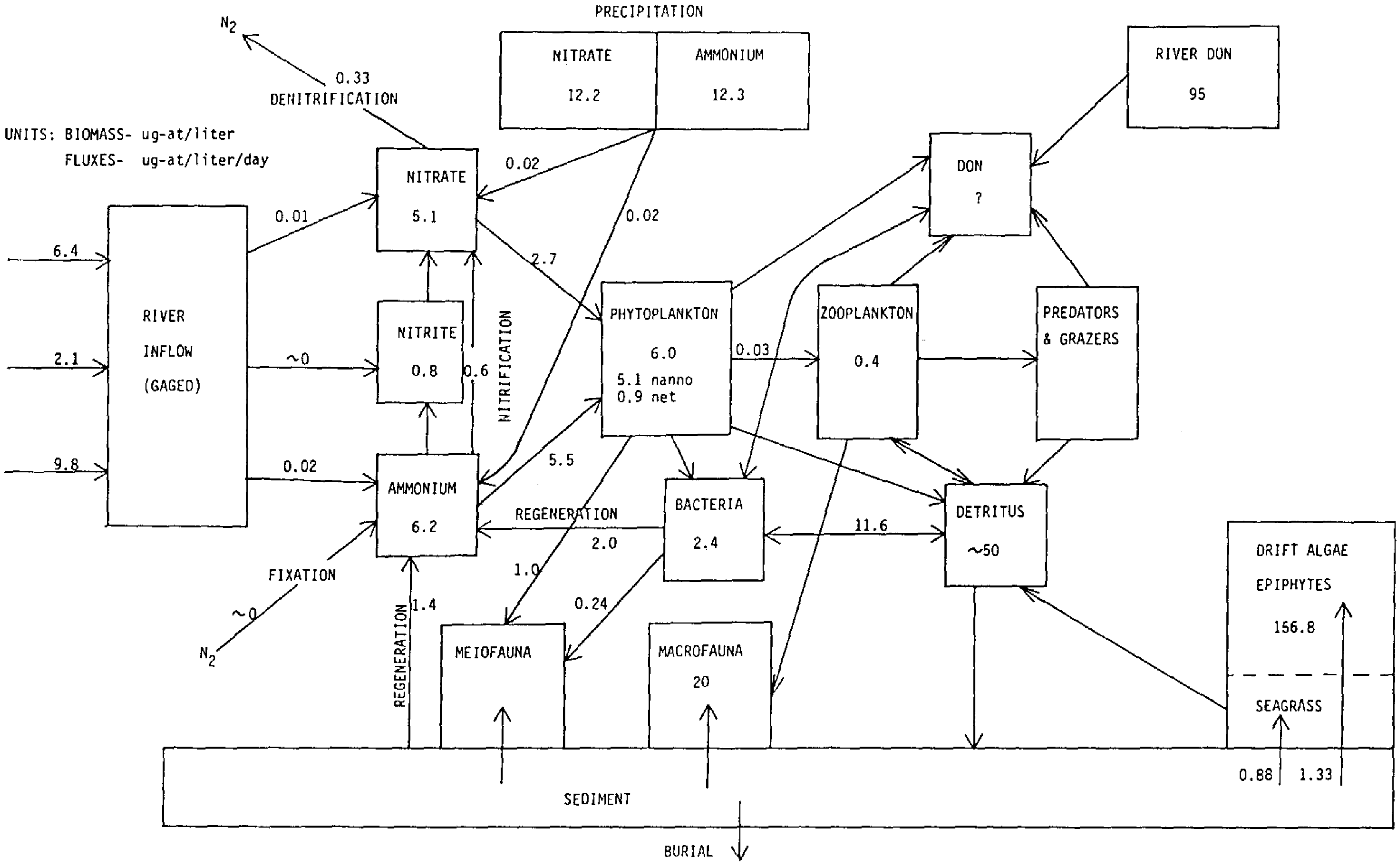


Figure 68. Ecosystem model of Nueces/Corpus Christi bay during mean annual conditions.

Table 24. Ecosystem Model Data Calculations for High Freshwater Inflow Conditions in Nueces/Corpus Christi Bay.

Biomasses

River Nitrate from data tables 6.42 μg-at/liter
River Nitrite from data tables 21.3 μg-at/liter
River Ammonium Table 15 9.82 μg-at/liter
Atmospheric Nitrate Table 5 mean of Victoria = 12.2 μg-at/liter
Atmospheric Ammonium Table 5 mean of Victoria = 12.3 μg-at/liter
River DON USGS Water Year 1983 mean at Three Rivers = 95 μg-at/liter
Bay Nitrate Table 17 mean 5.1 μg-at/liter
Bay Nitrite Table 17 mean 0.8 μg-at/liter
Bay Ammonium Table 17 mean 6.2 μg-at/liter
Phytoplankton Table 17 mean chl = 8.36 μg/liter using C/Chl = 50 and C/N = 5 then PN = 5.97 μg-at/liter
Zooplankton Buskey mean = 60 mg dw/m^3 at A-D using 10% N then 0.43 μg-at/l of N
Bacteria Benner mean biomass = 221 mg C/m^2 using C/N = 5 then 2.43 μg-at/liter if 1.3 m deep
Macrophytes Dunton-seagrass shoots = 35.9 and roots = 108.5 g dw/m^2; seagrass is 38% and C/N = 25 (Wolff, 1980) then shoots = 38.9 and roots = 118 for a total of 156 mg-at/m^2
Predators
Macrofauna Montagna p. 40 mean biomass = 2.77 g dw/m^2 = 280 mg N/m^2 = 20 μg-at/liter
Detritus Assume 75% of all imports to detritus is standing stock = 50 μg-at

Fluxes

Nitrate → Uptake Table 23 mean of year = 6.45 mg-at/m^2/day ÷ 2.4 m = 2.69 μg-at/liter/day
Ammonium Uptake Table 23 mean of year = 13.16 mg-at/m^2/day ÷ 2.4 m = 5.48 μg-at/liter/day
Nitrogen Fixation - See Nixon and Pilson, 1983, pp. 596 = 0
Denitrification - Benner - Table 2 mean = 33.35 μmole/m^2/hr = 0.8 mg-at/m^2/day ÷ 0.33 μg-at/liter/day
Nitrification - Benner - Table 4 mean = 59.35 μmole/m^2/hr = 1.42 mg-at/m^2/day ÷ 2.4 m = 0.59 μg-at/liter/day
Zooplankton Grazing - Buskey mean zooplankton grazing = 0.465 mg N/m^3/day = 0.033 μg-at/liter/day
Actual Benthic Regeneration - Benner - Table 1 mean = 3.35 mg-at/m^2/day ÷ 2.4 m = 1.4 μg-at-at/liter/day
Bacterial Production - Benner - Table 8 mean = 34 μg C/liter/hr (C:N = 5) then 11.6 μg-at/liter/day

