SEASONAL ANALYSIS OF ABIOTIC FACTORS IMPACTING PHYTOPLANKTON ASSEMBLAGES IN OFFATTS BAYOU, GALVESTON, TEXAS

A Thesis

by

LINDA RAE ROEHRBORN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2006

Major Subject: Oceanography

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Approved by:

Chair of Committee,	Antonietta Quigg
Committee Members,	James L. Pinckney
	Sammy Ray
	Steven F. DiMarco
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ABSTRACT

Seasonal Analysis of Abiotic Factors Impacting Phytoplankton Assemblages

in Offatts Bayou, Galveston, Texas. (December 2006)

Linda Rae Roehrborn, B.S., Arizona State University

Chair of Advisory Committee: Dr. Antonietta Quigg

The aim of this investigation in Offatts Bayou was to quantify natural shifts in distributions and abundances of algal groups and to examine spatio-temporal patterns of abiotic and biotic characteristics in the water column over a one year period. To accomplish this, hydrological and meteorological parameters were collected and phytoplankton biomass, community composition and chlorophyll *a* data were examined for significant relationships. Seasonal variations in water temperature, salinity, dissolved oxygen concentrations and pH levels, as well as wind effects, zooplankton grazing, light availability and hydrodynamic restriction were considered as the key controlling factors in phytoplankton dynamics in Offatts Bayou.

Surface water samples and water column hydrological data were collected at eleven stations in the Offatts Bayou embayment on a regular basis (2 to 4 times per month), along with phytoplankton tows on a monthly basis. Spatial patterns of phytoplankton abundance generally reflected the degree of circulation in Offatts Bayou with higher abundances observed in the restricted areas and lower abundances in the well mixed regions. Temporally, diatom blooms became more prominent during

winter, spring and autumn, which were characterized by cooler temperatures, less light availability, increased dissolved oxygen concentrations and reduced salinities than observed in summer. The most dominant diatoms were *Guinardia delicatula*, *Ditylum brightwelli, Rhizosolenia setigera, Dactyliosolen fragillissimus* and numerous *Chaetoceros* species. During summer, the waters of Offatts Bayou were warmer and more saline, which lead to the haptophyte, *Corymbellus aureus,* becoming the dominant taxa, with highest standing crops at the circulation restricted stations in Lake Madeline.

While the results of this study support the importance of temperature, dissolved oxygen and pH as the critical controlling factors ($p < 0.05$) of phytoplankton biomass and diversity, it is clear that phytoplankton dynamics in Offatts Bayou must be viewed within the broader context of additional parameters such as salinity, stratification and wind effects. The progressively degrading conditions within Offatts Bayou emphasize the significance of studying and understanding the interrelationships of factors and mechanisms that influence phytoplankton dynamics. Long term monitoring of Offatts Bayou is essential for tracking, recording and assessing various human impacts to phytoplankton distribution, abundance, and productivity as well as impacts to higher trophic levels such as fish and humans.

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1. INTRODUCTION

1.1 Galveston Bay and Offatts Bayou

The importance for ecological management of the Galveston Bay Estuary has long been recognized by various agencies and it is at the top of the Environmental Protection Agency's (EPA) list of priority conservation sites. The Galveston Bay National Estuary Program (GBNEP), a program of the Texas Commission on Environmental Quality (TCEQ), is part of a network of twenty-eight National Estuary Programs (NEP) in the United States (Lester *et al.*, 2002). The GBNEP was established in 1988 to specifically monitor and manage Galveston Bay's vital watershed of roughly 63,000 km^2 and to restore and protect it from threats, such as pollution and development.

The Galveston Bay Estuary is considered a region of high biological productivity and is the home, shelter, spawning, feeding and nursery areas of a largely diverse population of birds, mammals, fish, and plants. Besides being an essential habitat for marine animals, Galveston Bay's wetlands provide other critical services. Water drainage from the mainland carries sediments, nutrients, and other pollutants, which are then removed or utilized by aquatic plants as the water flows through the salt water marshes. Additionally, plants and soils of wetland habitats act as natural buffer by absorbing flood waters, stabilizing the shoreline, preventing erosion and dissipating

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This thesis follows the style of Journal of Experimental Marine Biology and Ecology.

storm surges.

Within the Galveston Bay Estuary (Fig. 1.1a) is Offatts Bayou (Fig. 1.1b and c); a shallow, blind embayment, with a narrow channel that widens at the mouth into West Bay. It is approximately 1 km wide x 2 km long, with depth ranging from 4 meters at the mouth to approximately 11 meters at the blind end. Offatts Bayou was initially created, after the 1900 Hurricane, by the city of Galveston as a borrow pit for notable local construction sites, such as Pelican Island (1904-1906), Fort Crockett (1907, 1909), the Galveston Seawall (1922-1923, 1925) and the Texas City dike (1915-1931) (Gilardi, 1942). Offatts Bayou constituted one of the greatest dredge-and-fill ventures of the early 1900's (Gilardi, 1942), contributing approximately 19×10^6 m^3 of soil and has now become a permanent back-island fixture of the Galveston Bay estuary system.

During WWII, Offatts Bayou was dredged as a military project to support the Galveston Air Base (U.S. Army Corp of Engineers, 1971). Initial dredging of the inner regions of Offatts Bayou caused recurring annual deaths of marine organisms that had not been observed in previous years. In 1971, the U.S. Army Corp of Engineers re-dredged the narrow boat channel in the hopes of correcting the dilemma, but poor circulation and input of nutrient-rich urban runoff continued to cause seasonal changes in the quality of the water column. Currently, excess nutrients from the inflow via lawn fertilization and storm drains produce high concentrations of contaminants in oysters, resulting in Offatts Bayou being ranked as "one of the most contaminated areas in the Gulf of Mexico" (Jackson *et al.*, 1998).

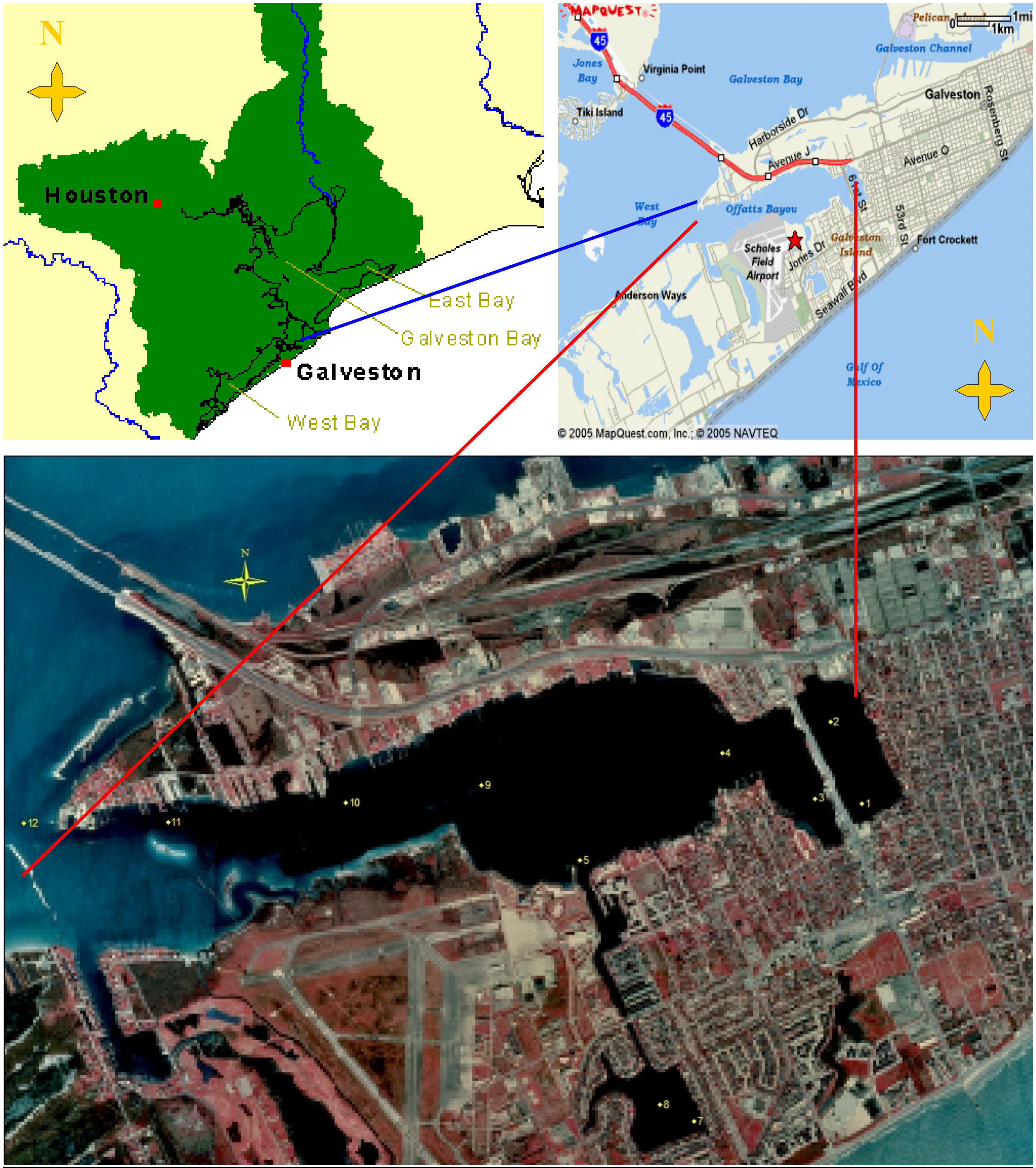

Fig. 1.1 Maps of study site and surrounding regions
a. Cities of Houston and Galveston, Texas. (Courtesy of U.S.EPA)
b. West Bay and Offatts Bayou, Galveston, Texas. (Courtesy of Mapquest)
c. Offatts Bayou, Galveston, Texas. (Courtesy of Allison Skinner – TAMUG)

By its very nature, Offatts Bayou experiences restricted exchange with waters in the adjoining West Bay, which results in hydrogen sulfide crises and frequent phytoplankton blooms. These potential problems are the cause of summer fish kills. For example, in the late 1930's, Gunter (1942) investigated the recurring summer fish kill in Offatts Bayou and concluded that hydrogen sulfide "boils" were the culprit. Conversely, in 1949, Connell and Cross (1950) associated the fish kill in Offatts Bayou to a phytoplankton bloom of *Gonyaulax* stating, "Nearby residents and fishermen reported the appearance of red tides and accompanying phenomena for almost every summer during the past 15-20 years, and that the fish did not die in the "red water" but died quickly when the redness settled and the water became "white" or "milky"". They attributed the milky discoloration to turbidity when the *Gonyaulax* settled to the bottom. Gunter and Lyles (1979) disagreed with this evaluation, but in later reflection realized Connell and Cross (1950) were correct in their analysis.

1.2 Hypoxia

Hypoxia refers to water with 2 mg/L or less of dissolved oxygen (Pavela *et al.*, 1983; Dauer *et al*., 1992). Observations of severe decreases in the abundances and diversity of marine species occur below this critical oxygen level. The U.S. Environmental Protection Agency (EPA) conducted laboratory experiments on sensitive marine species in the effort to define significant water quality criteria for dissolved oxygen (Thursby *et al.*, 2000). The EPA study resulted in two findings. First, to guarantee survival of the majority of coastal species, dissolved oxygen concentrations should not fall below 2.3 mg/L and second, to ensure normal growth of most coastal species, dissolved oxygen concentrations should never decline below 4.8 mg/L (Thursby *et al.*, 2000).

Hypoxia is a widespread phenomenon throughout the Texas coast, having been reported in Corpus Christi Bay (Montagna and Kalke, 1992; Applebaum *et al.*, 2005), Freeport (Harper *et al.*, 1981), Galveston Bay (Harper and Guillen, 1989) and the Louisiana/Texas continental shelf (Rabalais *et al.*, 2002). Reduced macrobenthic community diversity, abundance and biomass, as a result of hypoxia, were found by Ritter and Montagna (1999) in Corpus Christi Bay, Texas and by others in the Gulf of Mexico (Pavela *et al.,* 1983; Rabalais *et al.,* 2002). In Galveston Bay, Harper and Guillen (1989) determined that a dinoflagellate, *Gymnodinium splendens*, bloom associated with an influx of low saline water caused hypoxic water conditions, resulting in a fish kill of Atlantic threadfin (*Polydactylus octonemus*) in early summer, 1984.

1.3 Phytoplankton Information

1.3.1 Phytoplankton community changes

Phytoplankton are a vital component of marine ecosystems and are responsible for the majority of primary production that takes place in the world's oceans, lakes, reservoirs and streams. There is compelling evidence that spatial and temporal patterns in phytoplankton abundance, "phytoplankton patchiness", exists and is influenced by biological, chemical and physical factors (Platt and Denham, 1980). These factors can affect the phytoplankton community composition by naturally selecting species that can survive in the surrounding conditions. Phytoplankton abundance and diversity generally undergo successional patterns from season to season and year to year, much like terrestrial plant communities do (Elser *et al.*, 1995). During a one year study from Dec 1990 - Nov 1991 in the Dungeness, U.K., Chapman *et al.* (1998) observed and concluded that differences in salinity levels at five sites was the key determinant in the seasonal variation of the phytoplankton population.

1.3.2. Bacillarophyta (Diatoms)

It is well known that diatoms are associated with low temperatures, low salinities, high silica concentrations and are the prominent class of phytoplankton in temperate and high latitudes (Lalli and Parsons, 1997). Diatoms were found to be dominant during the colder fall and winter months in the upper and lower portions of Galveston Bay, as well as the Galveston Island beach front (Zotter, 1979).

