V. CHARACTERIZATION OF PLANKTON FROM THE GALVESTON ESTUARY

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INTRODUCTION

Phytoplankton, the small, single-celled algae that drift with the motion of the currents, are the most widespread group of autotrophic organisms in the nation's estuaries. They contribute substantially to estuarine productivity in all systems, although their importance compared to seagrasses, marsh grasses and algal macrophytes varies from estuary to estuary. Phytoplankton provide a major direct food source for both the pelagic and benthic food chains in estuaries.

The gross primary productivity of estuarine phytoplankton is regulated by the amount of light and nutrients available, and to a lesser extent by the temperature of the system. In temperate estuaries, the reduced availability of light and decreased temperatures will limit phytoplankton productivity in the winter, allowing nutrient concentrations to increase. When daylengths increase in the spring and water temperatures begin to warm, a spring bloom of phytoplankton usually occurs, taking advantage of the winter surplus of nutrients and the reduction in grazing pressure from lowered zooplankton populations. A fall phytoplankton bloom also occurs often (Cushing 1959).

In the warm temperate estuaries of Texas, including the Galveston Estuary, the distinct seasonal patterns of cold temperate estuaries are less evident and are often characterized by an increased importance of nanoplankton (Marsh 1974). For example, in Terminos Lagoon, Mexico, peak production and chlorophyll concentrations occur during the period of high river discharge in the fall (Day et al. 1982). The effects of light and temperature on productivity are also less predictable. In very turbid estuaries, the availability of light may limit the productivity of an estuary (e.g. Harding et al. 1986), but in most cases, availability of nutrients will have the greatest effect on estuarine productivity, and nitrogen is the nutrient most often thought to limit estuarine phytoplankton productivity (Day et al. 1987). Phytoplankton production in Texas estuaries is characterized by series of small blooms throughout the year that are extremely variable in spatial and temporal distribution (Stockwell 1989).

Phytoplankton populations are often subdivided based on their size. Cells retained on a 20 μm mesh are referred to as net plankton or microplankton, while those that pass through the mesh are referred to as nanoplankton (Malone 1980). In most temperate estuaries, nanoplankton may dominate the estuarine phytoplankton assemblage numerically, but net plankton usually dominate the phytoplankton biomass (Day et al. 1987). In Texas estuaries, nanoplankton often dominate the phytoplankton assemblage both numerically and in terms of biomass (Stockwell 1989). The relative proportion of nanoplankton and net plankton may have important implications for trophic transfer of primary production. Net plankton, including diatoms and dinoflagellates, are within the preferred food size range for mesozooplankton grazers such as copepods, which are important trophic links to fish and other tertiary consumers within the estuary. Nanoplankton are grazed primarily by the smaller zooplankton, the microzooplankton (20 - 200 μm length) which consist mainly of protozoans, rotifers and copepod nauplii. Microzooplankton may graze as much as 90 percent of the nanophytoplankton standing stock per day in south Texas estuaries, while mesozooplankton such as copepods may graze less than 5 percent of the net phytoplankton standing stock per day (Stockwell and Buskey in preparation).

Populations of zooplankton also exhibit population fluctuations that vary unpredictably both spatially and temporally in Texas estuaries. However, some predictable changes in zooplankton populations can be found to correlate with regions of known ranges of salinity. In addition, periods of extensive flushing of Texas estuaries are often followed by large increases in zooplankton populations (Buskey 1989). The factors controlling population abundance of zooplankton in Texas estuaries remain incompletely understood, and a combination of food limitations on population growth during some parts of the year, and of control by predators such as ctenophores, probably each contribute some regulatory effects on zooplankton populations (Day et al. 1987).

The purpose of this report is to summarize the published studies on phytoplankton and zooplankton in the Galveston Estuary. Before this project had begun, it was determined that there was insufficient long term data on plankton in the Galveston Estuary to attempt trend analysis. Information on phytoplankton species diversity, biomass and primary production, along with information on zooplankton species diversity and abundance, is summarized. This information is compared to similar data on other Texas and United States estuaries where available. Recommendations for a long term monitoring program are made. A bibliography of all Galveston Estuary plankton studies and an annotated bibliography of the major studies and publications are available in the GBNEP Information Center.

Figures V.1-V.3 show the temporal distribution of phytoplankton, zooplankton, and combined studies respectively, from 1950 to 1990. Most of the studies were done during the 1970s, fewer were done during the 1980s and no studies have been carried out since 1985. Many studies in the 1970s were associated with the opening of the Cedar Bayou Generating Station, and the interest regarding the effects of thermal pollution on plankton contributed to the number of studies of plankton in the Trinity Bay region.

PLANKTON STUDIES IN THE GALVESTON ESTUARY

Phytoplankton Species Diversity and Biomass (Chlorophyll a)

Detailed studies of the phytoplankton taxonomy in the Galveston Estuary are few. Hohn (1959) examined the diversity of species of phytoplankton at several locations in the

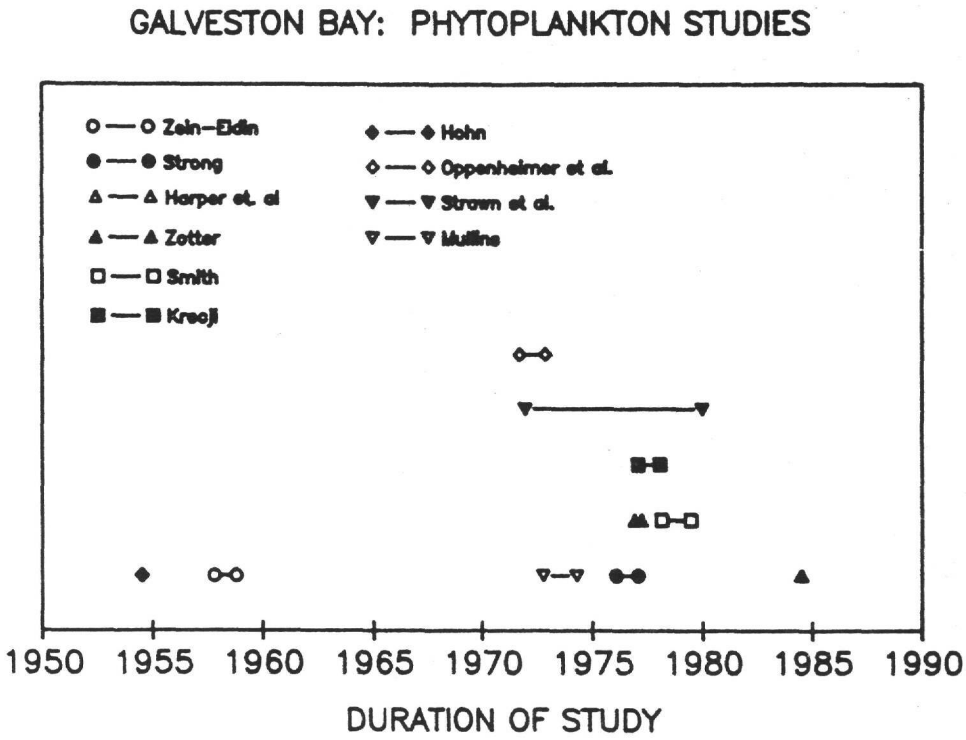


Figure V.1. Temporal distribution of phytoplankton studies in the Galveston Estuary from 1950 until 1990.

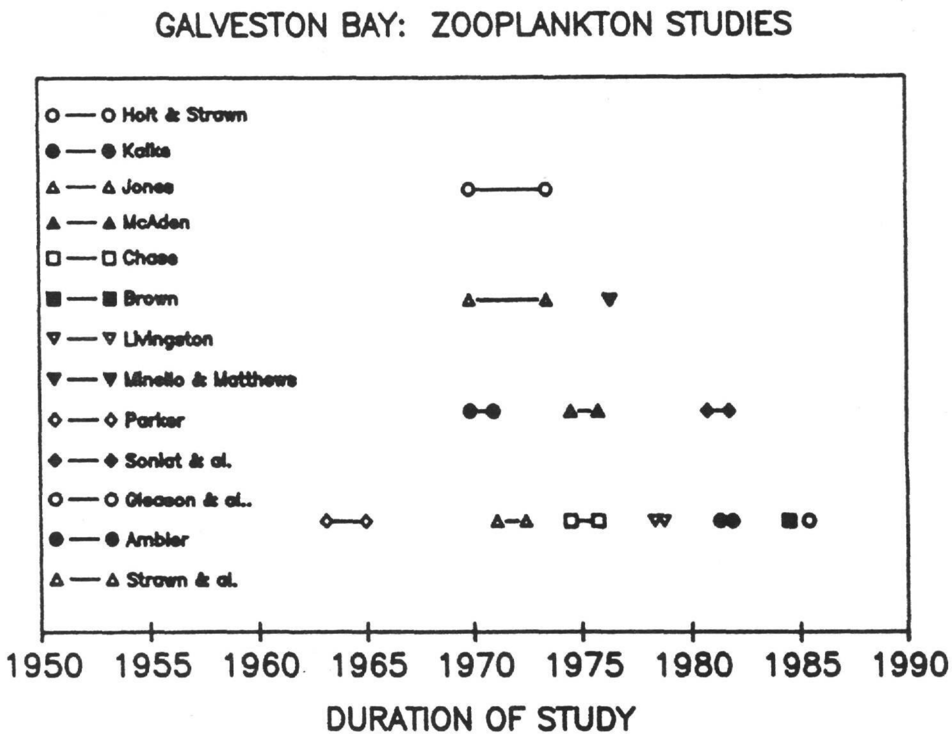


Figure V.2. Temporal distribution of zooplankton studies in the Galveston Estuary from 1950 until 1990.