Table 24. Continued

Water Column Regeneration - Benner - Table 2 mean = 4.83 mg-at/m^2/day ÷ 2.4 m = 2.01 μg-at/liter/day
Bacteria → Meiofauna - Montagna p.33 0.0099 x 24 = 0.24 μg-at/liter/day
Phytoplankton → Meiofauna - Montagna p.33 0.0411 x 24 = 0.986 μg-at/liter/day
Seagrass Production - Dunton 4.5 g N/m^2/yr over 30,985 m^2 = 0.88 mg-at/m^2/day
Total Macrophyte Production - Dunton 151 g C/m^2/yr and assume C/N = 26 = 1.33 mg-at/m^2/day
Nitrate in rainfall - Table 5 12 mg-at/m^3 x .742 = 8.90 mg-at/m^3/yr = 0.02 ug-at/liter/day
Ammonia in rainfall - Table 5 12 mg-at/m^3 x .742 = 8.90 mg-at/m^3/yr = 0.02 ug-at/liter/day
Nitrate Inflow (1.94 x 10^6 m^3/day) (6.42 mg-at/m^3/1.15 x 10^9 m^3 = 0.011 ug-at/liter/day
Nitrite Inflow (1.94 x 10^6 m^3/day) (2.13 mg-at/m^3)/1.15 x 10^9 m^3 = 0.004 ug-at/liter/day
Ammonium Inflow (1.94 x 10^6 m^3/day) (9.82 ug-at/m^3)/1.15 x 10^9 m^3 = 0.017 ug-at/liter/day

nitrogen inputs is seen by the lack of new nitrogen which provides the "fuel" to initiate the processes. It is noteworthy that both benthic and water column rates are reduced. The detrital decomposition processes for the water column and benthic processes cannot be separated with the data from this study but the deeper water column increases the importance to the water column processes. There is some suggestion from the data that the detrital decomposition processes are more important in Nueces/Corpus Christi Bay compared to San Antonio Bay.

During the winter which has historically been the time of low freshwater inflow in addition to low seasonal rates, the nitrogen based ecosystem model for Nueces/Corpus Christi Bay does not change very much (Fig. 69). Since the river flow was already very small, a change to low flow conditions is not a big change. The nitrate concentrations in the bay at this time are lower while ammonium are higher compared to the mean conditions which is somewhat puzzling. The daily nitrogen regeneration accounted for 115 percent of the ammonium uptake by phytoplankton so uptake has been reduced by the lower biomass and other conditions to maintain a balance with available nutrients. The bacterial biomass and decomposition rates are about 10-20 percent of their mean values.

During the late spring or summer conditions (Fig. 70) the freshwater inflow can be enhanced by the seasonal precipitation. About 15 times as much nitrogen can enter the bay compared to the mean but these conditions are still quite different compared to an unmanaged river/estuarine system such as San Antonio Bay. The regeneration processes in the Nueces/Corpus Christi Bay are producing about 63 percent of the ammonium utilization by primary producers which reflects the five fold increase of bacterial consumption of organic matter or detritus. The nitrification rates are about an order of

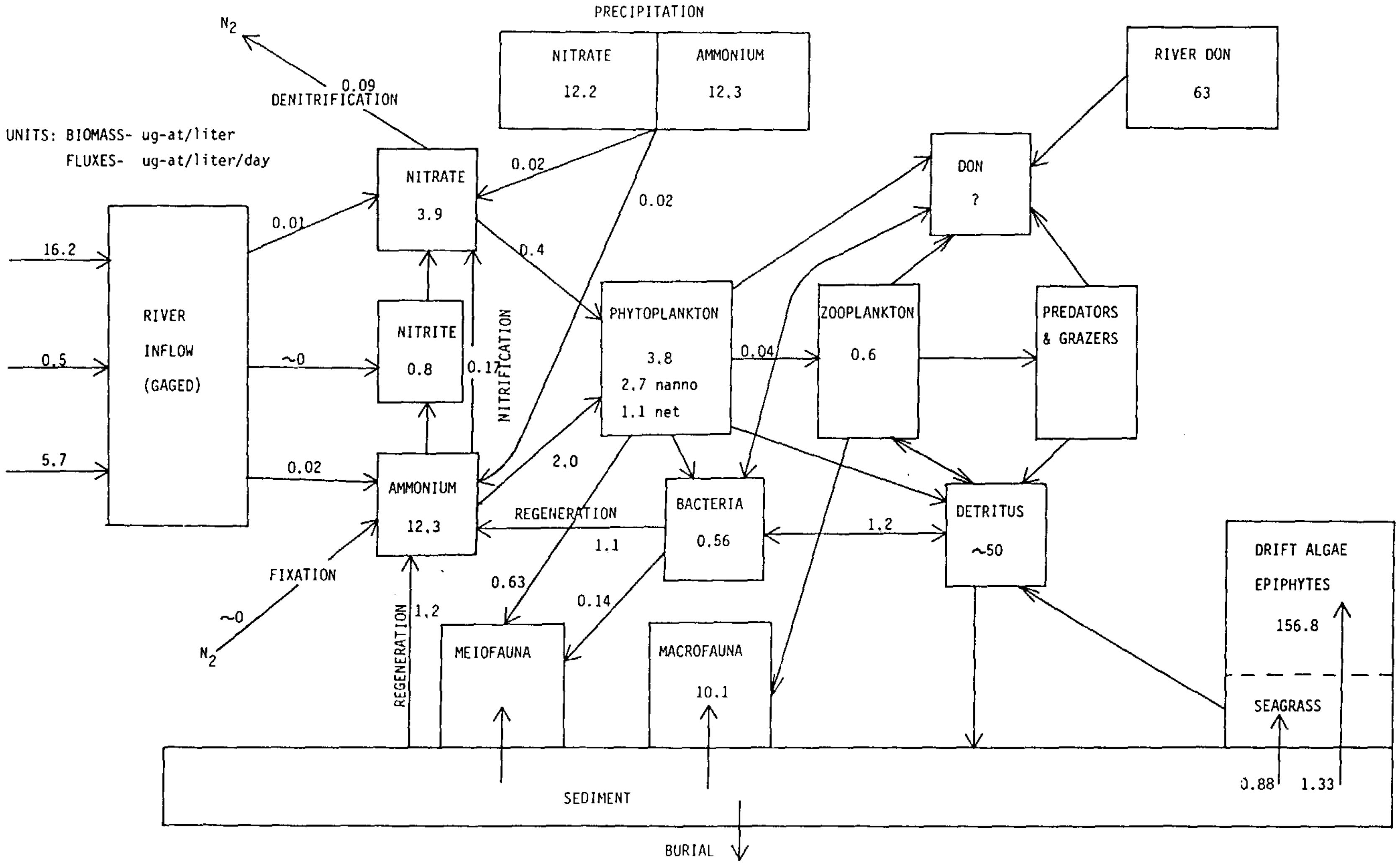


Figure 69. Ecosystem model of Nueces/Corpus Christi bay during winter.