Diatoms are well studied planktonic forms, with cell sizes ranging from 2 μm to greater than 1000 μm (Lalli and Parsons, 1997). The frustule of diatoms, composed of opaline silica (SiO_2), is an optimal shielded window thought to protect diatoms from predators but still allow sunlight to penetrate for photosynthesis. The frustule is also heavy and mechanisms for floatation are necessary to stay in the photic region to carry out photosynthesis. To remain buoyant, diatoms must increase their surface area by forming chains, encircling themselves with spines or storing oil internally to decrease the rate at which they sink.

Two classes of diatoms have been defined based upon the symmetry and structure of their frustule: Pennaceae and Centracae. Pennate diatoms have bilateral symmetry, appearing slender and curved like rods (Tomas, 1997; Quigg and Wardle, 2005). Representatives of the Pennate class include *Navicula* spp*., Pleurosigma* spp*.,* and *Pseudonitzschia* spp*.,* which can be found in single cells or as chains. Centric diatoms are radially symmetrical, appearing round like pillboxes or baskets (Tomas, 1997; Quigg and Wardle, 2005) and include *Coscinodiscus* spp*., Chaetoceros* spp. and *Skeletonema* spp that are found as single cells or in chains. Because of their shape, centric diatoms float better than pennate diatoms and, thus, centric diatoms tend to be strictly planktonic while pennate diatoms tend to be primarily benthic.

More then 54 species of diatoms have been identified in Galveston Bay thus far (Texas Department of Water Resources, 1981) and were the dominant genera in West Bay, near Offatts Bayou in 1969 (Armstrong and Hinson, 1973). Numerous phytoplankton species were found to inhabit Offatts Bayou inlet during a preliminary sampling expedition in Autumn 2004 (Table 1.1).

Table 1.1.
Common phytoplankton species in Offatts Bayou (Autumn 2004).

Division of Phytoplankton	Genus
Cyanobacteria	*Microcystis*
	Lyngbya
Bacillariophyta – Centric Diatoms	*Chaetoceros*
	Coscinodiscus
	Ditylum
	Guinardia
Bacillariophyta – Pennate Diatoms	*Pseudo-nitzschia*
	Rhizosolenia
	Thalassionema
	Odontella

1.3.3 Phytoplankton Bloom Dynamics

In shallow, turbid ecosystems, such as estuaries, human activities are altering the environment and causing phytoplankton changes in diversity and biomass to occur more frequently. Irigoien *et al.* (2004), stated that "Our knowledge of biodiversity patterns in marine phytoplankton is very limited compared to that of the biodiversity of plants and herbivores in the terrestrial world". Variations in phytoplankton composition or abundance have significant direct or indirect impacts on other marine communities (Cloern, 1996), such as episodes of anoxia in the Black Sea (Mee, 1992), Chesapeake Bay oyster population decline (Smith *et al.*, 1992), exotic invertebrate invasion in San Francisco Bay (Alpine, 1992) and Monterey Bay seabird mortalities (Walz *et al.*, 1994), to name a few. During summer of 2000, Galveston Bay experienced a major toxic phytoplankton bloom produced by the red tide dinoflagellate, *Karenia brevis*, which temporally closed harvesting of oyster beds (Denton, 2001; Evans and Jones, 2001). *K. brevis* produces brevetoxin, a neurotoxin that paralyzes the muscles and nerves of some estuary inhabitants, resulting in suffocation of those organisms affected and fish kill episodes.

1.4 Major Influences on Phytoplankton Community Dynamics

1.4.1 Stratification

Salinity, temperature, and water depth are principal parameters that affect the stratification status of estuarine waters. Vertical stratification, or layering of waters of different densities, may occur in an estuary when warmer and fresher water flowing outward overlies colder, saltier water flowing in from the ocean. This condition can be sustained only when wind and tidal effects are insufficient to mix the water column. Density stratification varies between and within seasons depending upon the amount of precipitation and air temperature. In most estuaries, density stratification of the water column generally intensifies in the spring as freshwater inflow increases due to rainfall or riverine inflow and is sustained through the summer when surface water temperatures increase. Large density differences can result in a reduced rate of dissolved oxygen mixing between the bottom and surface waters, potentially leading to the bottom waters becoming hypoxic or anoxic.

1.4.2 Temperature

Temperature is a measure of the water's kinetic energy and aids in the regulation of ecosystem health through its physiological effects on the organisms in the environment. Temperature as a factor in phytoplankton community dynamics has been investigated for many different species and certain phytoplankton species have been observed to have a unique temperature range for growth (Eppley, 1972). When water temperatures change, biological, physical and chemical reactions within an organism are altered, thus affecting community structure by selecting those best suited to survive. Reproduction, growth, metabolism, microbial processes and especially photosynthesis rates can all be increased or decreased by water temperature changes. For example, during the springtime in the Chesapeake Bay, phytoplankton can undergo rapid population growth or "algal blooms" when water temperatures rise in the presence of excess nutrients (Fisher *et al*., 1992). Phlips *et al*. (2002) measured phytoplankton concentrations at multiple points in a restricted lagoon along the Indian River, FL and concluded that there was a positive correlation between increasing temperature and increasing chlorophyll *a* concentrations in most of the study sites.

During a relatively recent study by Cooper and Morse (1996), summer surface values, from 1993, for the Deep Hole in Offatts Bayou (Fig. 1.1c) were 30.5 °C, decreased steadily to 29.5 °C at 6.5 m, then continued at that temperature throughout the remaining water column to the 9.5 m bottom. Winter temperature reflected a colder environment with surface waters measuring 16 °C, decreasing to 14.5 °C at 5m and below (Cooper and Morse, 1996). These values were very similar to the Offatts Bayou temperatures recorded by Gunter (1942) in 1940-1941. In his study, temperatures at the Deep Hole were 16.2 °C (surface) and 16.0 °C (bottom) during a mid December sampling and 31.0 °C (surface) and 29.2 °C (bottom) in late August.

1.4.3 Salinity

Salinity is the measure of the total content of salt in water and can be increased through evaporation or decreased through freshwater deposition via precipitation, river inflow, and ice or snow melt. Estuaries, such as Galveston Bay, experience extensive variability in their salinity ranges (0 – 30 ppt) via freshwater input from the mainland rivers (San Jacinto and Trinity rivers) and inflow of salt water from the Gulf of Mexico (Fig. 1.2).

Salinity is essential and significant to all marine organisms for their optimal health with some phytoplankton species having a relatively narrow window in which they can survive. When salinity levels increase above or below their range, osmoregulation is deleteriously affected and the organism may die through pressures from predation or competition (Lalli and Parsons, 1997). On the contrary, variations in salinity can also provide favorable conditions for opportunistic phytoplankton communities to become dominant in composition, distribution and abundance. In a study by Qian *et al.* (2003), links between salinity levels and temporal and spatial variations in phytoplankton community composition were found in the northeast Gulf of Mexico. They determined that greater concentrations of prymnesiophytes and pelagophytes were found to inhabit the waters with salinity greater than 30 ppt and higher concentrations of diatoms resided in waters of salinity less than 30 ppt (Qian *et al.,* 2003).

Cooper and Morse (1996) reported that 1993 summer salinity surface values for the Deep Hole in Offatts Bayou was 31.5 ppt, increased steadily to 33.75 ppt at 6.5 meters (m), and continued to increase to 34.0 ppt throughout the remaining water column to the 9.5 m bottom. In contrast, winter reflected surface salinities at 20.75 ppt, then increased to 21.0 ppt for the remaining water column (Cooper and Morse, 1996). Given the range of salinities measured by Cooper and Morse (1996) for Offatts Bayou, one could predict there will be a diverse phytoplankton community in this system.

1.4.4 pH

pH is a measure of the acidic $[H^+]$ or alkaline $[OH^-]$ nature of water and is represented on a numerical scale from 14 (alkaline) through 7 (neutral) to 0 (acidic). Marine coastal waters, such as those in Galveston Bay, general exhibit an average pH of 7.7 (Lester *et al.*, 2002), although there have been some recent reports of extreme pH values greater than 9.0 in the Houston Ship Channel, Trinity Bay, Clear Lake, Armand Bayou and Taylor Bayou and less than 6.0 in the deep waters of the Houston Ship Channel in winter (1986 and 1996) (Criner and Johnican, 2001).

As with temperature and salinity, organisms also have a narrow pH range that they can survive or be active in. Changes in pH can have numerous unfavorable affects on organisms through physiological processes, availability of metals and toxins and other chemical and biological processes (Lalli and Parsons, 1997). Daily photosynthetic activity by phytoplankton in estuarine waters can increase dissolved oxygen levels and, as a consequence, raise pH as dissolved carbon dioxide is removed. Nonetheless, during non-bloom periods, the pH in an estuary will tend to remain fairly constant (low variability) because the chemical components of seawater resist large changes in pH; dissolved carbonate minerals present in seawater tend to minimize or “buffer” pH changes by reacting with the ions that change pH (Millero, 1996).

1.4.5 Oxygen

Dissolved oxygen (mg/L) or percent (%) oxygen saturation measurements indicate the amount of oxygen contained in water and aids in determining the conditions that aerobic organisms live under in an estuarine environment. Salinity, temperature and atmospheric pressure influence the solubility of oxygen in water (as water temperature and salinity increases, the solubility of oxygen decreases; as pressure increases, solubility of oxygen increases). Consequently, estuarine dissolved oxygen levels vary seasonally, with lowest measurements recorded during the late summer months when water temperatures and salinities are at their highest peaks and highest dissolved oxygen concentrations during the colder winter and lowered salinity.

Excess inflow of nutrients or organic matter from runoff will generally stimulate phytoplankton growth into blooms that produce increased oxygen levels. When a phytoplankton bloom occurs and subsequently decomposes, the amount of dissolved oxygen in the water column generally decreases to hypoxic or anoxic levels that are detrimental to bottom dwelling organisms and other marine animals. Shallow, well mixed estuarine systems are generally less vulnerable to this problem because tidal action and circulation patterns can easily deliver oxygen throughout the water column. However, decreases in dissolved oxygen concentrations can be amplified in water bodies with poor circulation because the water column is not sufficiently re-oxygenated by vertical mixing processes. For example, the Houston Ship Channel which flows into Galveston Bay, before discharge permits were required of waste facilities, experienced seriously low dissolved oxygen, which decreased abundances of marine animals in the Galveston Bay Estuary (Lester *et al.*, 2002).

1.4.6 Photosynthesis and Chlorophyll *a*

Phytoplankton primary productivity occurs through photosynthesis in which inorganic materials (ex. nitrate and phosphate) are converted into organic materials in the forms of lipids, proteins and carbohydrates (Falkowski and Raven, 1997). Photosynthesis is the first step in the classical planktonic food chain.

$$\rightarrow \text{Photosynthesis with sunlight}$$
$$6CO_2 + 6H_2O \leftrightarrow C_6H_{12}O_6 + 6O_2$$
$$\leftarrow \text{Respiration}$$

Chlorophyll *a* (chl *a*) is the dominant pigment present in algae and measuring chl *a* is an important step in determining phytoplankton biomass in a particular water body and directly monitoring variation throughout the year. An intense precipitation event coupled with high summer temperatures and irradiance can fuel increased growth of phytoplankton into blooms, resulting in elevated concentrations of chl *a* (Cloern, 1999).

Highest chl *a* concentrations in Galveston Bay were recorded at 455.8 µg/L in Chocolate Bayou, Texas during a sampling study in 1978 (Lester *et al.*, 2002). Over the past 28 years, however, the average monthly chl *a* biomass has been declining in Galveston Bay, despite an increase in nitrate concentrations (Criner and Johnican, 2001). It is thought that the decrease in chl *a* may be a result of declining primary production and/or more rapid degradation by phytoplankton predators (Lester *et al.,* 2002). No chl *a* concentration or phytoplankton data has been reported for the Offatts Bayou system, so it is unknown if the embayment behaves similarly to or differently from Galveston Bay.

1.4.7 Environmental Parameters

Parameters such as wind speed and direction, turbulence, light availability, tidal height variances and flushing rates can all affect phytoplankton variability in biomass and diversity. These factors can affect the phytoplankton community composition by naturally selecting those species that can survive in the surrounding, possibly adverse water conditions.

In a small embayment, such as Offatts Bayou, wind and extreme events, such as hurricanes, may have dramatic affects on the area and organisms within it on short temporal (hours to days) and small spatial scales (meters to kilometers). Turbidity increases or decreases with changes in the amount of total suspended solids (TSS - algae, detritus, sediment or solid waste), thus influencing light availability to phytoplankton populations and limiting growth rate during extremely cloudy conditions. In Galveston Bay, turbidity ranges from 10-500 mg/L of suspended particle matter (SPM) (Santschi, 1995), depending upon the resuspension rate of sediment from the Trinity and San Jacinto Rivers. While there are no direct measurements of turbidity for Offatts Bayou, it is likely that the amount of sunlight that penetrates the surface waters and the depth that it penetrates to is an important controlling factor of phytoplankton dynamics. In numerous estuarine studies, low tidal stirring was shown to slow the downward descent of the phytoplankton biomass from the photic zone to benthic consumers (Koseff *et al.*, 1993; Cloern, 1991) and deepened the photic zone in which phytoplankton growth could occur (Schoellhamer, 1996). Tidal range within the Gulf of Mexico is less then 1m (Stumpf and Haines, 1998), while tidal influence in Galveston Bay is even less at 0.65 m (Ward, 1991). Hence, tides are not likely to be an important factor for governing phytoplankton composition and abundance in Offatts Bayou. According to Santschi (1995), the flushing rate of Galveston Bay is between 40 and 88 days (Santschi, 1995). It is likely that the flushing rate of Offatts Bayou would be greater than that of Galveston Bay, which could affect phytoplankton dynamics within the inlet differently than in the open bay.