Galveston Estuary in 1954, although the species identified were never named. Copeland and Bechtel (1971) also examined phytoplankton species diversity, but did not provide information on the species identified. Strong (1977) enumerated phytoplankton species based on 1/10 ml samples of whole seawater examined in a Palmer-Maloney cell during 1976-77. Strong found several species of diatoms to be most common at different times and locations, including Coscinodiscus pygmaeus, Skeletonema costatum, Thalassiosira sp. and Chaetoceros galvestonensis. Zotter (1979) enumerated "nanoplankton" species during 1976-77 from samples passed through a 65 μm mesh by concentrating a 15 ml sample of whole water through centrifugation and examining a subsample in a hemocytometer. A total of 59 genera were identified. Diatoms Skeletonema costatum and Thalassiosira exigua and the green alga Chlorella sp. were dominant during the cold months, and several other species were dominant during other times of the year. Species diversity was lower at the low salinity stations than at the high salinity stations, though dominant species were not found to correlate with temperature or salinity conditions. High cell numbers were more common in waters of lower salinity (0 to 15‰) than in waters of higher salinity (16 to 33‰). A summary of the spatial and temporal distribution of dominant phytoplankton genera in 1969 from Armstrong and Hinson (1973) is presented in Table V.1. This is one of the few phytoplankton studies with wide spatial coverage. From the few studies available, there is insufficient information for drawing conclusions regarding long term trends in phytoplankton species composition.

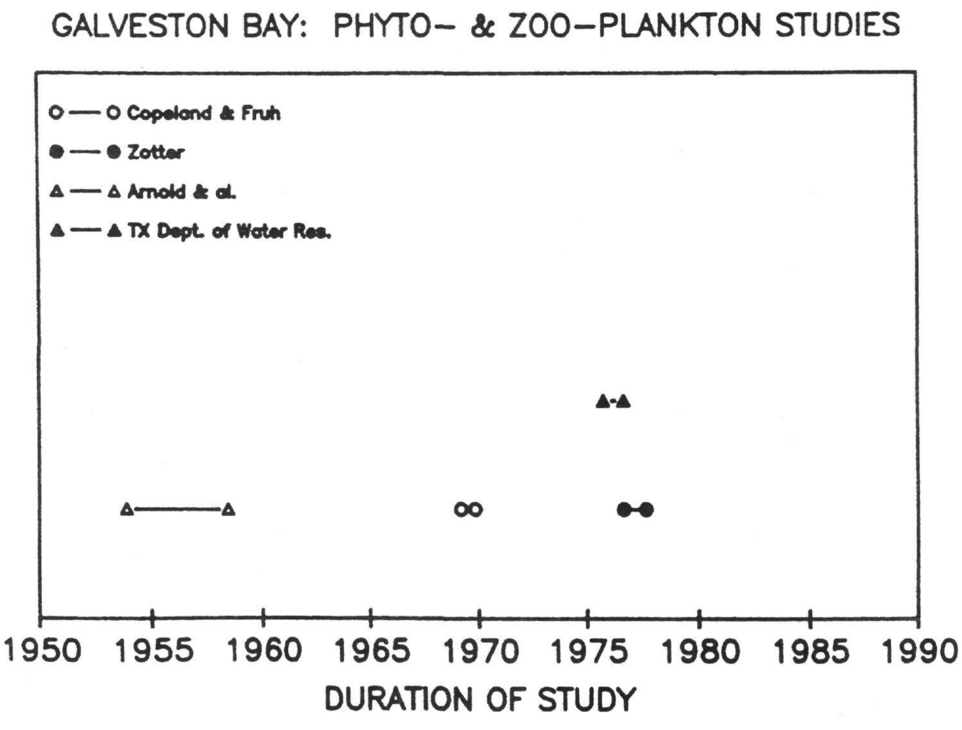


Figure V.3. Temporal distribution of combined phyto- and zooplankton studies in the Galveston Estuary from 1950 until 1990.

Table V.1. Dominant genera of phytoplankton in the Galveston Estuary during 1969 (from Armstrong and Hinson, 1973).

Study Area	February	April	July	October
Trinity Bay	Leptocylindricus Nitzschia Skeletonema	Nostocaceae Oscillatoriaceae	Nostocaceae Oscillatoriaceae	Thalassionema Filamentous Chlorophyta
Upper Galveston Bay	Euglenoid Chaetoceros Nitzschia	Thalassiothrix Nitzschia Skeletonema	Cyanophyta	Cyanophyta Chlorophyta Skeletonema
Lower Galveston Bay	Skeletonema Chaetoceros Nitzschia	Chaetoceros Nitzschia Skeletonema Thalassionema	Skeletonema	Thalassionema Chaetoceros Ditylum
East Bay	Skeletonema Asterionella	Skeletonema	Cyanophyta Coscinodiscus Nitzschia	Thalassionema Chaetoceros Rhizosolenia
West Bay	Chaetoceros Nitzschia	Nitzschia	Chaetoceros Skeletonema Rhizoselenia	Chaetoceros Nitzschia Thalassionema

A larger proportion of the phytoplankton studies have estimated phytoplankton biomass by measuring concentrations of chlorophyll a in water samples. Most reports of phytoplankton biomass do not separate it into nanoplankton and net plankton size fractions. Livingston (1981) found 80-90 percent of phytoplankton biomass to be in the nanoplankton during 1978 in East Lagoon. Zein-Eldin (1961) measured chlorophyll concentrations spectrophotometrically on a weekly basis during 1957-1959 (Figure V.4). Weekly mean chlorophyll concentrations for all stations ranged from ca 7 mg to 45 mg chlorophyll a per cubic meter (mg m^{-3}). There is considerable spatial and temporal variability in phytoplankton biomass, but there is no obvious seasonal pattern. Mullins (1979) examined the chlorophyll concentrations in the intake and discharge of the Cedar Bayou Generating Station from October 1972 through April 1974 (Figure V.5) and found chlorophyll concentrations to be lower in the discharge waters from the plant than in intake area or other Cedar Bayou stations. The range and mean chlorophyll concentrations are similar to those measured in 1959 (Figure V.4). Strong (1977) measured chlorophyll concentrations in the same region from January 1976 to January 1977 (Figure V.7). Chlorophyll concentrations ranged from 0.72 mg m^{-3} to 84.08 mg m^{-3}. These maximum chlorophyll concentrations are higher than those reported in previous studies. Krecji (1979) measured chlorophyll concentration in the same area for the following year, from January 1977 to January 1978. During this year, peak chlorophyll concentration during the winter months of January and February were among the highest recorded in the Galveston Estuary area (up to 120 mg m^{-3}), but chlorophyll a concentrations remained low during the summer and fall, with no evidence of additional blooms. Smith (1983) measured chlorophyll concentrations in the same area from February 1978 through June 1979. He found chlorophyll a concentrations to be

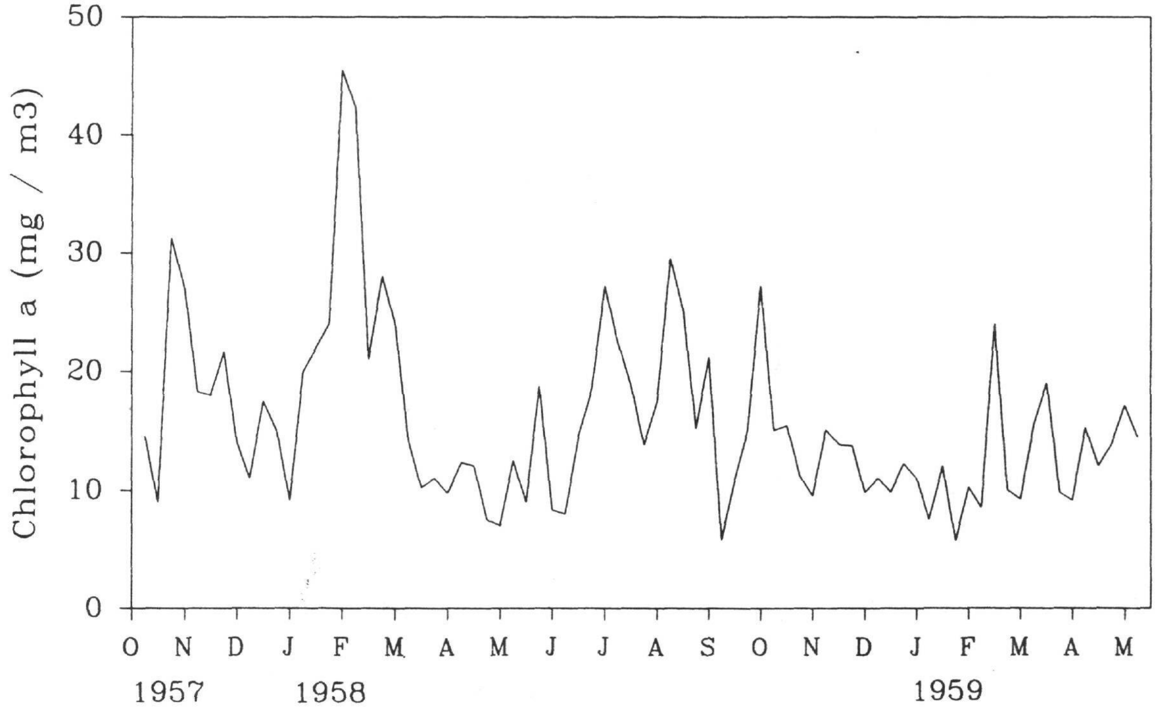
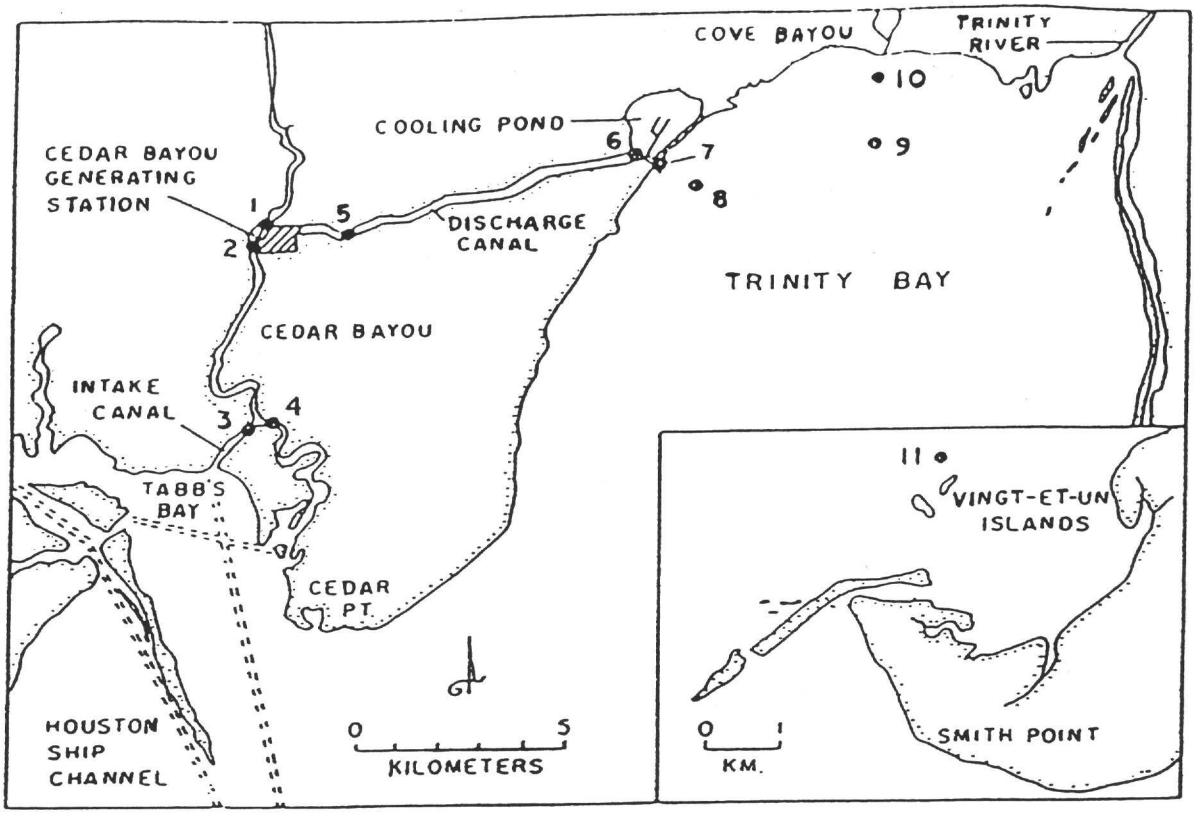