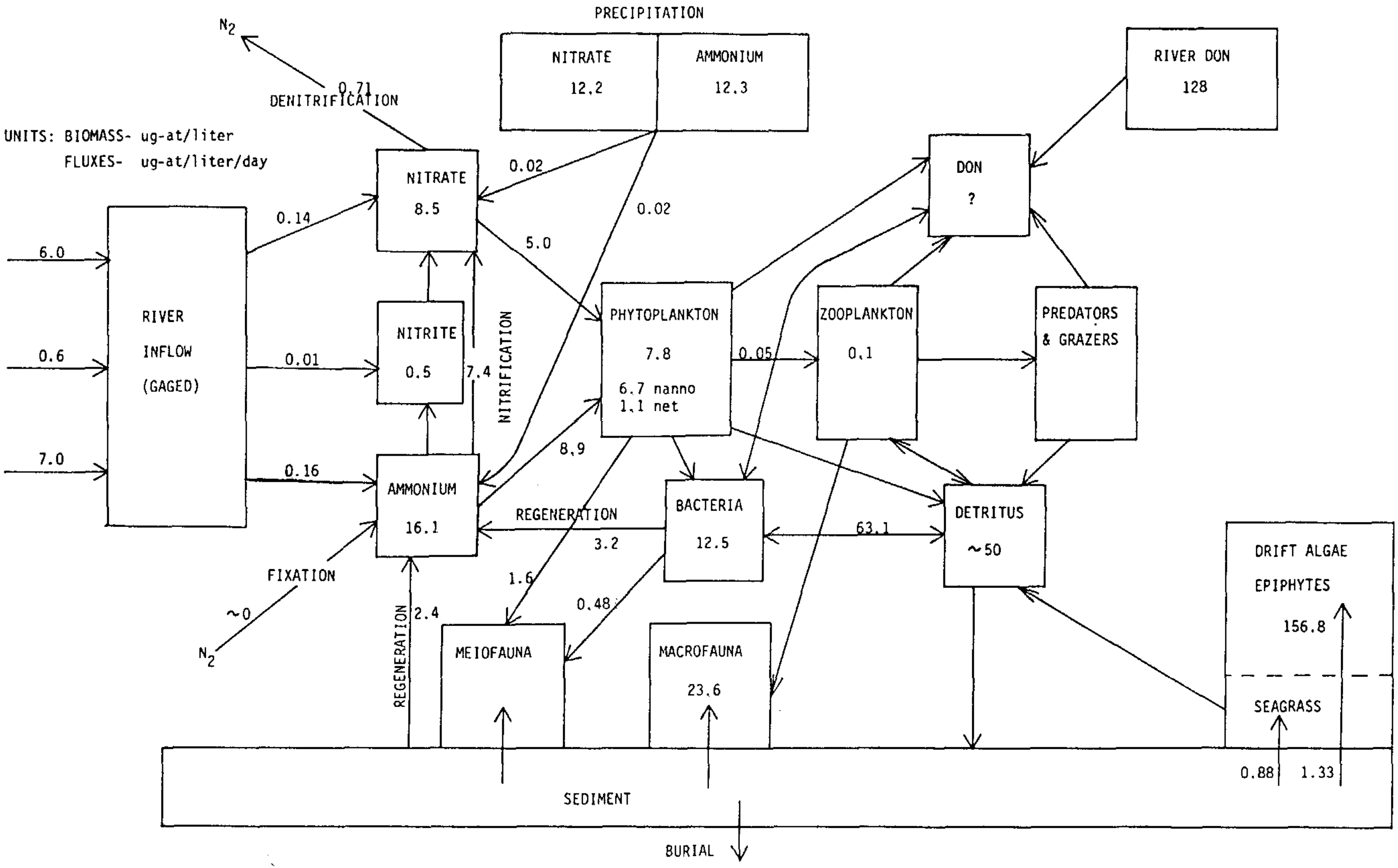


Figure 70. Ecosystem model of Nueces/Corpus Christi bay during summer.

magnitude larger than winter or mean annual conditions which conforms to the very large nitrate concentrations observed in the bay in June 1988 (Fig. 40).

CONCLUSIONS

The inflow of the Nueces River into Nueces Bay has only a small effect, if any, since there is no clear salinity gradient down the bay. The Nueces River is heavily managed by dams on the upper reaches so mean flow data from the past have very little meaning. The quantity of freshwater inflow during low rainfall periods may be reduced by water extraction for domestic purposes. The relatively high freshwater inflow period in June 1987 did decrease salinity to less than 1 ‰ for more than a month. The long term effects from this increased inflow were possibly observed in the low salinity and higher nitrate and chlorophyll in September 1987 compared to a year later. The products of more nutrient inflow and higher primary production could have been stored in the sediments and subsequently enhanced secondary processes like regeneration and grazing.

If Corpus Christi Bay is added to Nueces Bay for a combined unit, then the direct effects of Nueces River inflow becomes much less significant. The combined estuary has a much greater area and volume so both the storage capacity of the sediments and the relative contribution of water column processes are greatly enhanced.

The nutrients supporting primary production are plentiful on the average with an annual mean of 5.1, 0.9, 6.2, 2.0 and 12.1 μg-at/liter for nitrate, nitrite, ammonium, phosphate and silicate (Table 17). The minimum concentrations observed for these parameters however are all at 0.25 μg-at/liter or below (Table 7) so nutrient reduction could decrease primary production rates in small areas or for a short time. The mean conditions are a much better indicator of the general nutrient conditions in the Nueces/Corpus Christi Bay. The lack of significant freshwater inflow reduces the importance of imported nitrate compared to San Antonio Bay and the gradients of nitrate in the bay system are not nearly as evident. Other direct inputs such as precipitation has a larger impact as a result of the small freshwater inflow with as much as 71% of the total DIN resulting from rainfall.

The mean annual concentration of DIN amounts to 12.1 μg-at/liter and the monthly mean never falls below 2.7 μg-at/liter. Minimum mean values of phosphate and silicate are 0.6 and 10.5 μg-at/liter so the Nueces/Corpus Christi estuary is not a nutrient limited system in the classic sense. The utilization rates of nitrogen are large but decomposition and regeneration are also large which produces a very dynamic ecosystem.

The importance of nitrate as a nitrogen nutrient is relatively small in Nueces/Corpus Christi Bay compared to San Antonio Bay. The nitrate fraction of nitrogen uptake ranged from 9 to 37 percent during winter and summer calculations (Table 14) and probably represents a maximum range because ammonium uptake constants are usually larger than nitrate (Dugdale, 1976; MacIsaac and Dugdale, 1969). Nitrate uptake was apparently most significant during the summer period when nitrification would be maximum. Many studies of nitrogen uptake in the marine environment have shown nitrate to be more sensitive to the amount of ambient light than ammonium. Either a reduction of daylight hours or increased turbidity therefore favors ammonium uptake in a marine system. The turbidity factor could be a factor in the Nueces/Corpus Christi estuary however the vertical mixing is also large so a shallow bay could continually circulate the plankton population through the lighted zone. At this time no known experimental technique has been devised to study these possible small scale mixing and autotrophic processes.

Turbidity from the Nueces River was not a significant process so wind resuspension was the only effect. The data needed to accurately determine the relationship between wind and turbidity have not been collected. The Secchi depth readings are very reliable but there are so many variables like wind speed, wind direction, sediment type, length of fetch, water depth and water circulation patterns that a simple wind speed versus Secchi depth plot does not produce any significant relationship.

The relationship of nitrate to salinity was examined for conservative behavior but biological processes were always dominant throughout the year. Many estuaries display a conservative behavior in the low salinity region (e.g. Delaware Bay) but only small regions in upper Nueces Bay ever reached 20 ‰ or below.