1.4.8 Nutrients

All phytoplankton need dissolved nutrients, such as nitrate and phosphate, in a range of concentrations, depending upon their specific requirements (Eppley *et al.* 1969; Ducobu *et al.* 1998). Differing concentrations of nutrients in estuarine waters influence and aid the formation of diverse phytoplankton communities (Ducobu *et al.* 1998). Worldwide increased levels of nitrogen and phosphate introduced to an estuarine ecosystem, via urban and agricultural runoff, have been linked to alterations in phytoplankton communities and the amassing of frequent nuisance and harmful algal blooms (Nixon, 1995; Richardson, 1997). For example, in the Neuse River estuary, phytoplankton responded to a stratified and nutrient limited water column by shifting the taxonomic composition of the community from dinoflagellates in late winter/early spring to a diatom bloom during spring to a large concentration of cyanobacteria in summer (Pinckney *et al.,* 1998).

Galveston Bay (Fig. 1.2) is the drainage basin for approximately 60% of Texas industrial facilities and agricultural farms, thus receiving the majority of its nutrients in the form of urban and industrialized wastewater, treated and untreated sewage and agricultural runoff (Armstrong, 1982). These nutrients flow into Galveston Bay via the Trinity (northeast) and the San Jacinto Rivers (northwest) from the highly populated and industrialized cities of Dallas - Ft. Worth and Houston (Fig. 1.2), Texas (Armstrong, 1982). According to census data from 2005, there are more than 7 million people residing in the Galveston Bay watershed region and thus contributing to the high concentration of nutrients that continually flow into Galveston Bay (half of the Texas

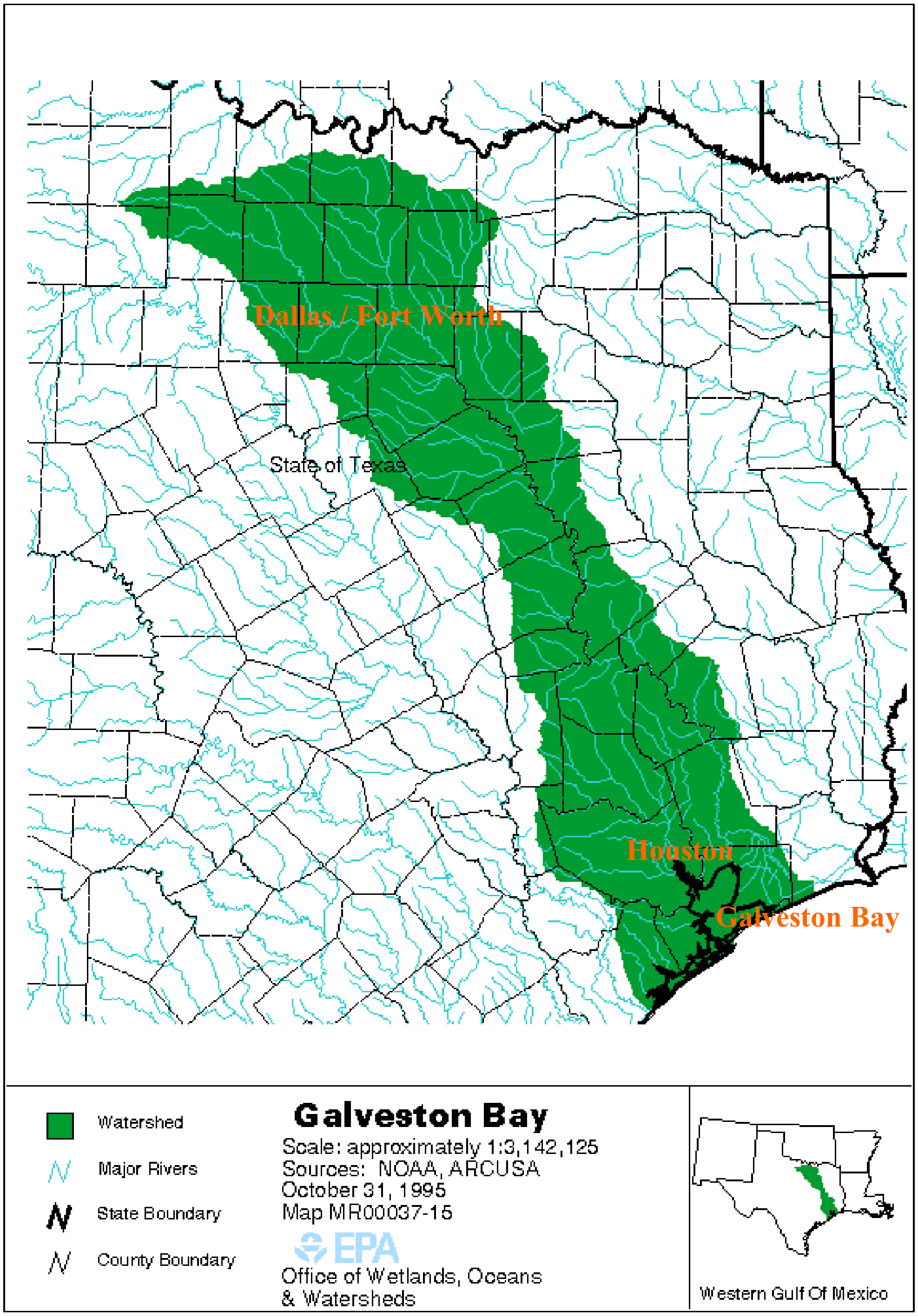

Fig. 1.2. Galveston Bay Watershed.
Courtesy of the U.S. Environmental Protection Agency
(www.epa.gov/owow/estuaries/programs/gb.htm)

population) (U.S. Census Bureau, 2005). As a result of the high anthropogenic input, nitrogen loading to the Galveston Bay estuary system is typically higher (16-45 g nitrogen m^{-2} $year^{-1}$) than in other Texas estuaries (Santschi, 1995). In April and May of 1969, Fruh (1969) showed that nitrogen bioassays fueled phytoplankton growth of Galveston Bay phytoplankton communities at 4 of the 6 sample stations. A more recent study by Örnólfsdóttir *et al.* (2004) in Galveston Bay further supported the concept that a phytoplankton biomass increases are directly linked to increases in nitrogen additions. Nitrate and phosphate (N+P) pulses on the growth and community composition of phytoplankton were significantly distinct from the control treatment, with diatom abundances significantly increasing by 30% to 100% in the N+P treatment (Örnólfsdóttir *et al.,* 2004). It was also established that phytoplankton can quickly respond to pulsed nitrate additions to the system (< 24 hours) (Örnólfsdóttir *et al.,* 2004). The nutrient status of Offatts Bayou is unknown, as no studies have been done there.

1.5 Objectives

The overarching purpose of this study is to obtain insight into the spatial and temporal variability of the phytoplankton community structure and how it will respond to changing physical and chemical regimes in Offatts Bayou over one annual cycle. To accomplish this, hydrological and meteorological parameters were collected and phytoplankton biomass (chl *a)*, community composition data were examined for significant relationships. In order to define the dominate influences and address the objective, the following hypotheses were tested:

H_1: There is no significant seasonal difference in surface, middle and bottom water hydrological parameters (T, S, DO_2, pH).

H_2: There is no significant seasonal change in surface phytoplankton diversity related to variability in hydrological parameters (T, S, DO_2, pH).

H_3: There is no significant seasonal change in surface phytoplankton abundance and biomass related to variability in hydrological parameters (T, S, DO_2, pH).

H_4: The water column in Offatts Bayou is not stratified and there was no significant difference between parameters (T, S, DO_2, density) of surface and bottom water.

2. METHODS AND MATERIALS

2.1 Introduction - Sampling Locations

Beginning in December of 2004, eleven stations in Offatts Bayou (Fig. 2.1) were selected along a transect from West Bay to the Back Bay and into Lake Madeline for sampling of hydrological parameters, phytoplankton diversity, abundance and chlorophyll a (chl a) analysis on a regular basis (2 to 4 times per month) for one year. The exact latitude and longitude of each sampling station was acquired using a global positioning satellite (Table 2.1) and the same stations were visited repeatedly with a 90-horse power, flat bottom, 7 meter boat owned by Texas A&M University at Galveston.

2.2 Hydrological Data Collection

Water column measurements (bottom to surface at 1 meter intervals) were collected two to four times per month from December 2004 through November 2005 between 0830 and 1030 Central Standard Time. Depth, temperature, salinity, dissolved oxygen, percent oxygen saturation, pH and conductivity were measured utilizing a MiniSonde hydrolab coupled with a Surveyor 4a datalogger to log data. Data was downloaded to a personal computer in the laboratory for analysis. The MiniSonde hydrolab was calibrated for conductivity and pH the first week of every month and the oxygen probe was calibrated two times during the sample period in accordance with the MiniSonde handbook.

Fig. 2.1. Offatts Bayou stations.

Table 2.1.

Location and GPS identifiers of field stations.

Station	Name	Latitude	Longitude
1	China Border (Back Bay)	N29° 16.856	W94° 49.942
2	Mouth of Back Bay	N29° 17.112	W94° 50.062
3	Charter Rental	N29° 16.869	W94° 50.111
4	Deep Hole (Black Hole)	N29° 17.008	W94° 50.450
5	Mouth to Lake Madeline (dock)	N29° 16.661	W94° 50.957
7	Left Corner of Lake Madeline	N29° 15.841	W94° 50.529
8	Center of Lake Madeline	N29° 15.891	W94° 50.653
9	Channel Marker #28	N29° 16.894	W94° 51.316
10	Channel Marker #24	N29° 16.832	W94° 51.805
11	Channel Marker #20	N29° 16.760	W94° 52.444
12	Channel Marker #11 (West Bay)	N29° 16.750	W94° 52.964

* Station 6 was sampled only for December, then dropped due to redundancy and is not included herein.

2.3 Relative Stratification of the Water Column

Relative temperature, salinity and dissolved oxygen stratification at each sampling station within Offatts Bayou was determined by using the method of Hansen and Rattray (1966). The difference between the bottom and top parameter values divided by the respective average water column parameter value was calculated. Equation 2.1 represents the relative stratification formula used for each parameter.

Equation 2.1 $$\text{stratification} = \delta S/S_o$$

Sigma-t (σ_t) is a measurement of the density that a parcel of water with a given temperature and salinity would have at the surface. Sigma-t at each station was calculated using the equation of Strobel *et al.* (1995) below:

Equation 2.2 $\sigma_t = (\text{density} - 1) * 1000$

The degree of density stratification of the water column is the difference between bottom water sigma-t and surface water sigma-t ($\delta\sigma_t$) over the average σ_t (Equation 2.3).

Equation 2.3 $\text{density stratification} = \delta\sigma_t / \sigma_{to}$

The degree of density stratification was classified into three categories: low < 1, moderate = 1 to 2, high > 2.

2.4 Phytoplankton Enumeration and Identification

Phytoplankton community diversity was monitored at the eleven stations from samples collected once per month. Routine procedures for sample collection involved submerging a plankton net just below the surface and allowing it to float with the current for approximately five minutes at each of the eleven stations. These samples were stored in an insulated, dark cooler (chilled with ice) and transported back to the laboratory within two hours of collection. At the laboratory, the sample's volume was measured. Formalin was added to the sample for preservation so that the final concentration was 3%. The preserved sample was examined under an Olympus light microscope in a 1ml Hausser Scientific counting chamber, which was 50 mm long by 20 mm wide and 1 mm deep and was calibrated by the manufacturer to hold exactly 1 mL of sample. The counting chamber was covered with a coverslip and phytoplankton cells were counted until 100 individuals were identified. With this information, percentages of phytoplankton diversity were calculated per liter of sample water and the dominate species identified. All phytoplankton were identified to species level when possible, except in the cases when the organism was too small (< 8 μm) under 20x on the microscope or damaged. Identification of phytoplankton species was aided by the taxonomic text of Tomas (1997).

2.5 Chlorophyll a Analysis

Discrete surface samples (0 - 0.25 m) were taken approximately once per week at each of the stations. These samples were stored in an insulated, dark cooler (chilled with ice) and transported back to the laboratory within two hours of collection. At the laboratory, samples (0.12 L) were filtered through Whatman Glass Microfibre filters (25 mm diameter; GF/F; nominal pore size of 0.7 μm) using low (< 250 mmHg) vacuum pressure. The filtered samples were stored at –20 ºC until time for pigment extraction and processing. Following established procedures (EPA Method 445.0; Arar and Collins, 1997), filters were placed into glass test tubes containing 0.0045 L of 100% acetone. After storing the samples in a dark refrigerator for 24 hours, the filter was removed from the test tube and discarded. The test tube was then centrifuged for one minute, wiped down to remove condensation and placed in a Turner Designs 10AU fluorometer. An initial fluorometric measurement was taken. Then two drops of 10% HCl were added to the sample to acidify the solution and the sample was remeasured.

The difference between the F_o (initial fluorometer reading) and F_a (fluorometer reading after acidification) was used to determine total pigment concentration in the sample.