Figure V.4. Variations in weekly means of chlorophyll a measurements in Galveston Bay during 1957-1959 from Zein-Eldin (1961).



Month	Stations 1	2	3	4	5	6	7	8	9	10	11
Oct.	57.1	32.2	26.7	16.1	17.0	10.3	3.6	21.6	24.4	25.7	9.5
Nov.	0.6	1.3	8.1	5.3	5.1	2.7	42.8	28.1	10.2	9.0	11.9
Dec.	1.9	2.6	13.9	12.2	7.0	4.6	7.3	23.5	10.7	15.7	37.7
Jan.	2.7	6.3	69.9	48.3	19.5	16.0	7.2	12.4	10.9	7.3	33.6
Feb.	1.2	3.0	23.4	23.4	8.6	5.1	5.8	23.0	14.4	7.7	48.3
Mar.	1.8	8.0	9.2	35.0	9.0	12.9	5.4	11.2	7.8	8.8	4.8
Apr.	5.8	4.2	10.4	11.9	2.8	3.7	2.2	4.6	4.2	6.8	13.8
May.	17.9	15.9	22.5	15.6	14.2	4.8	29.0	26.2	19.3	17.0	13.2
Jun.	26.2	25.7	11.9	13.3	18.8	3.9	10.5	6.8	14.2	10.2	12.4
Jul.	6.8	11.2	13.6	10.7	8.5	5.6	10.0	12.0	4.2	5.1	11.9
Aug.	6.0	7.7	37.5	30.0	18.4	11.2	10.9	5.8	5.8	7.3	9.5
Sep.	8.7	34.5	36.8	31.1	15.3	6.0	23.1	15.1	8.0	11.9	7.9
Oct.	4.5	2.7	5.6	6.8	2.2	2.3	5.1	9.5	10.0	9.6	11.3
Nov.	5.8	6.9	6.2	7.4	5.2	5.4	18.4	4.5	4.2	4.4	11.5
Dec.	3.9	5.0	3.7	20.6	6.9	7.1	26.8	7.3	7.6	6.0	12.0
Jan.	1.4	1.7	1.3	1.0	0.9	1.2	12.1	3.3	5.2	4.2	6.6
Feb.	23.3	18.2	19.3	15.5	20.6	25.6	22.5	14.2	30.8	17.4	13.6
Mar.	1.7	1.5	10.3	16.8	3.1	1.8	18.4	16.0	16.1	22.0	11.0
Apr.	24.3	17.4	17.4	11.9	9.2	3.9	17.6	9.4	8.8	7.4	6.1
Station Mean	10.6	10.8	18.3	17.5	10.1	7.1	14.7	13.4	11.4	10.7	15.1

Figure V.5. Location of sampling stations in Cedar Bayou area (top) and monthly chlorophyll a concentrations during 1972-1974 from Mullins (1979).

significantly lower in the discharge water than at the intake stations or in the bay control stations. Chlorophyll concentrations in control stations were similar to those found in earlier studies. The familiar pattern of a continuous succession of blooms through the year resumed during this study (Figure V.7).

It is difficult to draw conclusions about long term trends in phytoplankton biomass from the limited data set available. The mean chlorophyll a concentration measured by Zein-Eldin (1961) in the late 1950s is ca 16 mg m^{-3}. This is similar to the overall mean concentration of chlorophyll a measured in the 1970s by Mullins (1979) of ca 13 mg m^{-3} and of Strong (1977) of ca 17 mg m^{-3} in Trinity Bay. There is some evidence for an increase in maximum chlorophyll levels, however. The maximum chlorophyll concentration measured by Zein-Eldin (1961) in the late 1950s was ca 45 mg m^{-3}, whereas in the 1970s Mullins (1979) found a maximum chlorophyll concentration of ca 70 mg m^{-3}, Strong (1977) found a maximum concentration of ca 85 mg m^{-3} and Krecji (1979) found a maximum of ca 120 mg m^{-3}. However, Smith (1983) measured a maximum chlorophyll concentration of ca 45 mg m^{-3} in the late 1970s. It is also impossible to determine any spatial patterns of phytoplankton biomass for the Galveston Estuary from the studies of Mullins (1979), Strong (1977), Krecji (1979) and Smith (1983). The ten stations sampled in these studies are in intake or discharge channels for the Cedar Bayou Generating Station, or in upper Trinity Bay.

Phytoplankton Production

Published studies of phytoplankton primary production were made primarily during the 1970s, and most reported studies were made in the vicinity of the Cedar Bayou Generating Plant. Primary production was measured using the carbon-14 uptake method. Mullins (1979) measured phytoplankton primary production from October 1972 until

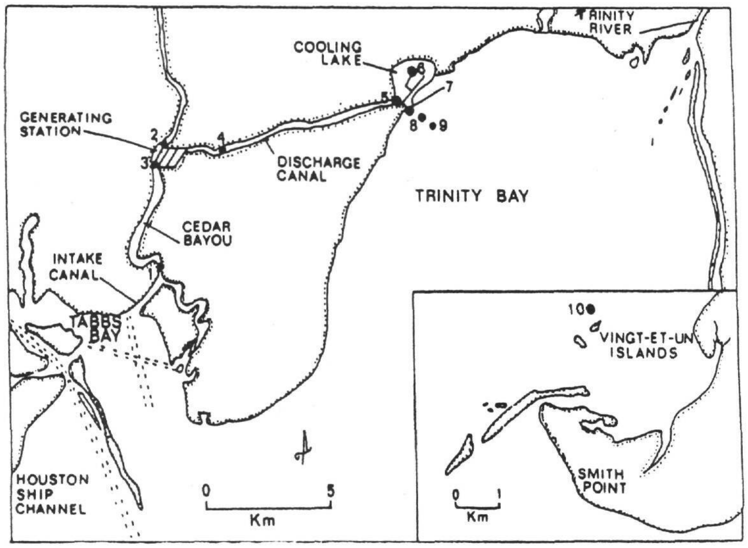


Figure V.6. Locations of sampling stations in upper Galveston and Trinity Bays used in studies of Strong (1977), Krecji (1979) and Smith (1983).