The most direct evidence of the relationship of nutrient concentrations or fluxes from the sediment by resuspension comes from the stirred benthic chambers. There was a clear increase in the ammonium concentrations as the stirring and water flow increased (Montagna's report). The concentration of phaeopigments also increased in the bays during windy periods. The most difficult processes to document in the bay studies were often related to winds which were always changing. The diurnal sea breeze didn't maintain a schedule or a steady range of velocities. The almost continual change in the winds shouldn't be dismissed because the biological population (especially plankton hardly ever have enough time to stabilize between the daily and event frequency of winds. A closer examination of the meteorological data in combination with the continuous *in situ* light measurements will be made in the future.

The circulation processes in Nueces/Corpus Christi Bay are dominated by the tides in Aransas Pass and the Nueces Bay Channel however the Kennedy Causeway Channel is affected by wind driven currents (Amos' Report). The salinity and nutrient distributions did indicate that outflow from Nueces Bay tended to flow along the south shoreline in most months and higher salinity water from Laguna Madre or the Gulf of Mexico were often distributed along the east and north shorelines. About the only vertical structure in the water column was observed in upper Laguna Madre.

The influx of freshwater into Nueces/Corpus Christi Bay in June 1987 increased the nitrogen content by about 18% compared to a normal inflow year. With only that small increase the primary production would not likely show a dramatic increase. The in situ salinity sensor on the Hydrosonde in mid Corpus Christi Bay did not show a significant change in salinity during the inflow event so the nitrogen and related productivity should not either. The effects in the smaller volume of Nueces Bay were clearly registered by the salinity sensor on the Hydrosonde but only the remnant portions of nitrate or chlorophyll from that event were observed. Given the nitrification and denitrification measurements of Benner and Yoon, the additional nitrogen for the June 1987 inflow probably increased denitrification and nitrification rates rather than going entirely through primary production. It is very possible that the large inflow events don't enhance primary productivity in a linear fashion with nutrient increases because the other transformation processes of the microbiological populations are also competing for the nitrogen.

The long term effect of freshwater inflow were not observed in Nueces/Corpus Christi Bay but the only storage capacity resides in either the sediments or biological populations. Actually both of these categories are the only memory devices in an open system. The nutrient properties associated with a larger biomass of organism or enhanced sediment organic matter would be larger regeneration fluxes and microbiological rates of decomposition. The appearance of large concentrations of nitrate and ammonium during mid summer in Corpus Christi Bay is a possible example of how organic matter could be accumulated in the sediment and then quickly metabolized when conditions are optimum.

The interaction of nutrients with primary production, regeneration and transformation processes in Nueces/Corpus Christi Bay is complex with several competing processes occurring simultaneously. The production of chlorophyll is well correlated with nitrate concentrations at stations A and B during March and February but ammonium is more closely related during May to July. The deeper waters at station C has chlorophyll well correlated to nitrate in June and early July but ammonium is better correlated by late July. The chlorophyll at station D has a slow increase but the largest change in late July corresponds to a decrease in ammonium. The relationship of nutrients and primary productivity follow the pattern of shallow water uptake of nitrate initially and switch to ammonium a while later. Likewise nitrate uptake by phytoplankton migrates from the shallow Nueces Bay to open Corpus Christi Bay and is followed by ammonium uptake as decomposition and transformation processes increase.

Regeneration processes consume organic matter and produce ammonium. At stations A and B there are five distinct ammonium peaks that are correlated in time but station B concentrations are smaller. The five peaks may be related to wind mixing and resuspension events in the shallow water. High ammonium concentrations were observed on all stations A-D during December through February. During May and June only stations A and B had high ammonium but in July all stations A-D had high concentrations. During September 1988 only stations A and B had ammonium peaks. The oscillation of ammonium are not entirely understood but most of the ammonium is being produced during the warm season of the year and the periodic increases may be due to input of fresh organic material and a resuspension event to distribute the material throughout the water column.

Transformations of nitrogen usually have nitrite as an intermediate product. The frequency of nitrite peaks in the water column were quite consistent with maxima in September, January, April and September on all stations A-D. An additional nitrite peak occurred in June only on station C and D. The cyclic behavior of nitrite cannot be explained at this time but measurements of nitrification and denitrification throughout an annual cycle would help clarify the interactions of microbiological processes.

Significant Findings

1. Nitrogen utilized by primary production processes is predominately in the form of ammonium for the Nueces/Corpus Christi estuary.
2. The lack of freshwater inflow into Nueces Bay increases the relative importance of DIN in rainfall to the point that the mean amount of precipitation produces 71% of imported nitrogen.
3. Primary production is the same as San Antonio Bay but nanoplankton ($< 20\ \mu$meter) are the dominant organisms during much of the annual cycle. Nanoplankton typically dominate ecosystems where large concentrations of ammonium are observed.
4. Nueces/Corpus Christi Bay has mean concentrations of nutrients that will always provide adequate quantities to support phytoplankton growth. Light limitation on growth would be a result of wind resuspension of sediment since freshwater inflow does not carry a significant sediment load.

5. Resuspension event caused by wind mixing produce ammonium enrichment of the water column.
6. There is not a strong coupling of nutrient concentrations to physical circulation patterns in Nueces/Corpus Christi Bay. No evidence of Gulf of Mexico water was ever observed in Corpus Christi Bay. Some subtle distribution patterns suggest that Nueces Bay waters transit along the west and south shorelines of Corpus Christi Bay.
7. The influx of new nitrogen from the June 1987 freshwater influx increased the nitrogen content in Nueces/Corpus Christi Bay by 18% but no demonstrated increase in primary production was observed. There was a suggestion in the data that increased nitrate and chlorophyll concentrations existed in Nueces Bay during September 1987.
8. The benthic production of ammonium decreases with distance from the river mouth.
9. The water column production of ammonium increased with water depth and distance away from the river.
10. Nitrification was occurring in the sediments and decreased with distance away from the river.
11. Denitrification processes decreased with distance from the river.

FUTURE WORK NEEDED

After the completion of a study and the analysis of data is underway, it is a good time to assess the deficiencies, recognize the oversights and contemplate new or additional measurements. The following general research questions arose during the analysis phase of the present study and are not listed in any order of priority.

1. General Circulation - The basis for understanding an estuarine ecosystem requires knowing the physical flow of water throughout the system. The circulation of Corpus Christi Bay has been studied especially in reference to tidal transport in the ship channel and the Gulf Intracoastal Waterway but a definitive set of observations have not been obtained. A series of shoreline and mid-bay current meter observations are especially needed to define water movements under both southeast and northern winds.
2. Dissolved Organic Nitrogen - Significant amounts of dissolved organic nitrogen enters the Nueces/Corpus Christi Bay either from the Nueces River or discharged by the municipal sewage plants in Oso Bay. The significance of this organic nitrogen source is unknown but it could nourish the microbiological degradation processes. Bacterial and phytoplankton utilization studies should be directed at defining the pathway of DON utilization by both of these ecosystem components.
3. Stock Assessments - One of the most significant data gaps for the Nueces/Corpus Christi Bay is the lack of knowledge of biomass and production of micronekton (shrimp), nekton (finfish) and shellfish (oysters). There is a perception that populations of some organisms are increasing and others are decreasing but the lack of good data is very apparent. This NIPS project has increased our knowledge of bacteria, phytoplankton and zooplankton a great deal, but the linkage to secondary consumers is not complete.
4. Discharges - An initial attempt was made to locate data for permitted discharges into the Nueces/Corpus Christi estuary. This information is especially significant because

the Nueces River is not really a river and the return flows of domesticly used water is placed in Oso Bay so discharges and ungaged local runoff are the only inflows.