The following equations from EPA Method 445.0 (Arar and Collins,1997) were used to determine the concentration of chlorophyll *a* (chl *a)* and phaeophytin *a* (phaeo *a*):

Equation 2.4

$$C_{s,c} = \frac{(F_s (r/r-1))(F_o - F_a)(\text{extract V}) (\text{DF})}{\text{Sample V}}$$

$$\text{Chl } a\ (\mu g/L) = \frac{(290.49\ (1.4))(\ F_o - F_a)\ (0.0045\ L)\ (10)}{(0.12\ L)}$$

Equation 2.5

$$P_s = \frac{(F_s (r/r-1))(F_a - F_o)(\text{extract V}) (\text{DF})}{\text{Sample V}}$$

$$\text{Phaeo } a\ (\mu g/L) = \frac{(290.49\ (1.4))(\ F_a - F_o)\ (.0045\ L)\ (10)}{(0.12\ L)}$$

where:

F_s = Fluroscence response factor for sensitivity = 290.49

r/r-1 = ratio of a pure chl *a* solution before to after acidification = 1.4

Extract V = volume (L) of solvent used for extraction before any dilutions = 0.0045L

DF = dilution factor (this was dependent on the sample)

Sample V = volume (L) of water sample filtered = 0.12L

F_o = initial fluorometer reading

F_a = fluorometer reading after acidification

2.6 Meteorological and Tidal Data Collection

Rainfall, air temperature and wind direction and speed were obtained from a weather station located at Scholes International Airport in Galveston, TX at 29º 16' 13" N Latitude and 94º 51' 51" W Longitude, less than ½ mile from Offatts Bayou. The weather data was collected from the National Oceanic and Atmospheric Administration (NOAA) and the National Climate Data Center and displayed on the Old Farmer's Almanac website for Galveston, TX (http://www.almanac.com/weatherhistory).

Tide data was obtained from the NOAA CO-OPS website (http://co-ops.nos.noaa.gov/data_res.html) for station #8771450 located at Galveston Pier 21, Galveston Channel, TX, roughly three miles from Offatts Bayou. The station at Offatts Bayou, West Bay, TX, #8771516, had no historical data.

2.7 Statistical Analysis

Several statistical analyses were preformed using SPSS 11.0 software and according to Dytham (2003) to test the null hypotheses. Statistical analysis of spatial (stations, depths) and temporal (weekly, monthly, seasonal) variations in surface water temperature, salinity and dissolved oxygen were used to define trends in phytoplankton biomass (chl *a*) throughout the year in Offatts Bayou.

A multivariate analysis of variance (MANOVA) test was utilized to determine if there was a significant difference between surface, middle and bottom water variables at each of the eleven stations, first on a monthly and then on a seasonal basis. For monthly assessments, the fixed factor was week and the dependent variables were temperature, salinity, dissolved oxygen and pH. For seasonal comparisons, the fixed factor was month and dependent variables were temperature, salinity, dissolved oxygen and pH. A Levene's test was run to determine if variances were homogeneous for each dependent variable. For *post hoc* analysis, a Dunnetts T3 "equal variances not assumed" test was run when error variances were not homogeneous. In a Dunnetts T3 test, a p value of $<$ 0.05 indicates that the tested values are non-homogeneous and a p value > 0.05 suggests that the values are homogeneous.

A second MANOVA was run to determine homogeneity between temperature, salinity, dissolved oxygen and pH on a monthly and seasonal basis. These results were utilized in determining first, the months of the seasons and secondly, spatial changes between stations in Offatts Bayou (Table 3.6). The MANOVA also determined which stations were homogeneous in respect to temperature, salinity and dissolved oxygen averaged over the annual sample period.

A stepwise regression analysis was preformed to determine which independent variable or variables (temperature, salinity dissolved oxygen, pH or seasons) had the most influence on the dependent variable, chl *a* concentration, throughout the sample year. The output was the best fit equation that expressed the relationship between the dependent variable and best predictor factors. The stepwise regression equation is: $y = a + bX + e$, where y = dependent variable, x = independent variable, b = regression coefficient (slope) and e = error term. A stepwise regression analysis is a combination of a backward and forward selection procedures which examines all possible combinations of the independent variables. The parameters are subjected to the inclusion procedures and the exclusion criteria, respectively. Parameters were selected and removed until the best predictor remains. This type of statistical analysis was useful in helping to identify the "cause" variables that are most important for assessing the habitat preference of the phytoplankton.

3. RESULTS

Hydrological, meteorological and phytoplankton data were collected from December 2004 to November 2005 to achieve an overall annual synopsis of the spatiotemporal dynamics in the Offatts Bayou region. Seasons were classified herein as Winter = December 2004, January, February and March 2005, Spring = April and May 2005, Summer = June, July, August and September 2005 and Autumn = October and November 2005.

3.1 Hydrological Data Analysis

Monthly and seasonal changes in temperature, salinity and dissolved oxygen were presented primarily for stations #1, 4, 8, 9 and 12. These stations were selected as being representative of the Offatts Bayou system. Station 1 was representative of stations 1 and 2 (Back Bay), station 4 of 3, 4 and 5 (back of Offatts Bayou), 8 of stations 7 and 8 (Lake Madeline), 9 of 9 and 10 (middle of Offatts Bayou) and station 12 of stations 11 and 12 (mouth to Offatts Bayou). Hydrological and stratification figures for all stations are summarized in Appendix A, along with a table of corresponding sample dates as Julian Dates.

. In the winter, surface water temperatures at all stations were below 15º C, salinity was between 19 and 21 ppt and dissolved oxygen levels were approximately 10 mg/L (Fig. 3.1a). During the springtime, temperature (~ 22 º C) and salinity (20 to 24 ppt) increased at all stations within Offatts Bayou, while dissolved oxygen (< 8 mg/L) decreased at all stations (Fig. 3.1b). The summer months revealed further temperature (29 to 31 º C) and salinity (26 to 30 ppt) amplification and diminishment of dissolved oxygen (~ 5 mg/L) at all stations (Fig. 3.1c). Autumn samples reflected a decrease in surface water temperature (~ 24 º C), salinity (20 to 24 ppt) and an increase in dissolved oxygen (~ 7 mg/L) (Fig. 3.1d).

Winter water column profiles of Offatts Bayou showed spatial heterogeneity between stratified and mixed conditions in the stations sampled (Fig. 3.1a). The water column condition (stratified or mixed) was dependent upon the depth of the station: shallow stations were 1, 9 and 12 and deep stations were 8 and 9. Stations 9 and 12 reflected a thoroughly mixed water column, while station 1 was only mixed in the upper 0.5 meters. At the deeper stations 4 and 8, the water column was mixed in the upper 4 meters with stratification beginning at the pycnocline (temperature and salinity increased) between 5 and 4 meters, with anoxic conditions continuing from 6 and 5 meters, respectively, to the sediment bottom. The spring season reflected a completely mixed water column at station 12. Minor mixing occurred in the top 1 meter in the remaining stations, 1,4, 8 and 9 (Fig. 3.1b) with the pycnocline and stratification occurring between 1 and 2 meters in depth. The pycnocline, hypoxic zone and anoxic layer rose 1 meter from the winter to spring measurements in Lake Madeline (station 8). At the Deep Hole (station 4) during spring, the anoxic layer present during winter reverted to hypoxia and temperature was constant throughout the water column. The hypoxic layer shifted to increasingly shallower depths during the summer months,

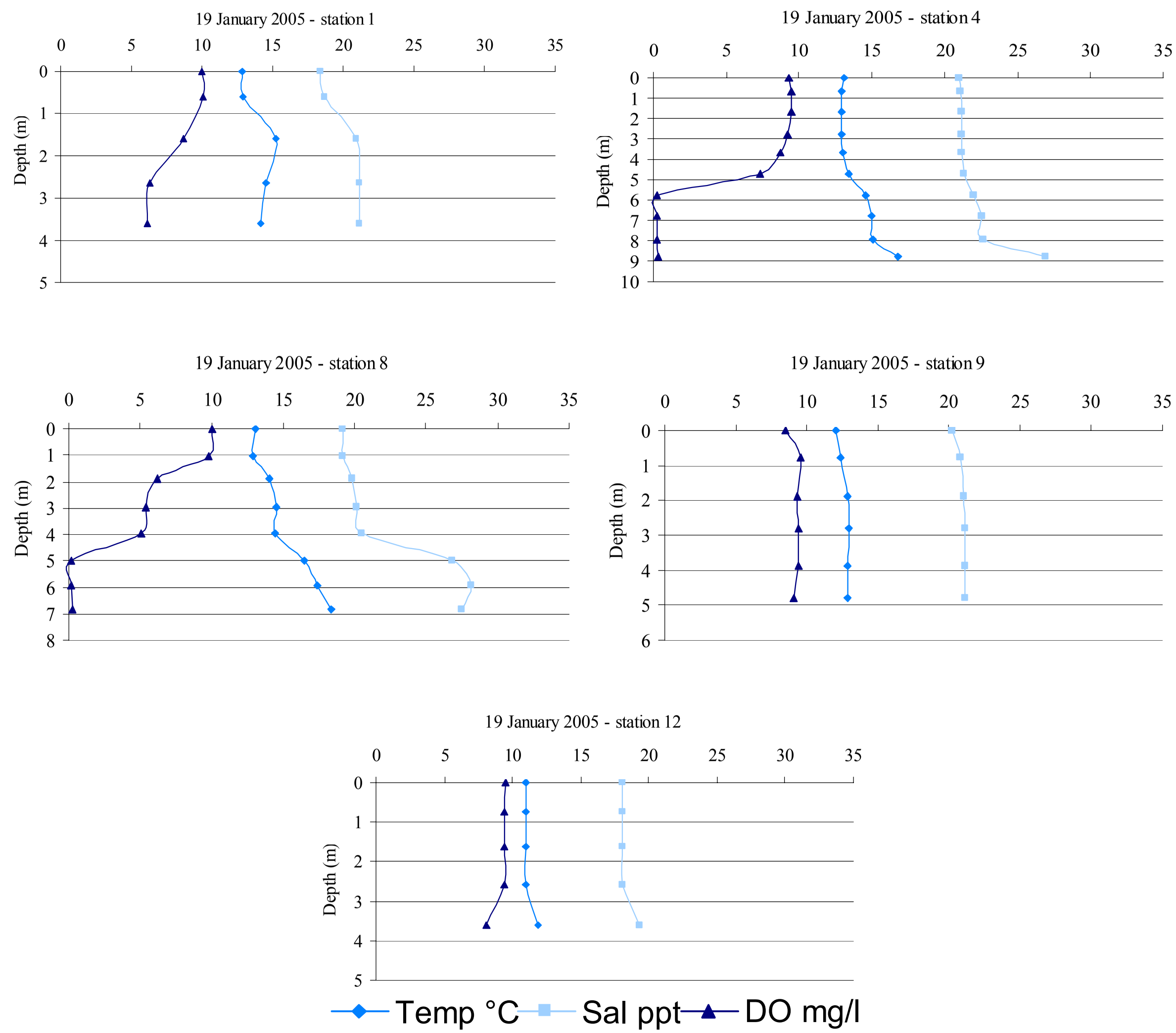

Fig. 3.1. Vertical water column profiles of temperature (Temp ºC), salinity (Sal ppt) and dissolved oxygen (DO mg/L) for selected stations # 1, 4, 8, 9, 12. a) Winter representative (19 January 2005).

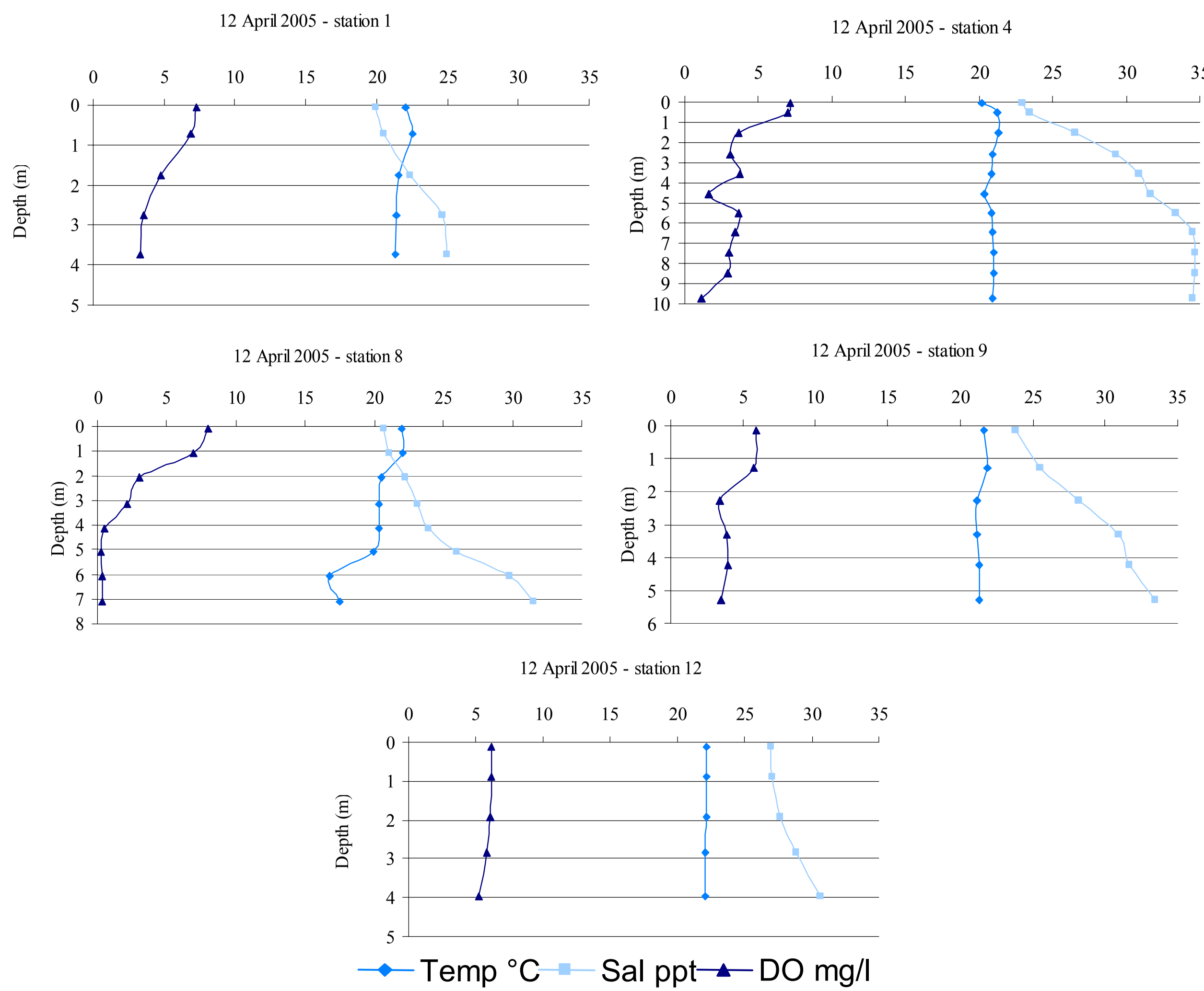

Fig. 3.1 continued. b) Spring representative (12 April 2005).