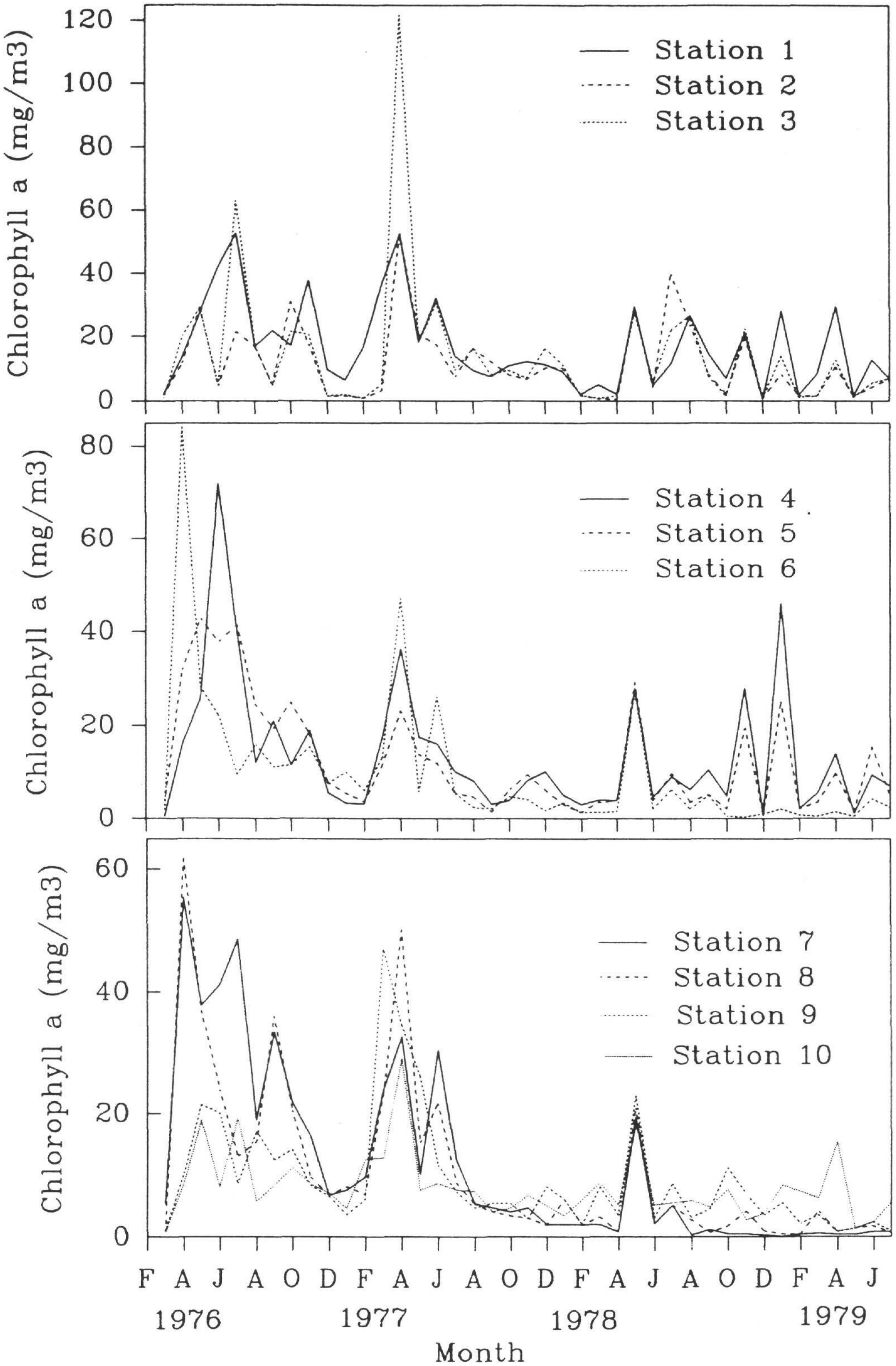


Figure V.7. Monthly chlorophyll a concentrations from ten stations in upper Galveston and Trinity Bays during 1976 (Strong 1977), 1977 (Krecji 1979) and 1978 (Smith 1983).

April 1974. Surface primary productivity rates ranged from 0 to 173 mg C m^{-3} hr^{-1} (Figure V.8). The mean production for all stations and times was 32.6 mg C m^{-3} hr^{-1}. Assuming 12 hours of productivity per day, this would correspond to an annual production of approximately 140 g C m^{-3} yr^{-1}. Peak periods of primary production in this study were during January 1973 and February 1974. Strong (1977) measured primary production in the same region from January 1976 through January 1977. He found peak levels of primary productivity in March of 1976, with production values exceeding 400 mg C m^{-3} hr^{-1} at some stations. Primary production remained below 50 mg C m^{-3} hr^{-1} for the summer and fall at all stations except at the mouth of the intake canal (station 1). The overall mean primary production rate for all stations was ca 55 mg C m^{-3} hr^{-1}. Krecji (1979) measured primary production at the same locations from January 1977 through January 1978. Again, primary production values were quite variable, ranging from near zero to greater than 400 mg C m-3 hr-1. The seasonal pattern of primary production was not as uniform during 1977 as it was in 1976. Peaks of productivity occurred at several stations during the winter months, as in 1976, but there were also productivity peaks in spring and fall. The overall mean primary production rate for all stations was ca 35 mg C m^{-3} hr^{-1}. Smith (1983) provides a somewhat incomplete data set of productivity values for the same area from February 1978 through June 1979. Maximum productivity measurements in this study were approximately 200 mg C m-3 hr-1, and there is no obvious seasonal pattern of primary production. The overall mean primary production rate for all stations was ca 35 mg C m^{-3} hr^{-1}. Again, it is difficult to recognize a pattern in the spatial distribution of primary production in the Galveston Estuary from these studies, because of the restricted locations of the sampling sites (Figure V.6).

There is little evidence for a consistent seasonal pattern on phytoplankton production in the Galveston Estuary. Primary productivity rates for the period of October 1972-April 1974 (Table V.2) showed months that during one year would be extremely low, then the next year would show dramatically more productivity (Feb 1973: 0.0 mg C $m^{-3}hr^{-1}$ and Feb 1974: 138.4 mg C $m^{-3}hr^{-1}$ at station 2). The reverse also occurs (Jan 1973: 165.0 mg C $m^{-3}hr^{-1}$ and Jan 1974: 2.8 mg C $m^{-3}hr^{-1}$ at station 3), where a highly productive month one year is almost non-productive the next year. During the period of January 1976-January 1977 (Figure V.8), the productivity at each station has a peak starting in February and continuing through April or May when it returns to a lower rate which seldom goes above 50 mg C $m^{-3}hr^{-1}$. During the period of January 1977-January 1978 (Figure V.8), some stations show consistent year-to-year values, while others show peaks throughout the year, such as stations 1, 2, and 3 which remain above 50 mg C $m^{-3}hr^{-1}$ most of the year. Also, stations 1-5 exhibit a peak in October and November which tapers off in December. During the period of February 1978 through June 1979 (Figure V.8), all stations start off with a peak early in the year. However, stations 1-5 and 10 show strong peaks over the entire duration of the study with the other stations following the peaks to a lesser degree. During this period, stations 6 and 7, which exhibited low production throughout the previous years, show nearly no production after the peak early in 1978. This early peak is not as extensive in 1979 as has been recorded in previous years.

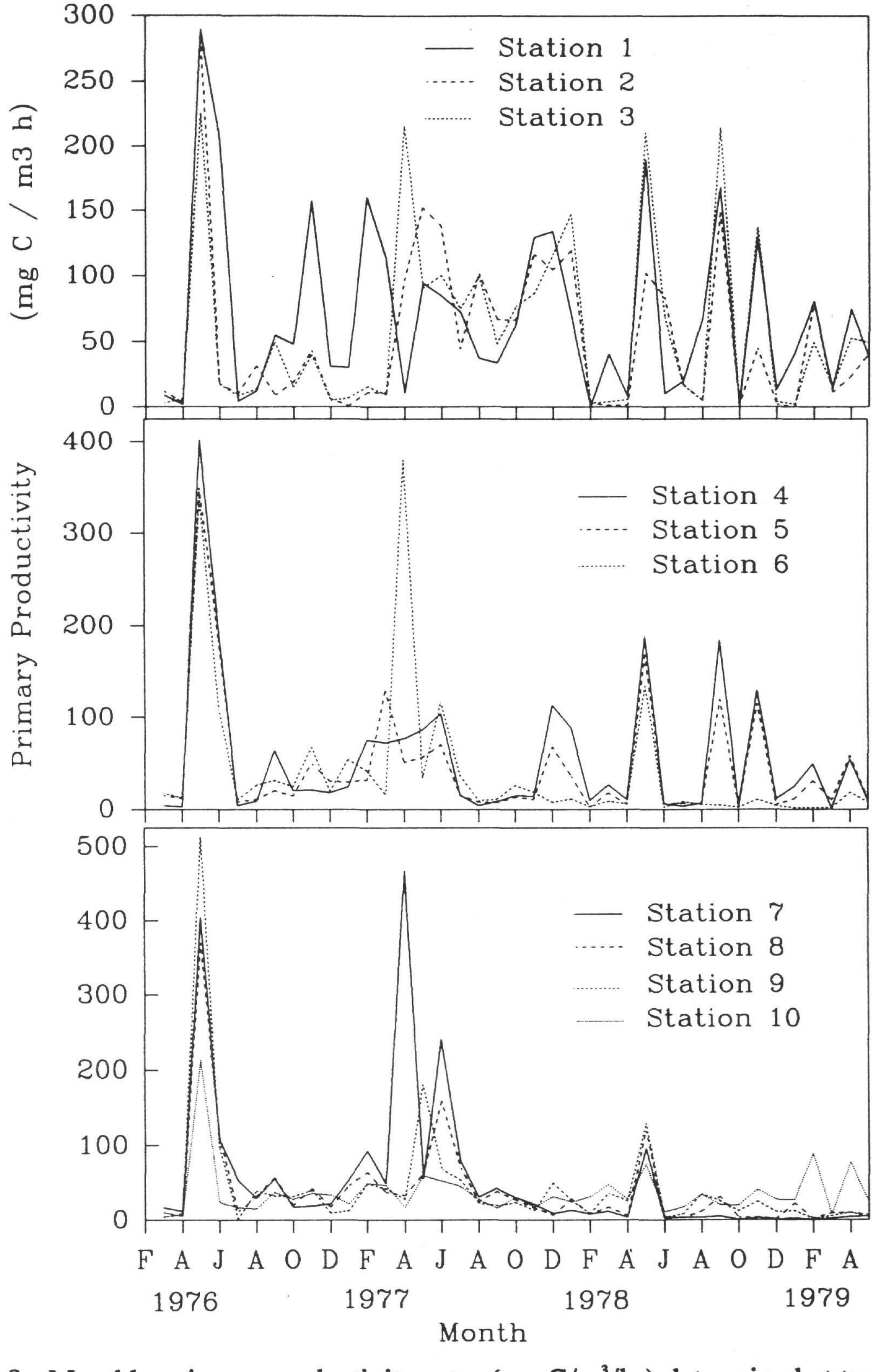


Figure V.8. Monthly primary productivity rates (mg C/m^3/hr) determined at ten stations in upper Galveston and Trinity Bays during 1976 (Strong 1977), 1977 (Krecji 1979) and 1978 (Smith 1983).