CHAPTER III

COMPARISONS OF LAVACA, SAN ANTONIO, NUECES/CORPUS CHRISTI AND OTHER U.S. ESTUARIES

INTRODUCTION

The funded study of three South Texas bay/estuary ecosystems provides relatively unique sets of data that allow interbay comparisons. The methods used in collecting samples, analytical procedures and data synthesis were similar because many of the personnel, instrumentation and techniques were used throughout the studies over the four year period. However changes were made to more tightly focus the experimental plan around the relationship of nitrogen in freshwater inflow to productivity in the bay ecosystems. As a result, the role of nitrogen introduced into the estuaries by freshwater inflow can be more closely compared to estuarine productivity and decomposition processes than in the past. There is also the recent opportunity to begin to compare characteristics of South Texas estuaries with a few other estuarine ecosystems in the Gulf of Mexico Western, Southeast and Northeast regions of the U.S. Several estuarine ecosystem components and their associated processes are amenable to such comparisons.

NITROGEN INPUT

A definitive investigation of nitrogen inputs into U.S. estuarine systems has not been accomplished because there are many direct and indirect potential sources of nutrients which can vary markedly over time. Nevertheless many estuaries have had quantitative assessments of their nutrient loading (Nixon and Pilson, 1983; Boynton *et al.*, 1982; Whitledge, 1985; Armstrong, 1987; NOAA, 1985; NOAA 1989). The overview of these compilations shows a large range of nutrient loading conditions ranging from a low of 10 for Long Island Sound to a high of about 4500 mmole DIN/m^3/yr with an approximate uniform density of estuaries distributed over that range (Fig. 71). The calculated nitrogen loading values for the estuaries in this study were 21.3 for Nueces/Corpus Christi, 208 for Lavaca, and 318 mmole DIN/m^3/yr for San Antonio Bay respectively. These loading estimates are quite sensitive to the actual physiography of the Bay (e.g. areal extent, mean depth) in addition to inflows, discharge and precipitation rates. In fact, there is such a wide range of these various controlling factors for nutrient loading that the concept of a generic bay is not presently realistic, however it is apparent that freshwater inflow is an important source of nutrients in many estuaries (Copeland, 1966). No attempt will be made to describe the changes that have occurred in the various loading factors because the data bases are not very numerous. However some comprehensive studies have detailed the nutrient content of atmospheric precipitation as NO_3 = 12.5, NO_2 = 0.36, NH_4 = 16.1, DON - 16.1, PO_4 = 0.16 and total dissolved phosphorus = 0.31 μg-at/liter (Meybeck, 1982). Total dissolved phosphorus and nitrogen in rivers have increased by a factor of two and in Western Europe and North America by factors of 10 to 50 (Maybeck, 1982). These increases were found to be directly proportional to the watershed population and to its energy consumption.

Phytoplankton biomass is not an easy parameter to measure so chlorophyll or elemental determinations are often used as approximations. The chlorophyll or other pigments are usually the preferred choice because detritus can be a substantial error in particulate elemental analyses. There are variations in chlorophyll content of phytoplankton cells that render this measurement a crude approximation but even the most sophisticated or detailed techniques (e.g. cell counts, particle counts, DNA, RNA, enzyme activities) have strict limitations.

One interesting technique of comparing phytoplankton biomass in estuaries has been the construction of diagrams to show the relationship of nutrient loading and chlorophyll concentrations. Enough data exists for upward of 50 to 60 estuaries to look for trends or groupings (Fig. 71). The trend of data indicates that phytoplankton chlorophyll concentrations increase in the central portions of most estuaries as DIN nutrient inputs become larger. The annual mean chlorophyll concentration may be either smaller or larger than the summer mean concentrations but both sets of values show a similar increasing trend. The annual maximum chlorophyll concentrations also increase with higher DIN loading but the response appears to be curvilinear with increasingly larger increments as loading becomes larger. So the total range of chlorophyll concentrations increases with larger DIN loading.

Chlorophyll values for Nueces/CorpusChristi, Nueces, Lavaca and San Antonio Bays correspond nicely with DIN input data from other U.S. estuaries. Nueces/Corpus Christi Bay is in the low range of DIN loading and chlorophyll biomass with Long Island Sound and Kaneoke Bay. Nueces Bay by itself falls into the middle range of estuaries along with Lavaca and San Antonio Bays. These bays are grouped with Apalachicola, South San Francisco, Pamlico, Barataria and Mobile Bays. The South Texas bays are therefore grouped in the midst of several well known eutrophic bays because of a special reason. The South Texas bays are all very shallow which make the surface area to volume ratio quite small thus there is less water to dilute the nutrient inflows and the shallow water is conducive to thorough mixing and resuspension of benthic constituents.