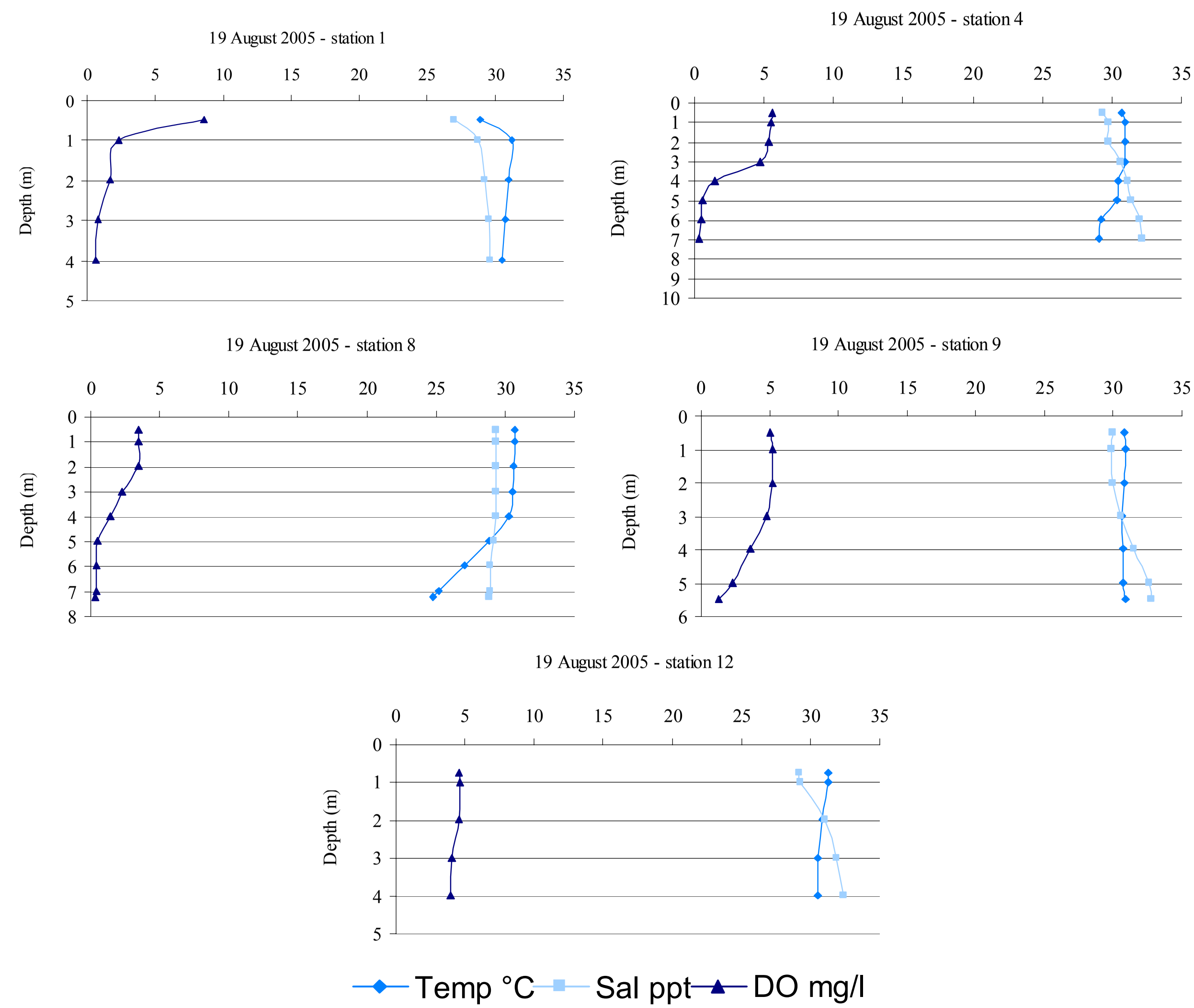

Fig. 3.1 continued. c) Summer representative (19 August 2005).

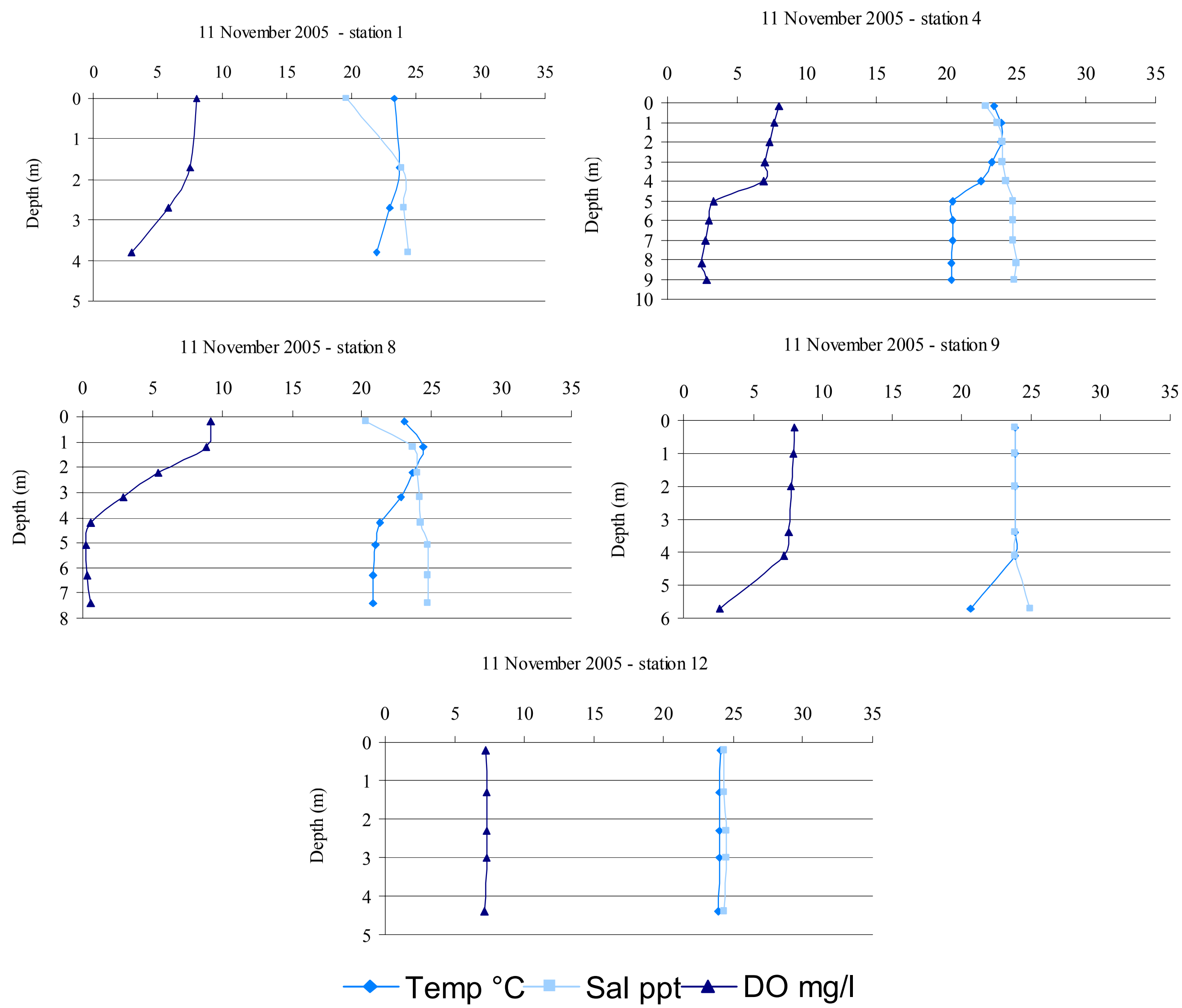

Fig. 3.1 continued. d) Autumn representative (11 November 2005).

beginning at 1 meters at station 1, 4 meters at station 4 and at 3 meters at station 8, while stations 9 and 12 continued to be mixed (Fig. 3.1c). Autumn samplings revealed a completely mixed system at station 12. Stations 4 and 9 were mixed until 4 m, where the temperature decreased and the water column became hypoxic. Station 8 encountered the pycnocline at 1m, became hypoxic from 2 to 4 m, then anoxic to the bottom sediment (Fig. 3.1 d).

Winter and summer surface water temperature and salinity measurements during the past 50 years were taken on three occasions at the Deep Hole by Gunter (1949), Cooper (1996) and Roehrborn (station 4, unpublished 2006). Temperature and salinity readings displayed definite changes throughout the years, but no obvious trend was visible (Table 3.1). Temperatures varied slightly in the winter, with the coldest occurring in 2005. In the summers of 1996 and 2005, temperature readings were similar. Precipitation rates for winter and summer, 1949 and 1996, were not included in the literature published, thus it was not possible to determine if rainfall rates were the responsible factor for the differences in salinity between samplings. Given the known variability, these three observations over the past 50 years most likely have no significance.

Table 3.1.
Comparison between three winter and summer measurements of temperature and salinity at the Deep Hole.

Season	Year	Location	temperature (˚C)	salinity (ppt)	author
winter	1949	Deep Hole	16.2	13.0	Gunter
winter	1996	Deep Hole	16.0	21.5	Cooper
winter	2005	Deep Hole	14.8	18.7	Roehrborn
summer	1949	Deep Hole	23.3	31.0	Gunter
summer	1996	Deep Hole	30.5	31.3	Cooper
summer	2005	Deep Hole	30.0	28.2	Roehrborn

3.1.1 Stratification vs. Mixed Water Column

Analyses of temperature, salinity and dissolved oxygen stratifications were based on changes in the relative stratification index for each parameter. For temperature and salinity, values between 0 and 1 indicated a relative mixed status, while those greater than 1 signified relatively stratified water. Dissolved oxygen relative stratification values between 0 and approximately -1.5 indicated a mixed water column and any number less than -1.5 was considered to indicate a stratified water column. Relative stratification indices for density less than 1 designated a low stratified system, 1 to 2 was moderately stratified and greater than 2 was highly stratified.

The water column condition (stratified or mixed) varied on a spatiotemporal basis throughout the sample year (Figs. 3.2 – 3.11). In general, thermal stratification was not strongly present at any of the stations throughout the sample year. The greatest salinity stratification was present at the more isolated stations (1 and 8), with station 8 (Lake Madeline) incurring the highest index of stratified water throughout the sample year (Fig. 3.2 and 3.6). The least stratified stations (9 and 12), with respect to temperature, salinity and dissolved oxygen were located in the open regions leading into Offatts Bayou from West Bay where circulation mixed the parameters throughout the water column (Figs. 3.8 and 3.19) . The highest degree of stratification based upon dissolved oxygen, was observed at stations 4 and 8, which were also the deepest stations (Figs. 3.4, 3.6). Station 1 was slightly stratified on a dissolved oxygen basis and relative dissolved oxygen stratification began to decrease from station 9 outwards towards 12 in West Bay (Figs. 3.8, 3.10).

A closer examination of station 1 revealed that it was mixed throughout the year with regard to temperature (< 1) and salinity (< 1) stratification indices (Fig. 3.2). The dissolved oxygen stratification index reflected a mixed winter, spring and late autumn, while a sustained stratification persisted throughout summer, with a dramatic stratification peak in late August (Fig. 3.2; Julian Date 231). The density index for station 1 indicated a very low (< 1) density stratified system throughout the entire sample year (Fig. 3.3), consistent with the mixing predicted by the relative temperature and salinity indices.

At the Deep Hole (station 4), temperature and salinity stratification indices indicated a mixed water column throughout the entire year (Fig. 3.4). Dissolved oxygen was slightly stratified from December 2004 (Julian Date 336) until about the beginning of March 2005 (Julian Date 63) , followed by an increase towards mixing at the end of March, then a complete stratification in the summer months (Fig. 3.4). In autumn, the system returned to a low stratified status with a point of mixing occurring at the beginning of November (Julian Date 306). The density index indicated a low stratification (< 1) of the waters in the Deep Hole of Offatts Bayou (Fig. 3.5) consistent with seasonal fluctuations in the relative low stratification indices for temperature and salinity. Density stratification increased through winter and spring, was highest in April (Julian Date 102) and June (Julian Date 166), then decreased through the rest of summer and autumn.