Table V.2. Surface primary production rates (mg C/ m^3/ hr) determined at each sampling station from October 1972 to April 1974 from Mullins (1979). Stations as in Figure V.5.

Month	Stations										
	1	2	3	4	5	6	7	8	9	10	11
October	60.7	86.5	56.9	41.3	8.5	6.1	2.6	22.5	28.4	26.1	11.9
November	29.7	26.7	53.3	62.7	26.7	0.5	128.3	64.5	19.7	65.1	89.3
December	0.0	2.6	13.5	10.7	8.6	5.4	5.4	15.5	22.1	11.7	23.4
January	43.0	20.9	165.0	162.2	47.9	46.7	70.4	34.9	58.2	38.4	161.8
February	0.0	0.0	0.3	0.0	0.0	0.4	0.0	0.0	0.0	0.0	0.1
March	3.4	33.4	44.6	136.3	0.0	4.1	11.5	55.0	28.9	45.5	24.4
April	37.9	14.8	31.9	20.1	3.1	4.9	1.4	9.3	12.1	14.1	39.5
May	54.4	64.9	61.5	27.9	32.3	1.5	16.2	45.7	57.2	101.1	39.9
June	55.1	52.9	24.2	21.3	3.6	3.5	14.1	11.2	33.5	18.4	21.9
July	8.9	5.9	13.0	11.1	0.0	6.1	6.1	5.0	0.0	4.9	9.8
August	47.4	65.7	172.7	120.3	43.7	1.7	42.4	0.8	26.8	19.7	41.1
September	22.6	78.1	90.1	43.3	11.3	2.7	76.1	35.4	27.6	19.5	11.7
October	0.0	0.0	0.0	1.1	0.0	0.4	0.0	2.0	5.0	6.5	2.7
November	15.6	36.7	35.9	24.3	13.7	13.5	39.2	8.7	14.7	15.4	51.5
December	5.0	6.4	25.7	39.3	22.4	12.3	124.0	17.9	20.4	17.2	36.2
January	5.7	9.5	2.8	2.2	1.0	3.6	25.5	12.0	15.6	11.9	17.8
February	77.8	138.4	189.3	102.6	67.8	104.7	95.7	26.4	162.9	49.3	91.6
March	10.2	4.5	2.9	39.0	0.0	20.9	59.8	40.5	40.5	65.9	33.7
April	70.6	85.5	32.8	25.7	34.9	5.0	90.7	20.2	45.2	26.3	13.1
Station Mean	28.8	38.6	53.5	43.1	17.1	12.8	42.6	22.5	32.6	29.3	38.0

There is no evidence for long term trends in primary production patterns in the Galveston Estuary based on these data from the 1970s. There is considerable spatial and seasonal variability in primary production, but the overall annual mean of primary production measures is always ca 35 mg C m^{-3} hr^{-1}, except for the study of Strong (1977) whose mean value was nearly 55 mg C m^{-3} hr^{-1}.

Zooplankton Abundance and Species Diversity

There have been a number of studies of zooplankton abundance and species diversity. Most studies have concentrated on the crustacean mesozooplankton and "macrozooplankton", and there have been virtually no studies of the microzooplankton (20-200 μm size fraction). This is especially unfortunate because recent studies show that microzooplankton are responsible for grazing more phytoplankton biomass than mesozooplankton (e.g. Buskey 1989). Mesozooplankton can also be important grazers of phytoplankton, however, and they are important trophic links in estuarine food webs. In addition, many benthic and nektonic organisms spend at least part of their lives in the plankton, and these juvenile stages of commercially important finfish and shellfish species are recognized as critical survival stages for recruitment to adult stocks.

A major problem in the comparison of zooplankton data collected by different researchers is that the results vary greatly with the type of equipment used for collection, and the time of day collections are made. Some studies, such as that of Arnold et al. (1960), used seven different nets with three different mesh sizes in their collections. A number of studies in the Galveston Estuary have been made with 0.5 m diameter, 500 μm mesh nets (e.g. Kalke 1972; Jones 1975; Holt 1976). These nets are designed to catch what these investigators call "macroplankton", but are too coarse to quantitatively capture the most important zooplankton grazers, such as Acartia tonsa. Nets of approximately 240 μm mesh have also been used (Bagnall 1976; Minello and Matthews 1981) but this mesh is also too coarse. Two other studies have used nets of approximately 153 μm mesh (McAden 1977; Chase 1977) which is generally considered appropriate for quantitatively capturing all mesozooplankton (defined as zooplankton from 200 μm to 2000 μm in length). It is inappropriate to compare abundance or species diversity data between collections made with gear of different mesh size.

The time of day zooplankton collections are made can also be important for estimates of zooplankton abundance, because many estuarine zooplankters are diurnal vertical migrators (Minello and Matthews 1981). Most of the zooplankton collections considered in this report were collected during the day, when a portion of the zooplankton community resides on or near the bottom, and are not sampled using zooplankton nets. Therefore, daytime zooplankton samples often underestimate total zooplankton population densities.

The longest running series of zooplankton studies in the Galveston Estuary are those carried out around the Cedar Bayou Generating Station. These studies were carried out by faculty and students from Texas A & M University from 1967 through 1973, then continued until 1980 by a private consulting company, the Southwest Research Institute

(Frank Schlict personal communication). The data from the last seven years of the study has never been processed, however, and no reports published. These studies have sampled with a 0.5 m diameter net with 0.5 mm mesh, collecting "macrozooplankton". These collections provide no information on mesozooplankton biomass or abundance. Organisms collected are mainly mysids, isopods, amphipods, decapods and fish. The mean catch per 35 m^3 of water sampled from October 1969 through December 1970 was 106 invertebrates and 26 fish (Kalke 1972). The mean catch for January 1971 through May 1972 was 123 invertebrates and 11 fish (Jones 1975).

The dominant zooplankton species in the Galveston Estuary are Acartia tonsa, Balanus sp. nauplii, Oithona sp., larval polychaetes, Pseudodiaptomus coronatus and Paracalanus crassirostris (McAden 1977). Zooplankton species found in the Galveston Estuary are listed in Table V.3. Little information about spatial distribution of zooplankton can be determined from this study, because the three stations sampled were in the intake canal and discharge canals of the Robinson Generating Station. There is no clear seasonal pattern in the abundance of any of the dominant holoplankton species.

Comparison of Galveston Bay Plankton Data to Other Texas Estuaries and to Other United States Estuaries

Phytoplankton Primary Production

Table V.4 (modified from Flint 1984) indicates that the Galveston Estuary is among the most productive in Texas. Daily primary production values are more than twice that of other Texas estuaries, and comparable to the higher productive, hypersaline Laguna Madre (Table V.4). If these daily primary production values were maintained throughout the year, the Galveston Estuary would be among the most productive in the country (Table V.5). It is unclear, however, how this value for primary production in the Galveston Bay was calculated. Examining the original data on which Flint's (1984) estimate is based (Armstrong and Hinson 1973), the mean gross primary production for all stations and dates, based on light/dark bottle O_2 measurements, appears to be ca 1.98 g C m^{-2} d^{-1}. Net production, based on the same set of measurements, is negative (respiration exceeds photosynthesis). The other values in Table V.4 are based on C-14 uptake rates, which are generally understood to measure no more precisely than between gross and net primary production (Valiela, 1984), so the value for the Galveston Estuary cannot be compared directly to estimates for other estuaries.

Furthermore, if we assume a 12 hour period of sunlight during which photosynthesis can occur, a primary production rate of 4 g C m^{-2} day^{-1} requires a mean hourly production rate of over 150 mg C $m^{-3}hr^{-1}$, assuming an average depth of 2 meters in the Galveston Estuary (Armstrong 1987). This is considerably higher than the values reported in most other studies (e.g. Strong 1977; Krecji 1979; Smith 1983). Using a mean primary production rate of 35 mg C m^{-3} hr^{-1} (as reported in Mullins 1979; Krecji 1979; and Smith 1983) and using the same assumptions as above, produces an estimate of 0.84 mg C m^{-2} d^{-1}. It should be noted, however, that the studies of Mullins (1979), Strong (1977), Krecji (1979) and Smith (1983) are based on small samples incubated

Table V.3. A list of zooplankton species collected in the Galveston Estuary during the period June 1974 through September 1975 (modified from McAden, 1977).

Phylum Ctenophora
- *Mnemiopsis* sp., *Beroe* sp.

Phylum Annelida
- Class Polychaeta
  - Polychaete larvae

Phylum Mollusca
- Class Gastropoda
  - Gastropod larvae
- Class Pelecypode
  - Pelecypod larvae

Phylum Arthropoda
- Class Crustacea
  - Order Diplostraca
    - *Diaphanosoma* sp., *Sida* sp., *Ceriodaphnia* sp., *Daphnia* sp., *Moina* sp., *Scapholeberis* sp., *Bosmina* sp., *Ilyocryptis* sp., *Macrothrix* sp., *Alona* sp.
  - Order Podocopa
    - Ostracods
  - Order Calanoida
    - *Paracalanus crassirostris, Centropages hamatus, C. velificatus, Diaptomus spp., Eurytemora sp., Temora turbinata, Pseudodiaptomus coronatus, Labidocera aestiva, Acartia lilljeborgii, A. tonsa, Tortanus setacaudatus*
  - Order Harpoaticoida
    - *Scottolana canadensis, Parategastes sphaericus*
  - Order Cyclopoida
    - *Oithona* spp., *Cyclops* sp., *Halicyclops* sp., *Saphirella* sp., *Corycaeus* sp., *Ergasilus* sp.
  - Order Caligoida
    - *Caligus* sp., *Argulua* sp.
  - Order Thoracica
    - *Balanus* sp. nauplii, cypris larvae
  - Order Mysidacea
    - *Bowmaniella brasiliensis, Mysidopsis almyra, Mysidopsis biglowi, Taphromysis lovisianae*
  - Order Cumacea
    - Cumaceans
  - Order Tanaidacea
    - *Leptochelia* sp.
  - Order Isopoda
    - *Edotea* sp., *Aegathoa* sp., *Cassidinidea* sp.
  - Order Amphipoda
    - *Corophium louisianum*
  - Order Decapods
    - *Penaeus aztecus, P. setiferus* postlarvae, *Acetes americanus, Lucifer faxoni, Marobrachium ohione* zoeae, *Palaemonetes pugio, P. vulgaris, Alpheus heterochaelis* zoeae, *Ogyrides limicola* zoeae, postlarvae, *Callianassa jamaicense, Upogebia affinis, Petrolisthes armatus* zoeae, *Callinectes sapidus* megalops, *Hexapanopeus* sp. megalops, *Menippe mercenaria* zoeae, *Rhithropanopeus harrisii* zoeae, *Pinnixa* sp. zoeae, *Uca* sp. zoeae

Table V.4. A comparison of phytoplankton assemblages, cell concentrations and primary production rates for various Texas estuaries. Modified from Flint 1984 and Armstrong 1987.