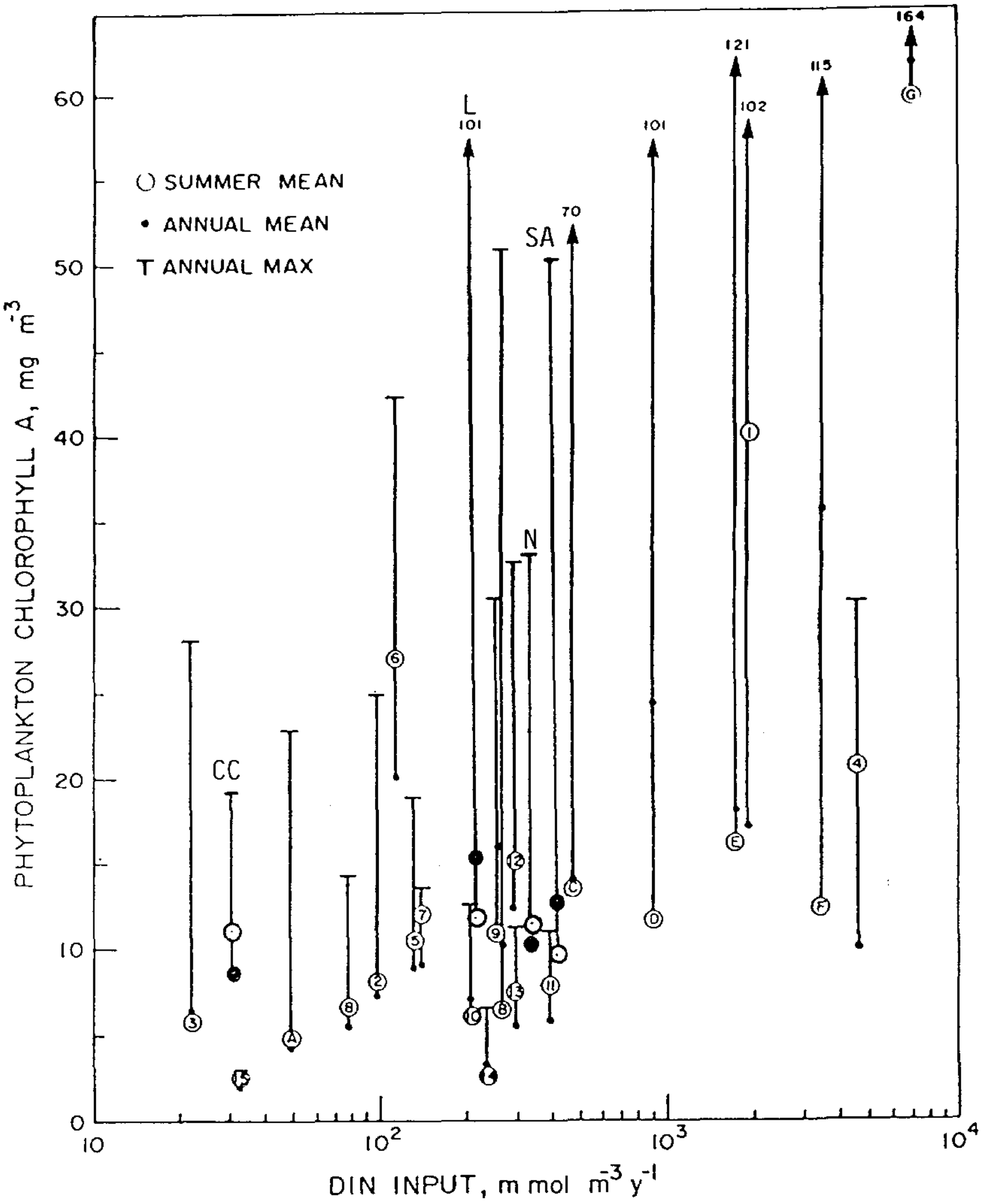


Figure 71. Concentrations of phytoplankton chlorophyll a in the mid-regions of various estuaries (1-15) and in the MERL tanks (A-G) as a function of dissolved inorganic nitrogen input. (1) Providence River; (2) Naragansett Bay; (3) Long Island Sound; (4) Lower New York Bay; (5) Delaware Bay; (6) Patuxent River; (7) Potomac River; (8) Chesapeake Bay; (9) Pamlico River; (10) Apalachicola Bay; (11) Mobile Bay; (12) Barataria Bay; (13) N. San Francisco Bay; (14) S. San Francisco Bay; (15) Kaneohe Bay; (CC) Corpus Christi Bay; (L) Lavaca Bay; (N) Nueces Bay; (SA) San Antonio Bay (after Nixon and Pilson, 1983).

The range of phytoplankton production in 45 national and international estuaries grouped into four categories of river dominated, embayments, lagoons (shallow) and fjords demonstrates the wide range of observed values. The mean primary production rates in each South Texas estuary corresponds to a cluster of other estuaries (Fig. 72). The range of primary production rates for the South Texas estuaries is quite large. The rationale for these large rates may be the shallow estuarine depths which resuspend phytoplankton and nutrients from the bottom thereby sustaining relatively continuous high production rates.

The primary production of phytoplankton also is influenced by the DIN input into estuaries. The direct relationship of increased primary production with greater nitrogen input is apparent (Fig. 73). Nueces/Corpus Christi Bay has a nitrogen loading that is relatively low but primary production rates are relatively high and more closely related to other Gulf of Mexico bays including the others in South Texas. All of these loading and primary production rates are much lower than the highly eutrophic Lower New York Bay.

RECYCLING AND REGENERATION PROCESSES

The importance of recycling and regeneration of nutrients in South Texas estuaries cannot be overstated. The inflow of freshwater delivers nutrients into the estuarine ecosystems but those nutrients are utilized many times as a result of recycling processes. Some losses of nutrients occur due to advection, denitrification, burial, and harvest but these losses are only about 10 percent of annual primary production and recycling processes in an estuarine embayment (Table 25) such as Naragansett Bay. When combined, all of the recycling processes contribute 36 percent of the primary production nitrogen requirements in Naragansett Bay but the actual amount is more correctly close to 50

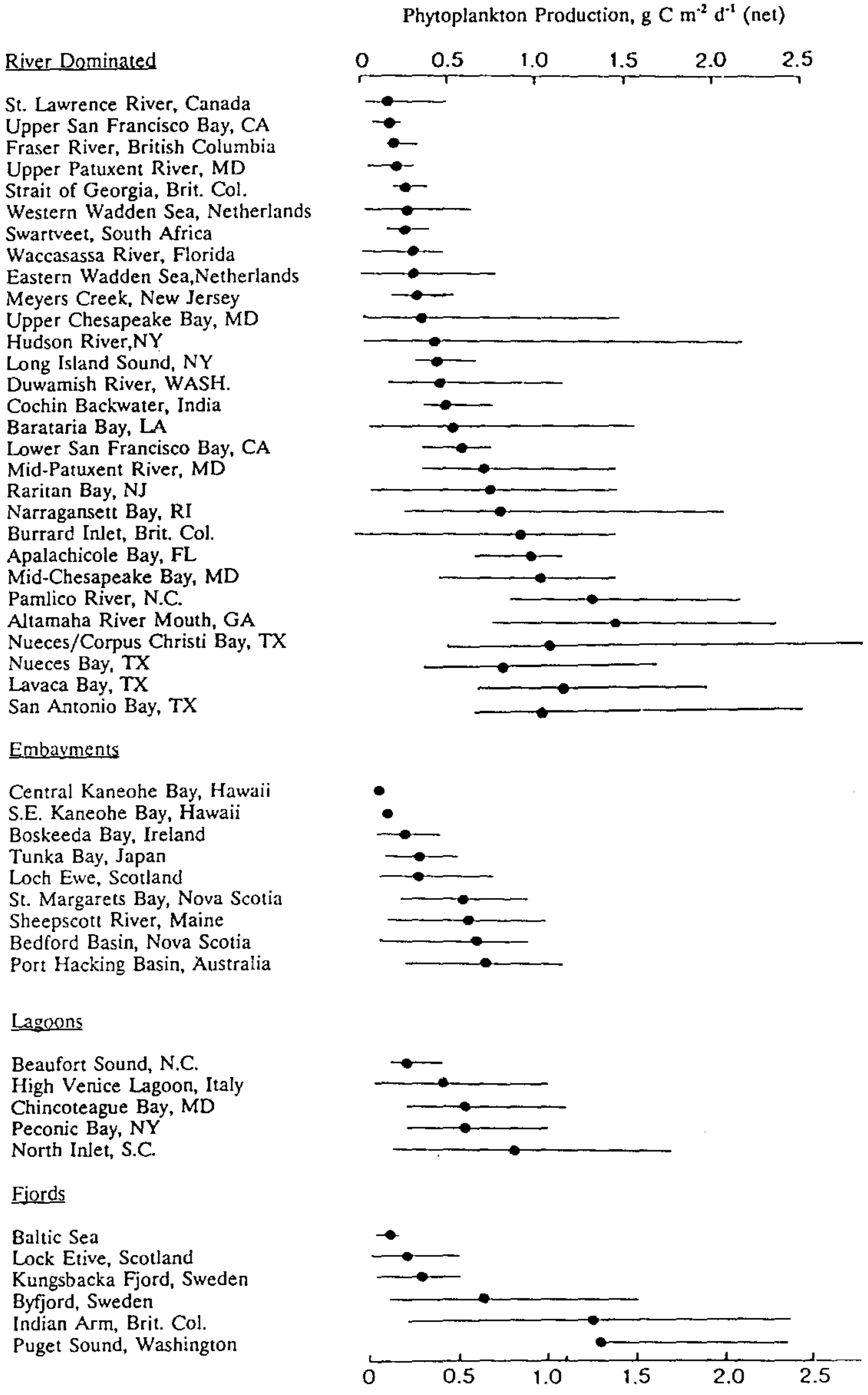


Figure 72. Summary of average daily phytoplankton production rates (●) in 49 estuarine systems. Horizontal bars represent annual ranges. (after Boynton et al, 1982).