Temperature and salinity stratification indices for Station 8, located in the center of Lake Madeline, revealed a well mixed water column throughout the sample year, with two slight salinity stratification episodes at the end of winter (March 2005, Julian Date 83) and middle of autumn (November 2005, Julian Date 306) (Fig. 3.6). Dissolved oxygen stratification indices fluctuated during the sample year, which demonstrated that the Lake Madeline system was moderately to highly stratified with an oxygen deficit near the bottom, year round. Following Hurricane Rita (Julian Date 272), a point of intense dissolved oxygen stratification developed, followed by strong mixing at the end of October. Density stratification indices were low throughout the sample period. During March, however, Lake Madeline was near moderately stratified (near 1) (Fig. 3.7, Julian Date 83), which coincided with the observed salinity stratification.

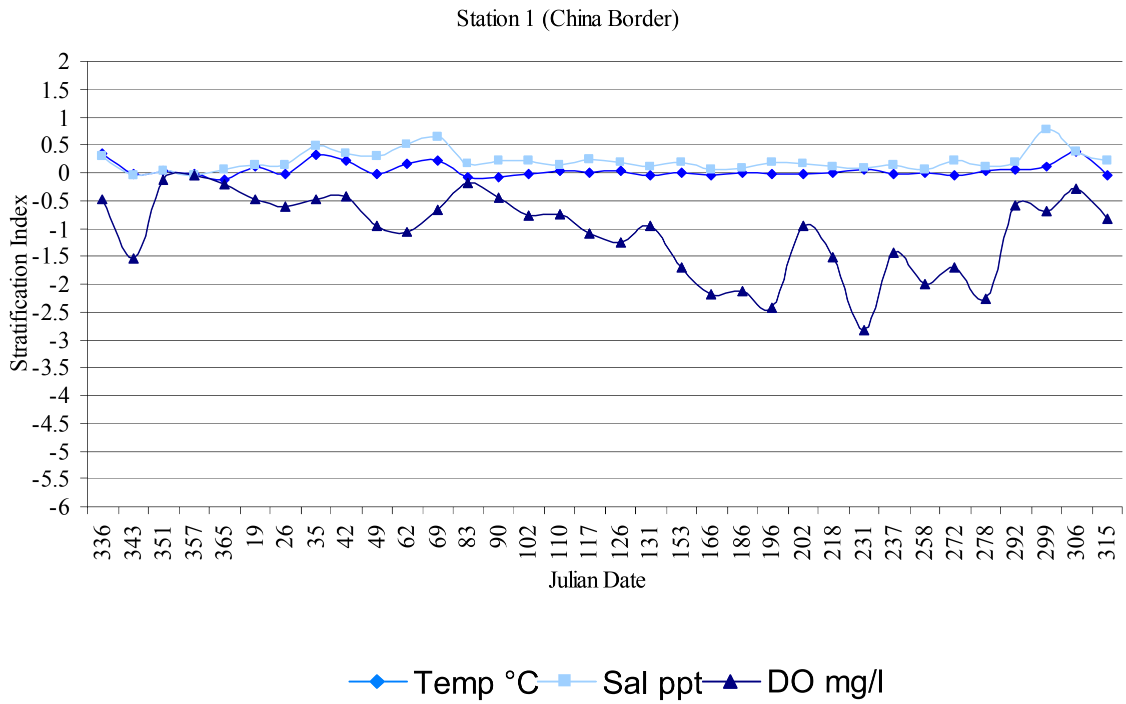

Fig. 3.2. Relative temperature, salinity and dissolved oxygen stratification for station 1.

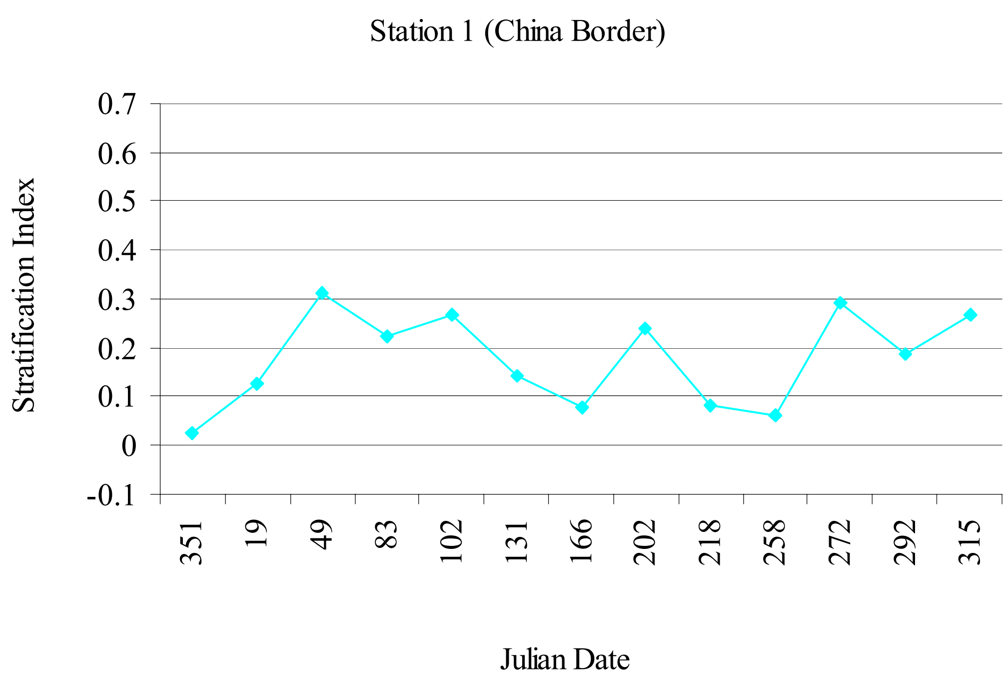

Fig. 3.3. Relative density stratification for station 1.
(low stratification < 1, moderate stratification = 1 to 2, high stratification > 2)

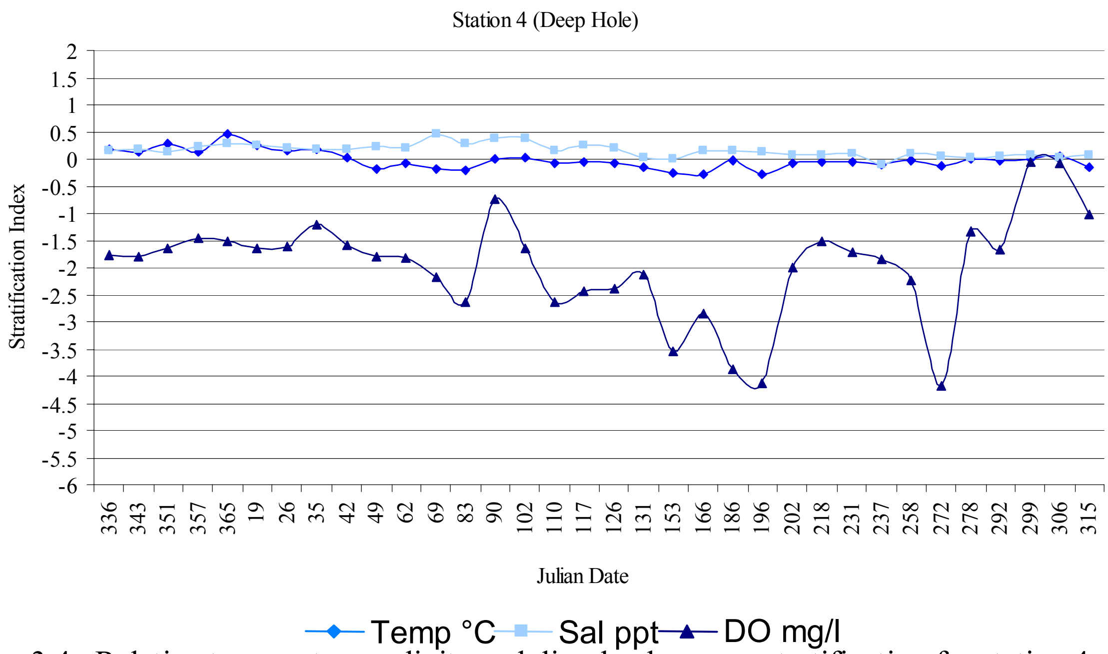

Fig. 3.4. Relative temperature, salinity and dissolved oxygen stratification for station 4.

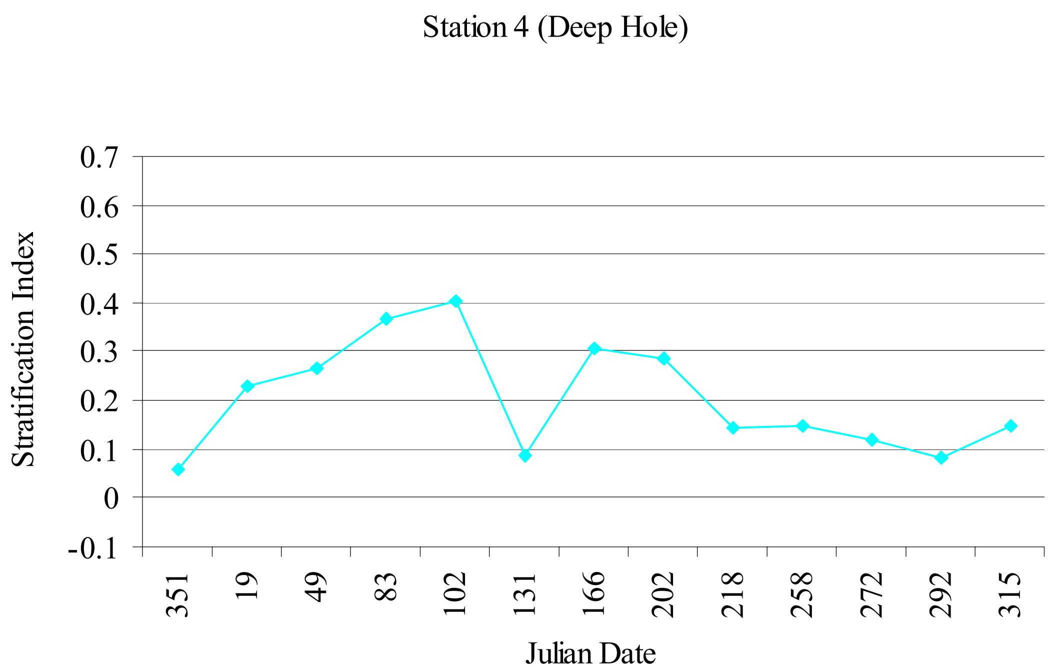

Fig. 3.5. Relative density stratification for station 4.
(low stratification < 1, moderate stratification = 1 to 2, high stratification > 2)

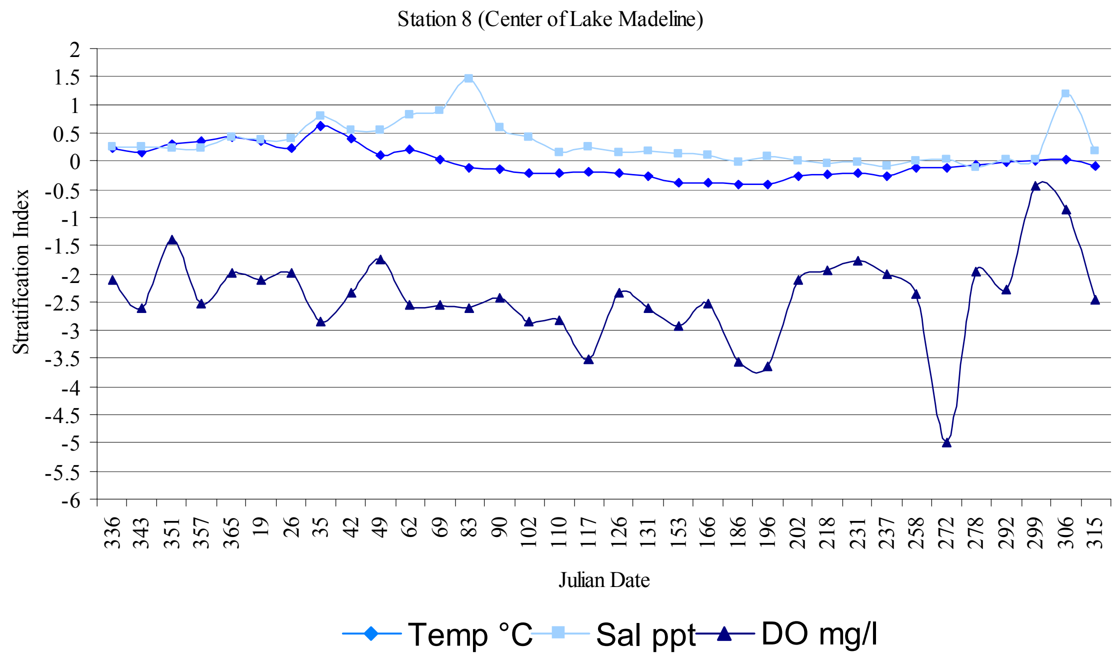

Fig. 3.6. Relative temperature, salinity and dissolved oxygen stratification for station 8.