Estuary	Phytoplankton abundance (cells/ml)	Dominant group	Primary Production (g C/m^2/day)
Galveston	50-400	Diatoms	4.11[1]
San Antonio	549-19,000	Dinoflag.	0.70[2]
San Antonio (1986-1987)			1.23[3]
Corpus Christi (1960-1962)	50-900	Diatoms Blue-green algae	1.26[4]
Corpus Christi Bay (1981-1983)			0.48[5]
Corpus Christi Bay (1987-1988)			1.20[6]
Upper Laguna Madre		Diatoms	2.68[4]
Lower Laguna Madre			4.78[4]

[1] Armstrong and Hinson (1973)
[2] Davis (1971)
[3] MacIntyre and Cullen (1988)
[4] Odum and Wilson (1962); Odum et al., (1963)
[5] Flint (1984)
[6] Stockwell (1989)

in the laboratory using 220-watt fluorescent light bulbs. Actual primary production rates in the field may vary considerably from these measurements because of variations in light intensities and container effects.

Oppenheimer et al. (1975) summarized comparative information on primary production for the Galveston, San Antonio and Corpus Christi Estuaries. Measurements of gross primary production were made by comparing changes in oxygen concentration in light and dark bottle incubation. They calculated primary production rates of 5.9, 1.0 and 2.5 g C m^{-3} day^{-1}, again providing evidence that the Galveston Estuary is one of the most productive in Texas.

Day et al. (1987) present a summary of primary production rates in 45 estuarine systems. The rates they report range from near zero to 4.8 g C m^{-3} d^{-1}. The average

Table V.5. Annual phytoplankton primary production estimates for selected North American estuaries. Modified from Flint 1984.

Estuary	Primary Prod. ($g\ C/m^2/yr$)	References
Hudson River Plume, New York	590	Malone 1984
Port Moody Arm, B. Columbia	531	Stockner & Cliff 1979
Pamlico River, North Carolina	500	Kuenzler et al., 1979
Puget Sound, Washington	465	Winter et al., 1975
Great South Bay, New York	450	Lively et al., 1983
San Antonio Bay, Texas (1986-1987)	448	MacIntyre & Cullen 1988
Corpus Christi, Texas (1987-1988)	430	Stockwell, 1989
New York Bight, Mid Atlantic	370	Malone 1976
Three North Carolina Estuaries (average)	320	Fisher et al., 1982
Beaufort Channel, N. Carolina	225	Williams & Murdoch 1966
Narragansett Bay, Rhode Island	220	Smayda 1957
South Bay, San Francisco Bay, California	210	Cloern 1987
Upper New York Harbor	200	Malone 1977
St. Margaret's Bay, Nova Scotia	190	Platt 1971
Corpus Christi Bay, Texas (1981-1983)	174	Flint, 1984
Georgia Bight	171	Haines & Dunston 1975
Wassaw Sound, Georgia	90	Turner et al., 1979
Suisun Bay, California	80	Cloern 1987

from all estuarine systems was approximately 0.7 g C m^{-2} d^{-1}. These values are higher than the 100 g C m^{-3} yr^{-1} that Ryther (1963) reported as an average value for coastal systems, and nearly as great as the 320 g C m^{-2} yr^{-1} reported for coastal upwelling systems. The mean primary production rates found in studies by Mullins (1979), Strong (1977), Krecji (1979) and Smith (1983) suggest that the average production rate for the Galveston Estuary is about 40 mg C m^{-3} hr^{-1}. Given the 2 m average depth of the Estuary, assuming 12 hours for primary production, this corresponds to 1 g C m^{-2} d^{-1}. Although the evidence is somewhat inconclusive, the Galveston Estuary appears to have slightly above average primary production rates for phytoplankton.

Zooplankton Biomass and Abundances

Table V.6 shows estimates of zooplankton biomass and abundances in Texas estuaries. Table V.6A shows data from studies of several estuaries performed by The University of Texas Marine Science Institute, sponsored by the Texas Water Development Board. These systems show zooplankton abundances of 3000-20,000 zooplankters per cubic meter of seawater. Table V.6B shows ranges of zooplankton abundances from Texas estuaries. Although these ranges are difficult to compare, this table indicates that the Galveston Estuary (Trinity Bay) may have lower zooplankton abundance than many other Texas estuaries. Table V.6C shows a comparison of Acartia tonsa abundances in Texas estuaries; A. tonsa is the dominant zooplankter in all. The lowest mean density is for Trinity Bay. It should be noted, however, that McAden (1977) reported a mean abundance of 9600 Acartia tonsa m^{-3} near the intake canal of the Robinson Generating Station. Preliminary interpretations of these data suggest that a high phytoplankton abundance coupled with a low zooplankton abundance may indicate the effects of industrial, agricultural and municipal discharges on the Galveston Estuary. Discharge of nutrients may be responsible for the high level of primary production, while industrial discharges may be suppressing zooplankton populations.

The comparison of zooplankton abundances in Texas estuaries to other estuarine systems in the United States is even more difficult than the comparison of bays along the Texas coast, because there are major climatic, oceanographic and geological differences between systems. Again, collecting technique and frequencies differ for the studies reported in Table V.7 below. The mean abundance of zooplankton found by McAden (1977) of ca 16,200 zooplankton m^{-3} (mainly A. tonsa and barnacle nauplii) using a 153 μm mesh net are higher than for most studies from northeastern bays where a coarser mesh net was used, but lower than densities found in Narragansett Bay, Long Island Sound and the Newport River Estuary, where a similar mesh net was used. For other tropical or subtropical bays, Hopkins (1966, 1977) found higher abundances in the Florida estuaries he studied, but he used a much finer net. Youngbluth (1980) found much lower zooplankton abundances in Jobos Bay, Puerto Rico using a coarser net. It appears that temperate estuaries may have higher zooplankton abundances than the shallow, subtropical bays along the Texas coast.

Table V.6. Comparison of zooplankton biomass and abundances for several Texas estuaries.

A) Comparison of data from UTMSI TWDB studies over the past four years. Biomass is mg dry weight per cubic meter of seawater sampled; zooplankton and _Acartia tonsa_ abundance is number of organisms per cubic meter of seawater sampled. Standard deviations are presented in parentheses.

Estuary	Biomass mg/m^3	Zooplankton abundance	_Acartia tonsa_ abundance
Lavaca Bay 1984-85	61.4 (208.9)	3258 (5910)	1956 (4088)
Lavaca Bay 1985-86	36.9 (57.3)	14864 (47071)	5707 (9532)
San Antonio Bay 1986-87	23.5 (121.8)	10987 (17620)	8310 (16821)
Corpus/Nueces Bay 1987-88	47.3 (45.4)	6879 (6675)	3529 (4592)
San Antonio Day Samples	43.6 (45.2)	8715 (15883)	6287 (15121)
San Antonio Night Samples	183.2 (211.8)	18558 (42332)	15051 (20897)
Corpus/Nueces Day Samples	37.6 (34.9)	6166 (6693)	3192 (4672)
Corpus/Nueces Night Samples	107.3 (73.6)	7103 (2765)	3292 (2667)
Laguna Madre unpublished results)	53.4 (61.2)	7499 (8364)	4536 (4621)

Fewer studies are available for comparison of microzooplankton abundance or biomass, but from the limited data presented in Table V.7, it is apparent that temperate bays have lower microzooplankton abundances than have been reported in Texas. This corresponds with the observation that most of the phytoplankton biomass and productivity is in the less than 20 μm size fraction.

B) Comparison of other Texas estuary studies, modified from Armstrong (1987). Abundances are given as number of organisms x 1000 per cubic meter.

Estuary	Minimum	Maximum	Dominant	Reference
Sabine Lake	0.4 (W-Sp)a	17.2 (S-F)	ND	Espey et al., (1976)
Trinity Bay	1.2 (W)	16.0 (F)	barn. naup. <u>A. tonsa</u>	TDWR (1981)
Lavaca Bay	1.9 (F)	27.9 (Sp)	barn. naup. <u>A. tonsa</u>	Gilmore (1974)
San Antonio Bay	0.8 (S)	46.0 (W)	<u>A. tonsa</u> (1974)	Matthews(1974)
Copano Bay	1.3 (F)	53.6 (W)	<u>A. tonsa</u> (1975)	Holland (1975)
Aransas Bay	2.5 (F)	653.5 (W)	<u>A. tonsa</u>	Holland (1975)
Cor. Christi Bay	5.2 (F)	11,705 (W-Sp)	<u>A. tonsa</u> barn. naup. <u>Noctiluca</u>	Holland (1975)
Nueces Bay	3.3 (F)	2,139 (W)	<u>A. tonsa</u> barn. naup.	Holland (1975)
Alazan Bay	7 (F)	78 (Sp)	<u>A. tonsa</u> (1984)	Cornelius (1984)

C) Comparison of <u>Acartia tonsa</u> abundance in Texas estuaries, from Lee et al., 1986. Densities are number per cubic meter of seawater sampled.