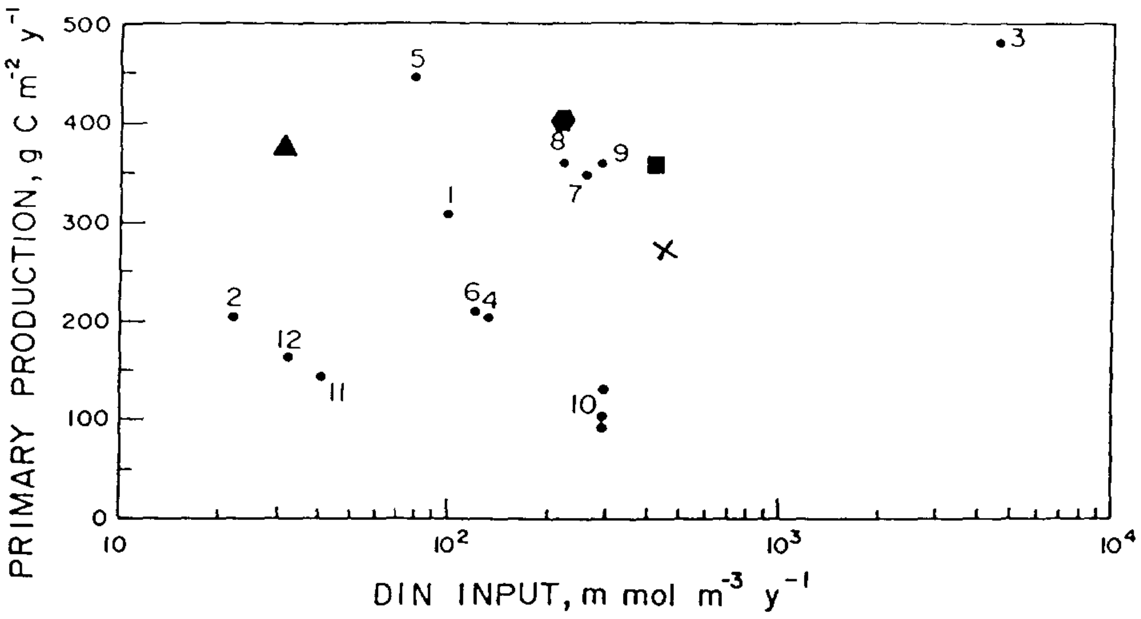


Figure 73. Annual measurements of primary production as a function of

Figure 73. Annual measurements of primary production as a function of the estimated annual input of dissolved inorganic nitrogen in various estuaries. (1) Naragansett Bay; (2) Long Island Sound; (3) Lower New York Bay; (4) Lower Delaware Bay; (5) Chesapeake Bay; (6) Patuxent estuary; (7) Pamlico estuary; (8) Apalachicola Bay; (9) Barataria Bay; (10) North and South San Francisco Bay; (11) Kaneohe Bay; (▲) Nueces/Corpus Christi Bay; (X) Nueces Bay; (⬢) Lavaca Bay; (■) San Antonio Bay (after Nixon and Pilson, 1983).

Table 25. Nitrogen Process Rates of Naragansett, Lavaca, San Antonio and Nueces/Corpus Christi Bays (mg-at/m^2/yr) (after Nixon and Pilson, 1983).

	Naragansett Bay					Lavaca Bay				
	PN	DON	NH_4	NO_3	Total	PN	DON	NH_4	NO_3	Total
Sources										
Nitrogen fixation ( )	<0.7	0	0	0	<0.7	?	0	0	0	?
Precipitation (direct)	0	?	24	30	54	0	0	13.2	13.3	26.5
Runoff (ungaged)	?	?	?	?	60	?	?	?	?	435
River (gaged)	74	258	236	322	890	90	392	23	348	853
Sewage & Industrial	178	485	365	25	1053	?	?	?	?	?
Offshore	?	?	?	?	?	∿0	∿0	∿0	∿0	∿0
Total					>2058					1314
Sinks										
Sedimentation	132	0	0	0	132	?	0	0	0	?
Denitrification	0	0	0	515	515	0	0	0	?	?
Fisheries	<5	0	0	0	<5	?	0	0	0	?
Offshore	?	?	?	?	?	?	?	∿0	∿0	∿0
Total					>652					?
Recycling										
Microbiological Processes	0	?	?	0	?	0	?	?	0	?
Microzooplankton Excretion	0	?	?	0	?	0	0	16	0	16
Mesozooplankton Excretion	0	132	242	0	374	0	0	3	0	3
Ctenophore Excretion	0	14	16	0	30	0	0	?	0	?
Fish Excretion	0		3	0	3	0	1	1	0	2
Benthic Flux	0	114	886	0	1000	0	?	823-21000	0	800-21000
Nitrification	0	0	0	?	?	0	0	0	?	?
Total					>1407					820-21,000
Primary Production	3900	?	0	0	3900	5555	?	0	0	5555

Table 25. Cont.

Sources	San Antonio Bay					Nueces/Corpus Christi Bay				
	PN	DON	NH_4	NO_3	Total	PN	DON	NH_4	NO_3	Total
Nitrogen Fixation	?	0	0	0	?	?	0	0	0	?
Precipitation (direct)	0	0	12.4	12.4	24.8	0	0	9.3	9.3	18.6
Runoff (ungaged)	?	?	?	?	240	?	?	?		28
River (gaged)	75	245	219	386	925	34	141	15	13	203
Sewage & Industrial	0	0	0	0	~0	0	8.8	~0.1	12.1	21
Offshore	~0	~0	~0	~0	~0	~0	~0	~0	~0	0
Total					1190					271
Sinks										
Sedimentation	?	0	0	0	?	?	0	0	0	?
Denitrification	0	0	0	40→302	40-300	0	0	0	36→624	36-624
Fisheries	.03	0	0	0	<1	?	0	0	0	?
Offshore	?	?	0	0	~0	?	?	0	0	~0
Total					>40-300					>40-600
Recycling										
Microbiological Processes	0	?	3015	0	3015	0	?	1752	0	1752
Microzooplankton Excretion	0	0	52	0	52	0	0	22	0	22
Mesozooplankton Excretion	0	0	9	0	9	0	0	3	0	3
Ctenophore Excretion	0	0	?	0	?	0	0	?	0	?
Fish Excretion	0	1	1	0	2	0	0	1	0	1
Benthic Flux	0	?	1642-4022	0	1600-4000	0	?	270→2073	0	270-2100
NItrification	0	0	0	354→697	350-700	0	0	0	149→1226	
Total					5000-7800					2200-5100
Primary Production	5146	?	0	0	5146	5347	?	0	0	5347

percent when microzooplankton and nitrification are estimated. The real value of an analysis tool like Table 25 is similar to a mathematical model because it defines data gaps and uncertainty for an ecosystem. The question marks in the table therefore indicate quantitative needs where little or no data exists.