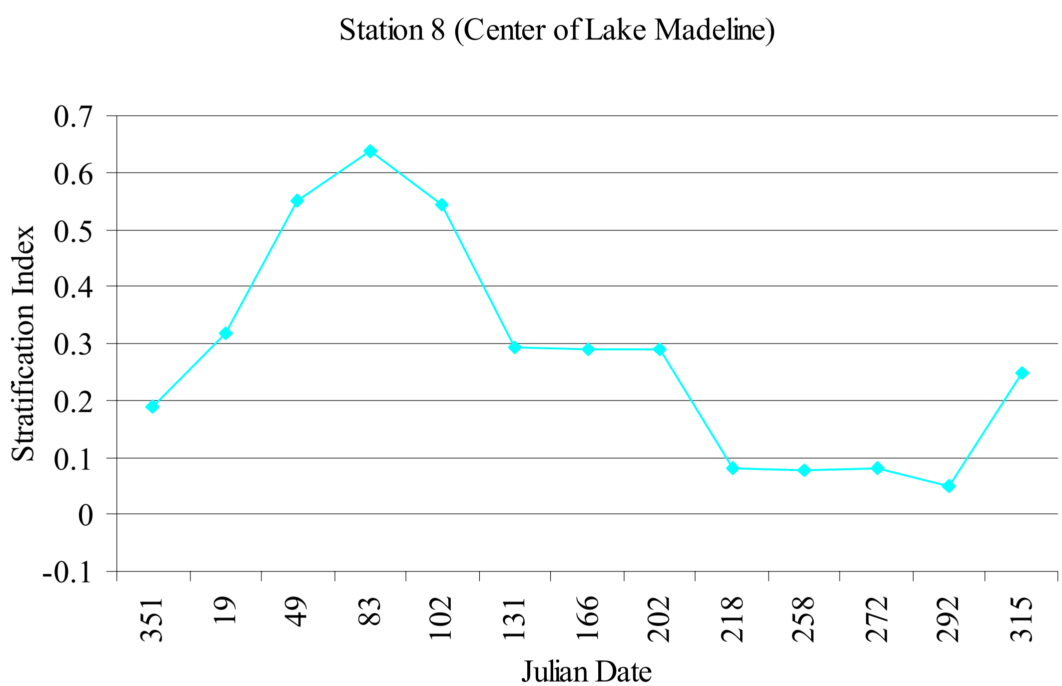

Fig. 3.7. Relative density stratification for station 8.
(low stratification < 1, moderate stratification = 1 to 2, high stratification > 2)

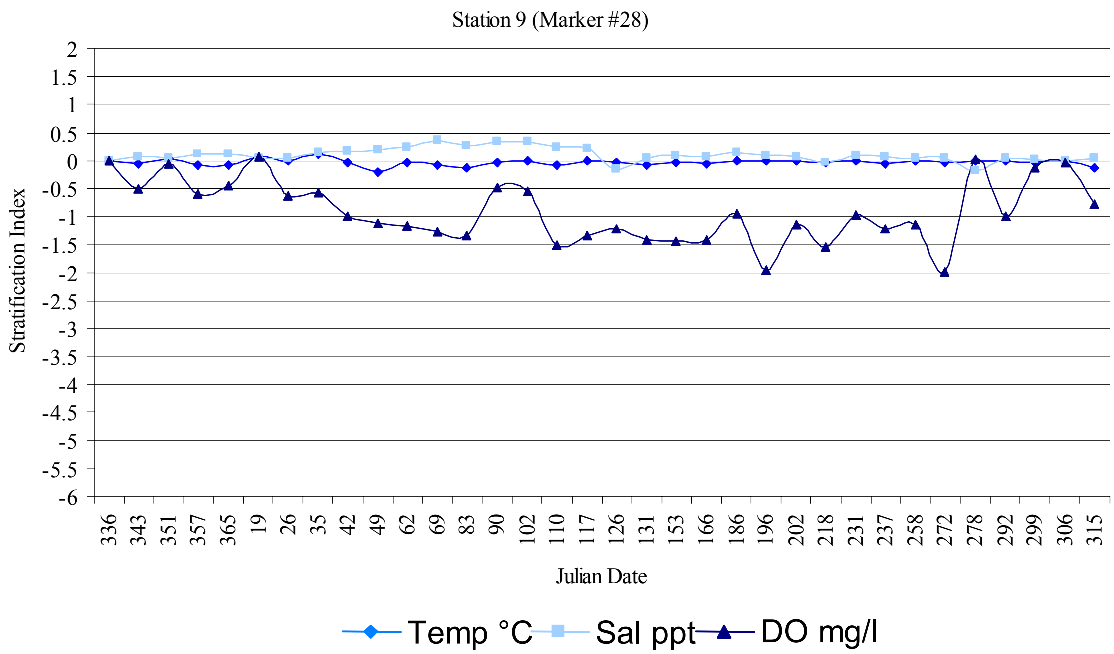

Fig. 3.8. Relative temperature, salinity and dissolved oxygen stratification for station 9.

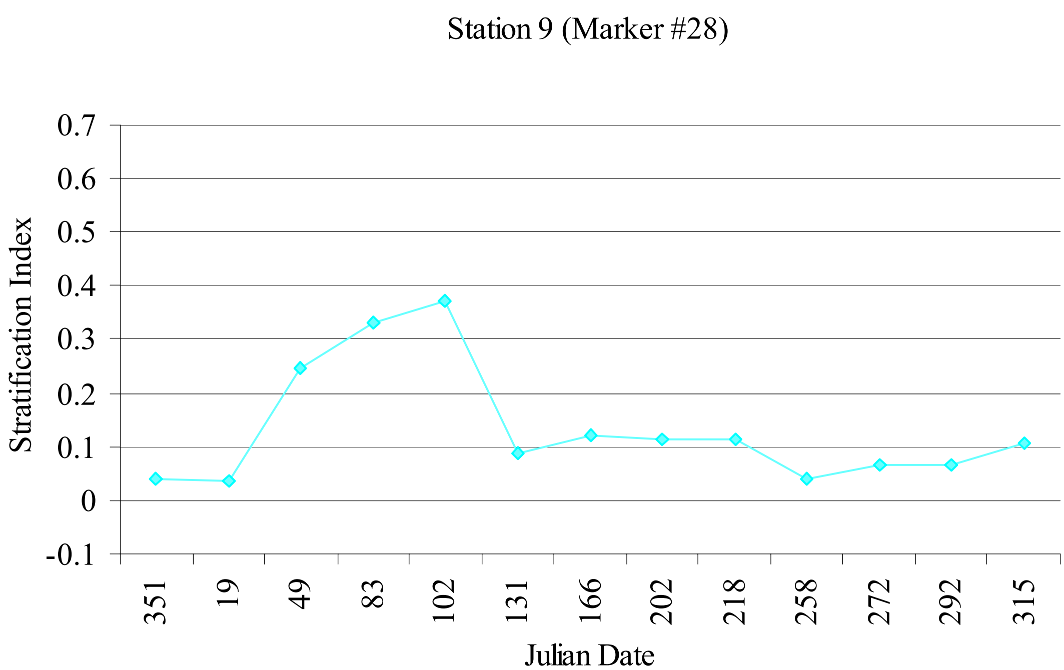

Fig. 3.9. Relative density stratification for station 9.
(low stratification < 1, moderate stratification = 1 to 2, high stratification > 2)

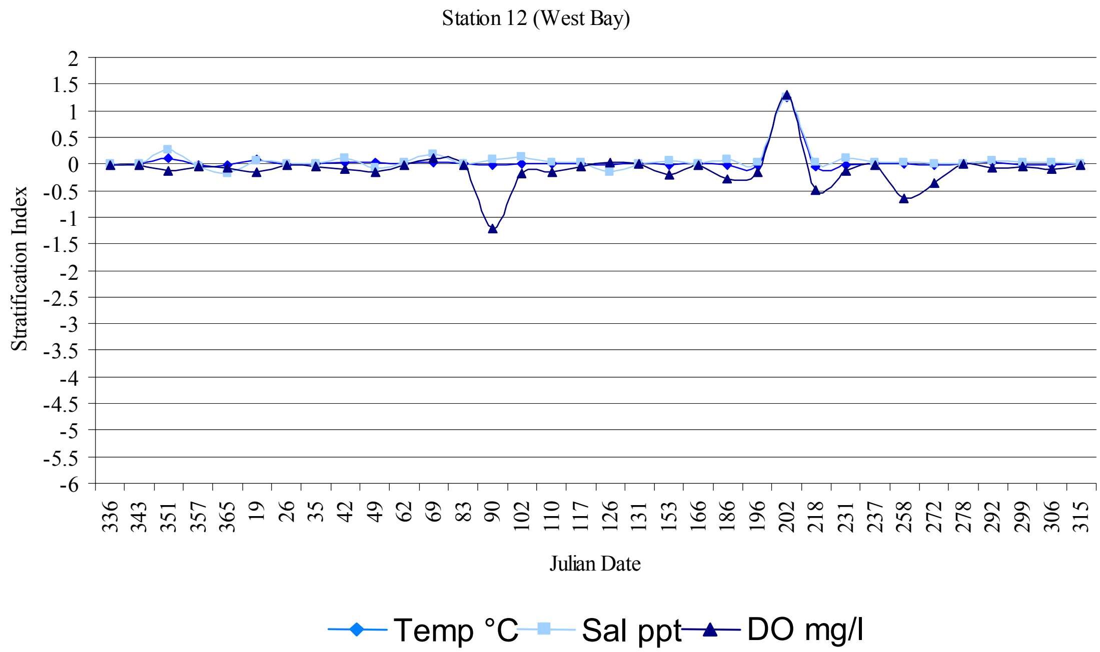

Fig. 3.10. Relative temperature, salinity and dissolved oxygen stratification for station 12.

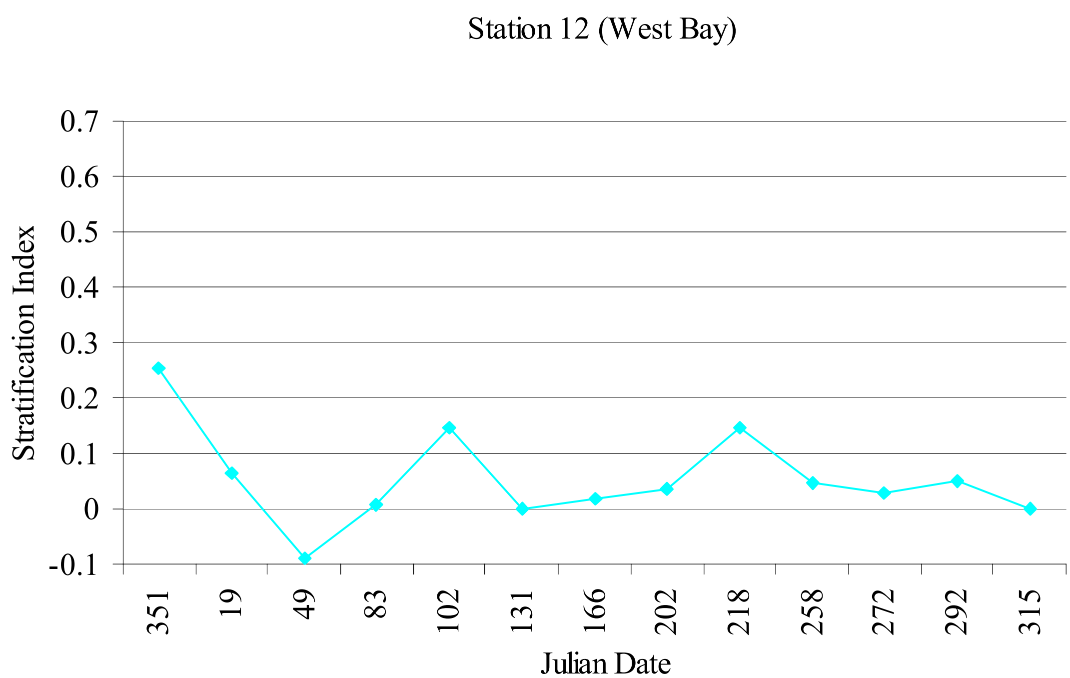

Fig. 3.11. Relative density stratification for station 12.
(low stratification < 1, moderate stratification = 1 to 2, high stratification > 2)

Station 9, in the middle of Offatts Bayou, demonstrated no major temperature or salinity stratification events throughout the sample period (Fig. 3.8). Dissolved oxygen mixing occurred in winter, gradually decreased to a slightly stratified system through the summer months, followed again by a mixed status in autumn. Density stratification was relatively low throughout the sample year, with only a slight increase through late winter/early spring (Fig. 3.9), which reflected the mixed temperature and salinity stratification indices (Fig. 3.8).

Station 12, in West Bay, was completely mixed throughout the entire year, except for one slight dissolved oxygen (March 2005, Julian Date 90) and one temperature/salinity/dissolved oxygen (late July, Julian Date 202) stratification event (Figure 3.10). Density stratification was extremely low for the entire year (Figure 3.11) and corresponded to the mixing of temperature and salinity throughout the water column.

3.1.2 Statistical Analysis of Hydrological Data

In order to interpret twelve months of data comprising eleven stations, together with the measured abiotic (T, S, DO, pH) factors, the data was subjected to two multivariate analysis of variance (MANOVA) tests.

The first MANOVA was performed on the surface hydrological parameters (T, S, DO) collected two to four times per month. These data were inputted into the MANOVA with month as fixed factor and temperature, salinity and dissolved oxygen as the dependant variables. (Levene's Test: Temp $p < 0.05$, Sal $p < 0.05$, DO $p < 0.05$).

Associated resulting values are located in Appendix B. Throughout all the tables, homogeneity is indicated with a continuous underline.

The mean surface temperature followed a seasonal trend (Table 3.2). August, July, September were homogeneous for the highest recorded temperatures, while January and February had the lowest. Intermediate temperatures were observed for May, April and November. October, March and December were different from all other months.

September, August and July were homogeneous for highest surface salinity values, while lowest salinities were observed in November, January and February (Table 3.3). March was the only month that was different from all other months and also had the lowest salinity during the sample period.

February, January, December, March and November were homogeneous for the highest surface dissolved oxygen (Table 3.4). Low dissolved oxygen concentrations were represented by the group comprised of June, July and August. May possessed the lowest concentration during the entire year and was heterogeneous from all other months.

Table 3.2.
Homogeneous months (T) according to the Dunnetts T3 multiple comparison.