Location	Mean <u>Acartia</u> density	Number of Observations
Corpus Christi	15,916	96
Nueces	6,296	708
San Antonio	5,113	330
Matagorda	423	419
Sabine	75	167
Trinity	42	328

Table V.7. Comparison of zooplankton abundances for several U.S. estuaries.

Macrozooplankton

Estuary	Mesh (μm)	Zooplankton abundance (#/m^3)	Reference
Delaware Bay	241	4,650	Maurer et al., (1978)
Narvesink Estuary	203	320	Knatz (1978)
Sandy Hook Bay, N.J.	203	8,500	Sage & Herman (1972)
Long Island Sound, N.Y.	158	61,500	Deevey (1956)
Narragansett Bay, R.I.	153	22,000	Hulsizer (1976)
Peconic Bay N.Y.	202	6,100	Turner (1982)
Newport River Estuary, N.C.	150	21,900 (copepods only)	Fulton (1984)
Tampa Bay Florida	74	46,595	Hopkins (1977)
St. Andrews Bay Florida	74	40,100	Hopkins (1966)
Jobos Bay Puerto Rico	202	819	Youngbluth (1980)
Microzooplankton (number/liter)			
Narragansett Bay, R.I.		2,029	Verity (1986)
Gulf of Maine		2,400	Montagnes (1988)
Georges Bank		3,120	Stoecker et al., (1989)
Corpus Christi Bay, Texas		37,600	Buskey (1989)

RECOMMENDATIONS

Implications for the Priority Problems List

The most significant challenges facing the Galveston Bay National Estuary Program have been summarized in the Priority Problems List. The four major problems addressed by this list are: A. Reduction/Alteration of Living Resources, B. Public Health Issues, C. Resource Management Issues and D. Shoreline Erosion. Studies of the plankton populations of the Galveston Estuary have direct implications only for the first priority problem: reduction and alteration of living resources. Studies of phytoplankton biomass and productivity have important implications for identifying areas of excess nutrient loading, leading to excess phytoplankton production and potentially hypoxic conditions.

Increased growth of phytoplankton in estuarine systems becomes problematic only when phytoplankton growth exceeds the ability of grazers to pass this resource on to higher trophic levels. When excess nutrients are discharged into the estuary along with industrial and agricultural wastes which may be toxic to grazers, the potential for excessive phytoplankton growth increases. High levels of primary production, accompanied by water column stratification can result in hypoxic conditions that cause fish kills and severely degrade the environment. Long term data on phytoplankton standing stocks is needed to determine if eutrophication is occurring.

Recommendations for Future Monitoring

In order to design a program to monitor the plankton of the Galveston Estuary, the long term goals of the program must be clearly stated. If the goals of the program are to detect long term changes in the plankton population of the Galveston Estuary and to monitor the system for signs of perturbation caused by eutrophication, several recommendations can be made. Sampling sites should be randomly chosen to sample several sites each within areas that typically have low, medium and high (full strength seawater) salinity ranges. Sampling intervals should be as frequent as practical, because rapid changes in phytoplankton populations can occur in a matter of days.

Perhaps the easiest parameter to measure on a routine basis is phytoplankton biomass as chlorophyll a concentration. Seawater samples can be collected at each site and kept in the dark on ice until filtration of samples can be performed. Preferably samples should be size fractionated with a 20 μm screen to measure the proportion of chlorophyll in the net plankton and nanoplankton fractions. Chlorophyll concentrations can be easily and reliably measured using fluorometric techniques (Parsons et al. 1984). Samples can also be collected for taxonomic identification of phytoplankton species composition, but this is a tedious, time-consuming process that requires personnel with considerable technical expertise. Additional information about the relative composition of major taxonomic groups in the phytoplankton can be obtained through analysis of the suite of phytoplankton pigments in the sample, and identifying the relative proportion of pigments characteristic of various taxonomic groups using high-performance liquid chromatography (Bidigare et al. 1985).

Measures of primary production would also be useful, but these measures are expensive, time-consuming and require the use of radioactive isotopes in field incubations (Carbon 14 uptake method, Parsons et al. 1984). Primary production is measured over a few hours in field incubations, and these measures are quite variable depending on sunlight, nutrient availability and other factors. A more useful approach may be to determine photosynthesis-irradiance relationships for the Galveston Estuary phytoplankton during several times of the year, monitor submarine irradiance with a submersible photometer and model primary production over the annual cycle (Platt et al. 1977; Lewis and Smith 1983).

Monitoring zooplankton populations would also be useful for both microzooplankton and mesozooplankton size fractions. Microzooplankton can be collected as whole water samples in estuarine systems because they have high population densities. Samples can be preserved in the field using Lugol's Iodine or formaldehyde, but these samples will not preserve chlorophyll fluorescence, and can only be used to enumerate ciliates, rotifers, copepod nauplii and other distinctive forms. Ideally, samples should be preserved in glutaraldehyde and refrigerated in darkness until enumeration. These samples will retain autofluorescence of chlorophyll, allowing for differentiation between autotrophic and heterotrophic flagellates. A small volume (ca 5-10 ml) should be placed in a settling chamber, and enumerated using an inverted epifluorescence microscope. Organisms need not be identified to species, but should be categorized and measured. Mesozooplankton sampling should be performed with a 1/2 m diameter 153 μm mesh net, fitted with a flow meter. Ctenophores and other gelatinous zooplankton can be separated from the catch with a coarse mesh (ca 5 mm) and the displacement volume of gelatinous zooplankton can be measured in the field and the organisms released. Mesozooplankton samples can be preserved in a 5 percent buffered formaldehyde solution. If dry weight estimates of biomass are desired, these should be taken using an unpreserved split of the sample. Dry weight of zooplankton decreases after preservation.

REFERENCES

Armstrong, N. E., and M. O. Hinson. 1973. Galveston bay ecosystem freshwater requirements and phytoplankton productivity. Pages II-1--II-98 in C. H. Oppenheimer, editor. Toxicity Studies of Galveston Bay Project. Report to Texas Water Quality Board, Contract #IAC (72-73), Austin, Texas.

Armstrong, N. E. 1987. The ecology of open-bay bottoms of Texas: a community profile. U.S. Fish and Wildlife Service Biological Report 85(7.12).

Arnold, E. L., Jr., R. S. Wheeler and K. N. Baxter. 1960. Observations on fishes and other biota of East Lagoon, Galveston. U.S. Fish and Wildlife Service Special Scientific Report Fisheries No. 344.

Bagnall, R. A. 1976. Definition and persistence of an estuarine zooplankton assemblage. Doctoral dissertation, University of Houston, Houston, Texas.

Bidigare, R. R., M. C. Kennicutt and J. M. Brooks. 1985. Rapid determination of chlorophylls and their degradation products by high-performance liquid chromatography. Limnology and Oceanography 30:432-436.

Buskey, E. J. 1989. Effects of freshwater inflow on the zooplankton of Texas coastal bays. Texas Water Development Board, Austin, Texas.

Chase, C. L. 1977. Survival of zooplankton entrained into the cooling system and supplemental cooling towers of a steam electric generating station. Master's Thesis. Texas A&M University, College Station, Texas.

Cloern, J. E. 1987. Turbidity as a control on phytoplankton biomass and productivity in estuaries. Continental Shelf Research 7: 1367-1381.

Copeland, B. J. and T. J. Bechtel. 1971. Species diversity and water quality in Galveston Bay. Water Air and Soil Pollution Vol. 1 (1):89-105.

Cornelius, S. E. 1984. An ecological survey of Alazan Bay, Texas. Vol 1. Technical Bulletin no. 5.

Cushing, D. H. 1959. The seasonal variation in oceanic production as a problem in population dynamics. Journal de Conseil International pour l'Exploration de la Mer 24:455-464.

Davis, E. M. 1971. Development of methodology for evaluation and prediction of the limnological aspects of Matagorda and San Antonio Bays. Report to the Texas Water Development Board, Contract #IAC (72-73), Austin, Texas.

Day, J. W., R. H. Day, M. T. Barreiro, F. Ley-Lou and C. J. Madden. 1982. Primary production in the Laguna de Terminos, a tropical estuary in the Southern Gulf of Mexico. Oceanologica Acta 269-275.

Day, J. W., Jr., C. A. S. Hall, W. M. Kemp and A. Yanez-Arancibia. 1987. Estuarine Ecology. Wiley-Interscience.

Deevey, G. B. 1956. Oceanography of Long Island Sound, 1952-1954. Vol. V: Zooplankton. Bulletin of the Bingham Oceanographic Collection, Yale University. 17: 5-53.

Espey, Huston and Associates, Inc. 1976. Ecological studies in Sabine Lake, 1974-1975. Texas Department Water Resources, Austin, Texas.

Fisher, T. R., P. R. Carlson, and R. T. Barber. 1982. Carbon and nitrogen primary productivity in three North Carolina estuaries. Estuarine Coastal and Shelf Science 15: 621-644.

Flint, R. W. 1984. Phytoplankton production in the Corpus Christi Bay Estuary. Contributions in Marine Science 27:65-83.

Fulton, R. S. 1984. Distribution and Community Structure of Estuarine Copepods. Estuaries 7: 38-50.

Gilmore, G., G. Matthews, and G. Clements. 1974. An ecological study of the plankton and benthos in Lavaca Bay, Texas. Texas Parks and Wildlife Department, Technical Report to Texas Water Development Board, Austin, Texas.

Haines, E. B. and W. M. Dunstan. 1975. The distribution and relation of particulate organic matter and primary production in the Georgia Bight, 1973-1974. Estuarine and Coastal Marine Science 3: 431-441.

Harding, L. W., Jr., B. W. Meeson, and T. R. Fisher, Jr. 1986. Phytoplankton production in two east coast estuaries: photosynthesis-light functions and patterns of carbon assimilation in Chesapeake and Delaware Bays. Estuary and Coastal Shelf Science 23:773-806.