Although zooplankton excretion was not specifically measured thIs water column process quantifies some of recycling that occurs as the result of particulate consumption processes. The calculated zooplankton excretion from zooplankton biomass for Lavaca, San Antonio and Nueces/Corpus Christi Bay has been partitioned into small and large size classes according to the relative biomasses and excretion rates. It is clear that the estimated recycling for all of the water column higher organisms are quite small compared to bacterial and benthic components. The bacterial components were not listed in the original Naragansett Bay table but there was an obvious necessity to include a bacterial category when the South Texas estuaries were included. The bacterial rates contribute 30-100 percent of the annual primary production nitrogen requirements and the ranges listed result from the annual cycle of those processes that occur. The lack of bacterial regeneration is puzzling for the Naragansett Bay data because it probably represents a large portion of the difference between sources, sinks and primary production rates.

The best literature for estuarine processes is available for regeneration, especially benthic recycling (Nixon, 1981; Fisher *et al.*, 1982; Kemp *et al.*, 1982; Nixon and Pilson, 1984; Flint *et al.*, 1986 and Teague *et al.*, 1988). In general, the South Texas estuaries in this study have sediment nitrogen release rates and water column nitrogen demands that are in the middle to upper ranges of values (Fig. 74). Several of the data points represent U.S. estuaries and the remainder are shallow continental shelf areas. The South Texas

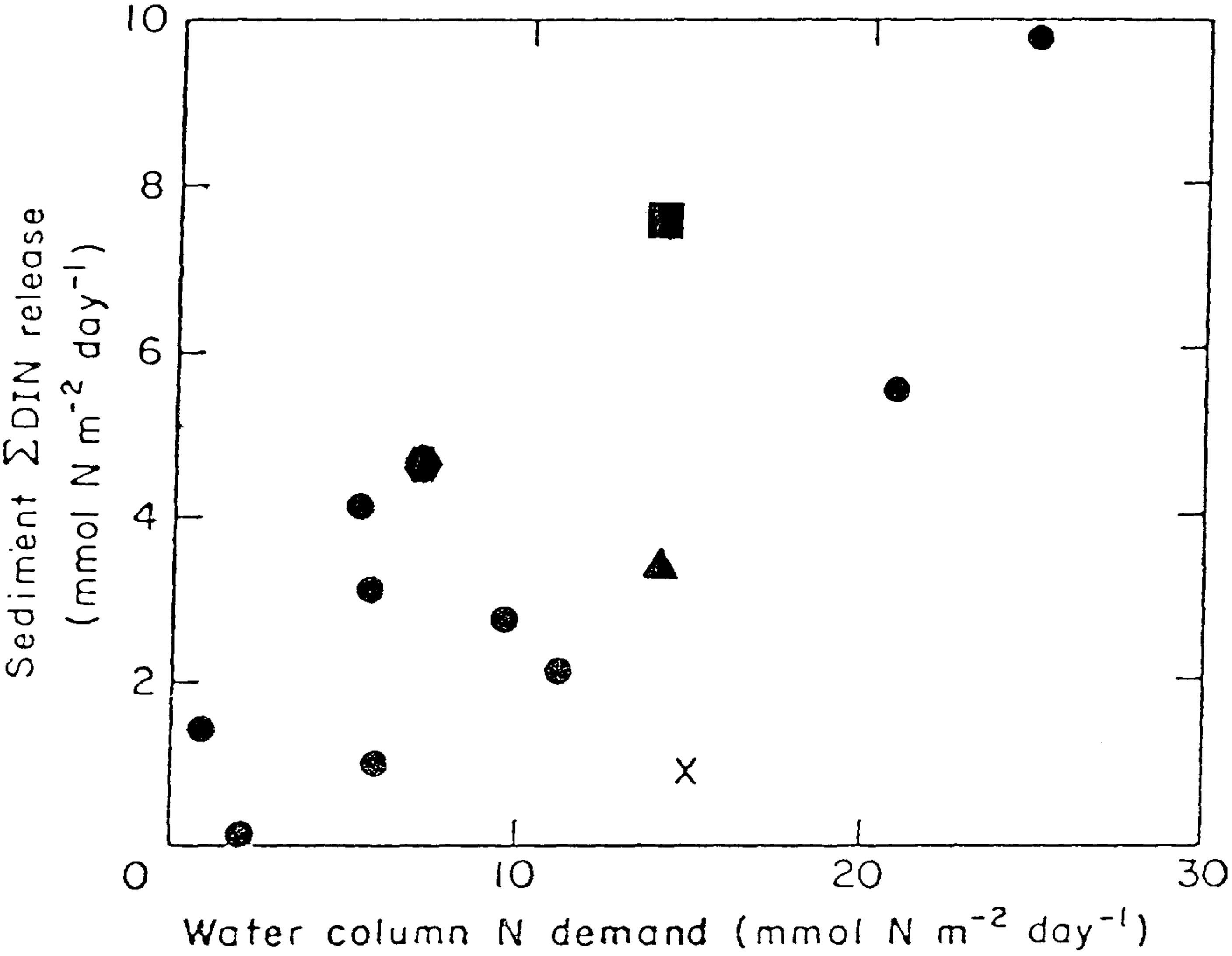


Figure 74. Sediment inorganic nitrogen release and calculated water column demand for the following 13 shallow marine ecosystems: South River, Neuse River, Newport River, Naragansett Bay, Buzzards Bay, Coastal North Sea, Offshore North Sea, Loch Thurnaig, Cap Blanc, (X) La Jolla Bight, (▲) Nueces/Corpus Christi Bay, (⬢) Lavaca Bay, and (■) San Antonio Bay (after Fisher et al, 1982).

estuaries have rates that are only exceeded by the coastal upwelling area off Northwest Africa and the Neuse River in North Carolina. The other coastal regions are much lower which is in agreement with Flint *et al.* (1986).

Two aspects that are missing in the studies described in this report are the role of dissolved organic nitrogen (DON) and nitrogen burial in the sediments. DON analyses were not included in these studies because few data existed that indicated it to have a significant benthic flux, however a recent report indicates that DON may be an order of magnitude larger than ammonium release in Fourleague Bay (Teague, 1988). Since the sediments are the temporary storage area of organic matter, both the DON production and/or uptake by the sediments need to be addressed in Lavaca, San Antonio and Nueces/Corpus Christi Bays. In addition, nitrogen burial should be studied to obtain an estimate for the local bays. Naragansett Bay has a nitrogen burial of about 33 mg-at/m^2/yr (Nixon and Pilson, 1984) or about 1.5 percent of the primary production (Nixon, 1981). The local bays and estuaries in South Texas should also have a low value but the percent dry weight carbon and nitrogen in the sediments have enough variance in the San Antonio and Nueces/Corpus Christi Bay (see Parker component) that some estimates should be made.

In summary, the influence of freshwater inflow in Lavaca, San Antonio and Nueces/Corpus Christi Bays is significant with respect to the quantity of nutrients introduced. Each of these three estuaries have different freshwater inflow characteristics which influence the initial primary production and regeneration processes. Other characteristics of each of the bays such as depth, salinity, wind mixing and temperature tend to maximize the benthic and water column regeneration processes to a very high level compared to other U.S. estuaries. The close proximity of the bottom to the surface primary production processes does indeed produce a close coupling of these regions. The small tidal ranges and relatively small freshwater flows does not flush the organic matter from the bays hence the recycling of nutrient material may occur more frequently than in deeper estuarine ecosystems.

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