Hohn, M. H. 1959. The use of diatom populations as a measure of water quality in selected areas of Galveston and Chocolate Bay, Texas. Publications of the Institute of Marine Science, University of Texas 6:206-212.

Holland, J. S., N. S. Maciolek, R. D. Kalke, L. Mullins, and C. H. Oppenheimer. 1975. A benthos and plankton study of the Corpus Christi, Copano, and Aransas Bay Systems. Final Report to Texas Water Development Board from University of Texas Marine Science Institute, Austin, Texas.

Holt, G. J. 1976. Final report on community structure of macrozooplankton in Trinity and Upper Galveston Bays, with special reference to the cooling water system of Cedar Bayou electric generating station. Doctoral dissertation. Texas A&M University, College Station, Texas.

Hopkins, T. L. 1966. The plankton of the St. Andrew Bay system, Florida. Publications of the Institute of Marine Science, University of Texas 11: 12-64.

Hopkins, T. L. 1977. Zooplankton distribution in surface waters of Tampa Bay, Florida. Bulletin of Marine Science 27: 467-478.

Hulsizer, E. H. 1976. Zooplankton of Lower Narragansett Bay, 1972-1973. Chesapeake Science 17: 260-270.

Jones, R. L. 1975. Species composition, distribution and abundance of macro-plankton in the intake and discharge areas after construction and operation of the Cedar Bayou Electric Power Station. Master's Thesis. Texas A&M University, College Station, Texas.

Kalke, R. D. 1972. Species composition, distribution and seasonal abundance of macrozooplankton in intake and discharge areas before and during early operation of the Cedar Bayou generating station. Master's Thesis. Texas A&M University, College Station, Texas.

Knatz, G. 1978. Succession of copepod species in a middle Atlantic estuary. Estuaries 1: 68-71.

Krecji, M. E. 1979. The effects of the effluent from an electrical generating station on the phytoplankton of Trinity Bay, Texas. Master's Thesis. Texas A&M University, College Station, Texas.

Kuenzler, E. J., P. W. Stanley, and J. P. Koenings. 1979. Nutrient kinetics of phytoplankton in the Pamlico River, North Carolina. Water Resources Research Institute, University of North Carolina, Report #139. Chapel Hill, North Carolina.

Lee, W. Y., C. R. Arnold, and R. D. Kalke. 1986. Synthesis of data on Acartia tonsa in Texas bay systems: correlation between its abundance and selected environmental factors. Report to Texas Water Development Board, Austin, Texas.

Lewis, M. R., and J. C. Smith. 1983. A small volume, short-incubation-time method for measurement of photosynthesis as a function of incident irradiance. Marine Ecology Progress Series 13:99-102.

Lively, J. S., C. Kaufman, and E. J. Carpenter. 1983. Phytoplankton ecology of a barrier island estuary: Great South Bay, New York. Estuarine Coastal and Shelf Science 16: 51-68.

Livingston, G. P. 1981. Distribution of the crustacean zooplankton in a subtropical estuarine system. Doctoral dissertation. Texas A&M University, College Station, Texas.

MacIntyre, H. L., and J. J. Cullen. 1988. Resuspension of sediment and microphytobenthos in a shallow bay: effects on net productivity. Abstract, American Society of Limnology and Oceanography Winter Meeting 1988.

Malone, T. C. 1976. Phytoplankton production in the apex of the New York Bight: environmental regulation of production/chlorophyll a. American Society of Limnology and Oceanography, Special Symposium 2: 260-272.

Malone, T. C. 1977. Light saturated photosynthesis by size fractions in the New York Bight, U.S.A. Marine Biology 42: 281-292.

Malone, T. C. 1980. Algal size. Pages 433-463 in I. Morris, editor. The physiological ecology of phytoplankton. Blackwell, Oxford.

Malone, T. C. 1984. Anthropogenic nitrogen loading and assimilation capacity of the Hudson River Estuarine System, USA. Pages 292-311 in V.S. Kennedy, editor. The Estuary as a Filter. Academic Press.

Marsh, J. A. 1974. Tropical inshore plankton systems. Pages 488-513 in H. T. Odum, B. J. Copeland, and E. A. McMahan, editors. Coastal Ecological Systems of the United States. Vol. I. Conservation Foundation Publication, Washington, D.C.

Matthews, G. A., C. A. Marcin, and G. L. Clements. 1974. A plankton and benthos survey of the San Antonio Bay System. Texas Parks and Wildlife Department Final Report to Texas Water Development Board. Austin, Texas.

Maurer, D., L. Watling, R. Lambert, and A. Pembroke. 1978. Seasonal fluctuation of zooplankton populations in lower Delaware Bay. Hydrobiologia 61: 149-160.

McAden, D. C. 1977. Species compostion, distribution and abundance of zooplankton (including icthyoplankton) in the intake and discharge canals of a steam-electric generating station located on Galveston Bay. M. S. Thesis, Texas A&M University, College Station, Texas.

Minello, T. J. and G. A. Matthews. 1981. Variability of zooplankton tows in a shallow estuary. Contributions in Marine Science, University of Texas 24:81-92.

Montagnes, D. J. S., H. D. Lynn, J. C. Ross, and W. D. Taylor. 1988. The annual cycle of heterotrophic planktonic ciliates in the waters surrounding the Isles of Shoals, Gulf of Maine: an assessment of their trophic role. Marine Biology 99: 21-30.

Mullins, H. L. 1979. The effects of power plant effluents on the growth of phytoplankton in adjacent areas of Trinity Bay. Master's Thesis. Texas A&M University, College Station, Texas.

Odum, H. T. and R. Wilson. 1962. Further studies on reaeration and metabolism of Texas Bays, 1958-1960. Publications of the Institute of Marine Science, University of Texas 8: 23-55.

Odum, H. T., R. P. Cuzondurest, R. J. Beyers, and C. Allbaugh. 1963. Diurnal metabolism, total phosphorus, and zooplankton diversity of abnormal marine ecosystems of Texas. Publications of the Institute of Marine Science, University of Texas 9:404-453.

Oppenheimer, C. H., T. Isensee, W. B. Brogden and D. Bowman. 1975. Establishment of operational guidelines for Texas coastal zone management. Biological uses criteria. Final Report to the National Science Foundation IAC (74-75) - 0685.

Parsons, T. R., Y. Maita and C. M. Lalli. 1984. A manual of chemical and biological methods for seawater analysis. Chapter 4: Plant Pigments. Pergamon Press.

Platt, T. 1971. The annual production by phytoplankton in St. Margaret's Bay, Nova Scotia. Journal du Conseil International pour l'Exploration de la Mer 23: 324-334.

Platt, T., K. Denman and A. D. Jossby. 1977. Modeling the productivity of phytoplankton. Pages 807-856 in E. D. Goldberg, editor. The Sea, Vol. VI. John Wiley, New York.

Ryther, J. H. 1963. Geographical variations in productivity. Pages 347-380 in M.N. Hill, editor. The Sea, Vol. II. Wiley-Interscience, New York.

Sage, L. E. and S. S. Herman. 1972. Zooplankton of the Sandy Hook area, New Jersey. Chesapeake Science 13: 29-39.

Smayda, T. J. 1957. Phytoplankton studies in lower Narragansett Bay. Limnology and Oceanography 2: 342-359.

Smith, J. M. 1983. The effects of Cedar Bayou Electric Generating Station on phytoplankton in adjacent waters. Master's Thesis. Texas A&M University, College Station, Texas.

Stockner, J. D. and D. D. Cliff. 1979. Phytoplankton ecology of Vancouver Harbor. Journal of the Fisheries Research Board of Canada 36: 1-10.

Stockwell, D. A. 1989. Effects of freshwater inflow on the primary production of a Texas Coastal Bay System. Report to Texas Water Development Board, Austin, Texas.

Stockwell, D. A., and Buskey, E. J. in prep. Phytoplankton primary production and zooplankton grazing within the Upper Laguna Madre of South Texas.

Stoecker, D. K., A. Taniguchi, and A. E. Michaels. 1989. Abundance of autotrophic, mixotrophic, and heterotrophic planktonic ciliates in shelf and slope waters. Marine Ecology Progress Series 50: 241-254.

Strong, C. B. 1977. Discharge waters from a power plant as an influent of phytoplankton in adjacent estuarine waters. Master's Thesis. Texas A&M University, College Station, Texas.

Texas Department of Water Resources. 1981. Trinity-San Jacinto Estuary: a study of the influence of freshwater inflows. LP-113. Austin, Texas.

Turner, J. T. 1982. The annual cycle of zooplankton in a Long Island Estuary. Estuaries 5: 261-274.

Turner, R. E., S. W. Woo, and H. R. Jitts. 1979. Phytoplankton production in a turbid, temperate salt marsh estuary. Estuarine and Coastal Marine Science 9: 603-613.

Valiela, I. 1984. Marine Ecological Processes. Springer-Verlag.

Verity, P. G. 1986. Grazing of phototrophic nanoplankton by microzooplankton in Narragansett Bay. Marine Ecology Progress Series 29: 105-115.

Williams, R. B. and M. B. Murdoch. 1966. Phytoplankton production and chlorophyll concentration in the Beaufort Channel, North Carolina. Limnology and Oceanography 11: 73-82.

Winter, D. F., K. Banse, and J. C. Anderson. 1975. The dynamics of phytoplankton blooms in Puget Sound, a fjord in the northwest United States. Marine Biology 29: 139-176.

Youngbluth, M. J. 1980. Daily, seasonal, and annual fluctuations among zooplankton populations in an unpolluted tropical embayment. Estuary and Coastal Marine Science 10: 265-287.

Zein-Eldin, Z. P. 1961. Plankton Pigments in East Lagoon, Galveston, Texas. Transactions American Fisheries Society 90:32-41.

Zotter, J. 1979. Species composition and seasonal occurrence of nanoplankton in the Galveston Bay estuary. Master's Thesis. Texas A&M University, College Station, Texas.