Temperature (T)

Aug05 Jul05 Sep05 Jun05 Oct05 May05 Apr05 Nov05 Mar05 Dec04 Jan05 Feb05

Table 3.3.
Homogeneous months (S) according to the Dunnetts T3 multiple comparison.

Salinity (S)

Sep05 Aug05 Jul05 May05 Jun05 Oct05 Apr05 Dec05 Nov05 Jan05 Feb05 Mar05

Table 3.4.

Homogeneous months (DO) according to the Dunnetts T3 multiple comparison.

Dissolved Oxygen (DO)

Feb05 Jan05 Dec04 Mar05 Nov05 Sep05 Apr05 Oct05 Jul05 Jun05 Aug05 May05

Based on these results, seasons were defined as the following months:

*Winter: December 2004, January, February and March 2005

*Spring: April and May 2005

*Summer: June, July, August and September 2005

*Autumn: October and November 2005

Along with the first MANOVA, all eleven stations were entered as a fixed factor and temperature, salinity and dissolved oxygen as dependent factors in order to determine spatial differences in Offatts Bayou. The Levene's test indicated variances were heterogeneous ($p < 0.05$) and so the Bonferroni multiple comparisons test was utilized to determine homogeneity between stations. The Bonferroni *post hoc* indicated that all the stations for surface temperature and dissolved oxygen were homogeneous for each month sampled ($p < 0.05$, Table 3.5).

Table 3.5.
Homogeneous stations (T and DO) according to Bonferroni multiple comparison.

Temperature (T):

7	10	9	11	5	4	8	3	12	2	1

Dissolved Oxygen (DO):

8	4	2	9	5	7	10	3	12	11	1

In addition, surface salinities were shown to be heterogeneous throughout Offatts Bayou with highest values at stations 12, 4, 3, 9, 11, 10 and 5 and lowest at 7, 8, 2 and 1 ($p < 0.05$, Table 3.6).

Table 3.6.
Homogeneous stations (S) according to Bonferroni multiple comparison.

Salinity (S):

12 4 3 9 11 10 5 7 8 2 1

The spatial and temporal statistical results for surface temperature, salinity and dissolved oxygen were summarized in Table 3.7 ($p < 0.05$) and the seasonal trends of each sample station were revealed. The highest annual temperature mean (22.6 ºC ± 6.5 ºC S.D.) was observed in Lake Madeline (station 7) and the middle of Offatts Bayou (station 9; 22.6 ºC ± 6.4 ºC S.D.). The Back Bay (station1) represented the lowest annual temperature mean at 21.9 ºC ± 6.5 ºC S.D. All of the station's annual temperature means were within ± 1 ºC of one another which is consistent with the homogeneity observed across all stations throughout the 2004-2005 sample period (Table 3.5). The mean annual salinity was highest (24.8 ppt) in West Bay (station 12) and lowest (20.9 ppt) in the Back Bay (station 1), which demonstrated the heterogeneity between stations throughout the sample year (Table 3.6). Lake Madeline (station 8) contained the highest annual dissolved oxygen mean (7.2 mg/L) and the lowest (6.4 mg/L) was determined to be at the mouth to Lake Madeline. As with temperature, dissolved oxygen concentrations at all stations were within 0.8 mg/L of one another, which corresponded to the homogeneity of dissolved oxygen across the Offatts Bayou region (Table 3.5).

Table 3.7.
Seasonal and annual mean with standard deviation (S.D.) for surface temperature (ºC), salinity (ppt) and dissolved oxygen (mg/L) of all stations.
Highest values = bold and lowest = italics.

Station						
Temp (ºC)	winter	spring	summer	Autumn	annual mean	S.D.
1	14.4	22.4	29.6	21.3	*21.9*	*6.5*
2	14.9	22.1	29.9	22.1	22.3	6.3
3	14.9	21.8	29.9	23.2	22.4	6.3
4	15.1	21.0	30.1	23.1	22.4	6.3
5	15.1	21.8	29.9	23.2	22.5	6.2
7	14.9	22.2	30.2	23.7	**22.6**	**6.5**
8	15.1	20.0	30.2	23.5	22.3	6.5
9	15.0	22.0	30.1	23.3	**22.6**	**6.4**
10	14.4	22.7	30.2	23.3	22.5	6.7
11	14.2	22.6	30.1	22.8	22.3	6.7
12	14.4	22.8	30.3	22.3	22.4	6.7
Salinity (ppt)	winter	spring	summer	autumn	annual mean	S.D.
1	16.1	23.6	25.5	18.6	*20.9*	*4.5*
2	17.0	23.0	25.9	20.1	21.5	4.4
3	19.7	26.7	28.4	25.4	24.7	4.0
4	19.9	27.0	28.4	24.8	24.7	4.0
5	19.2	26.6	28.5	19.8	23.6	5.1
7	17.6	24.0	28.2	22.9	23.1	4.9
8	16.8	25.7	28.2	19.9	22.6	6.3
9	19.7	24.9	28.9	25.6	24.6	4.0
10	19.6	24.3	29.0	23.3	24.1	4.4
11	19.4	24.5	29.3	25.1	24.5	4.3
12	19.1	25.6	29.7	25.4	**24.8**	**4.5**
DO (mg/L)	winter	spring	summer	autumn	annual mean	S.D.
1	9.0	4.3	5.0	7.5	6.6	2.3
2	9.1	5.2	5.7	7.9	7.1	1.9
3	9.2	3.4	6.1	7.0	6.8	2.8
4	9.3	3.6	6.4	7.3	7	2.7
5	8.9	3.3	5.1	6.8	*6.4*	*2.6*
7	10.7	4.0	5.8	6.0	7.1	3.6
8	10.7	3.9	5.9	6.5	**7.2**	**3.2**
9	9.2	3.4	6.2	7.5	6.9	2.4
10	9.1	6.0	5.2	7.4	7	1.8
11	8.7	6.3	5.4	7.2	6.9	1.5
12	8.7	6.3	5.1	7.5	6.9	1.6

A second MANOVA was preformed to examine differences between the surface, middle and bottom depths, with regard to temperature, salinity, dissolved oxygen and pH. Levene's test indicated abiotic variances were heterogeneous for the surface, middle and bottom depths, so Bonferroni was selected for the multiple comparisons test.

The MANOVA revealed that temperatures of the surface, middle and bottom water depths were homogeneous to one another overall while, surface, middle and bottom water depths of salinity, dissolved oxygen and pH were significantly different from one another ($p < 0.05$, Table 3.8).

Table 3.8
Homogenous sampling depths (T, S, DO, pH) according to Bonferroni multiple comparison.

Temperature (T)

Surface	Middle	Bottom

Salinity (S)

Surface	Middle	Bottom

Dissolved Oxygen (DO)

Surface	Middle	Bottom

pH

Surface	Middle	Bottom

The second MANOVA also revealed surface, middle and bottom differences of temperature, salinity, dissolved oxygen and pH on a monthly basis. These results are illustrated in figures 3.12 to 3.15 and corresponding values are in Appendix B.

In December and January, there was a turnover of water so that the bottom water was warmer than the surface (Fig. 3.12, arrow 1). This trend did not last very long. A reversal of the water masses occurred, between February and March, so that colder temperatures were again on the bottom and warmer temperatures were on the surface (arrow 2). This trend continued through the remaining months until autumn when all three water levels decreased and were very close to the same temperature (arrow 3).

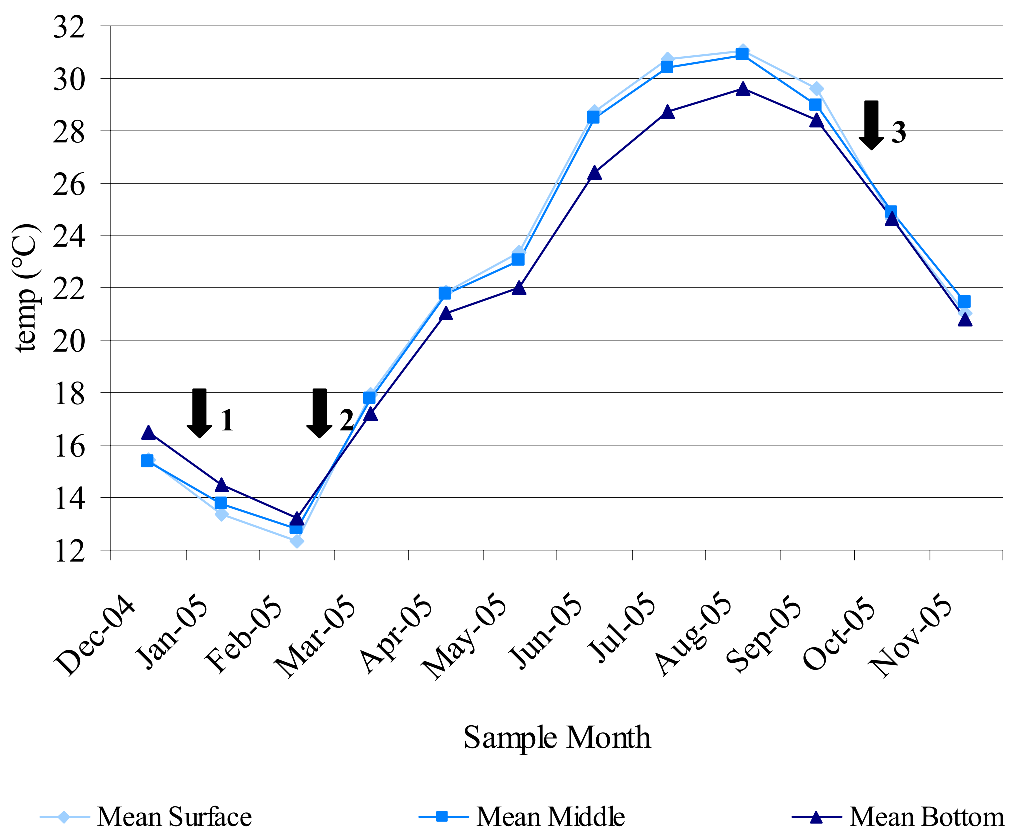

Fig. 3.12. Surface, middle and bottom water temperature.

Average monthly salinity values were higher in the bottom waters, then decreased towards the surface in all months (Fig. 3.13). This occurred due to the higher salinity waters flowing in at the bottom from West Bay and less saline water flowing out of Offatts Bayou at the surface.

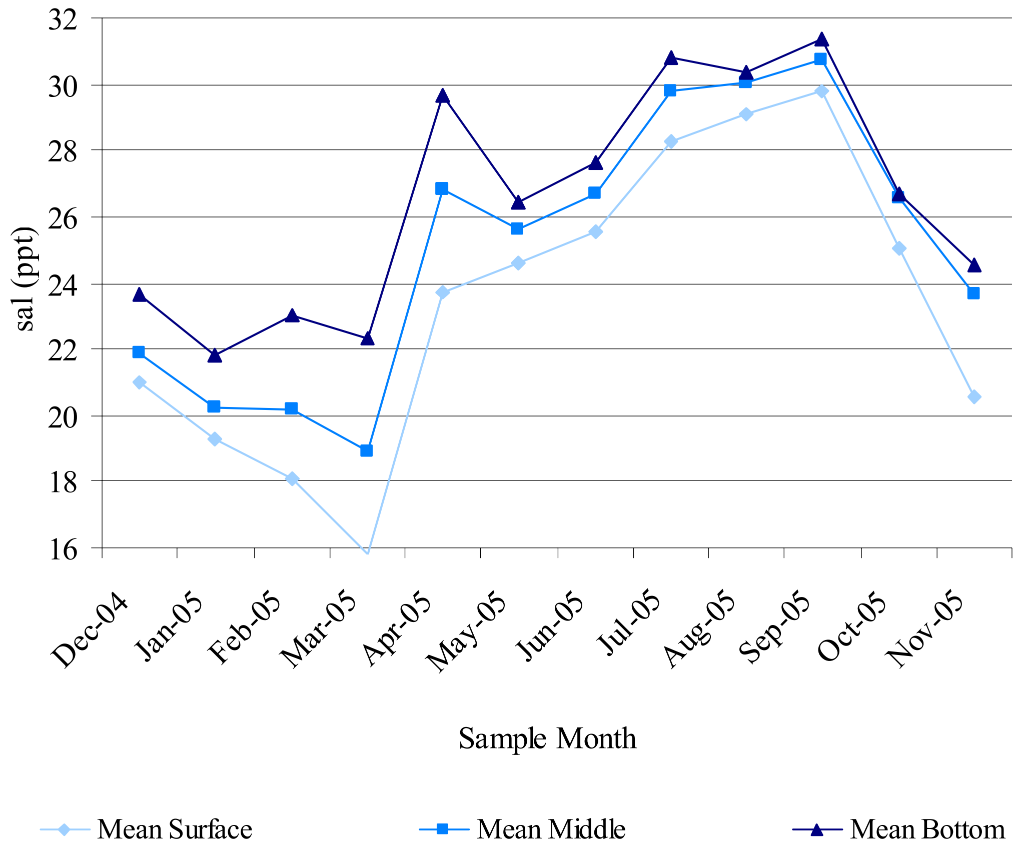

Fig. 3.13. Surface, middle and bottom water salinity.

Concentrations of dissolved oxygen (DO) followed a standard pattern throughout the entire sampling period (Fig. 3.14). Higher concentrations of DO were visible in the surface waters, decreased through the middle of the water column, then became very low in the bottom waters. Bottom waters became hypoxic (< 2 mg/L) between June and October 2005. The highest dissolved oxygen concentrations occurred during the winter months of December, January, February and March (arrow 1) in all depths of the water column. There was a gradual decrease through spring and early summer to the minimum in August (arrow 2), then a dramatic increase through October and November.

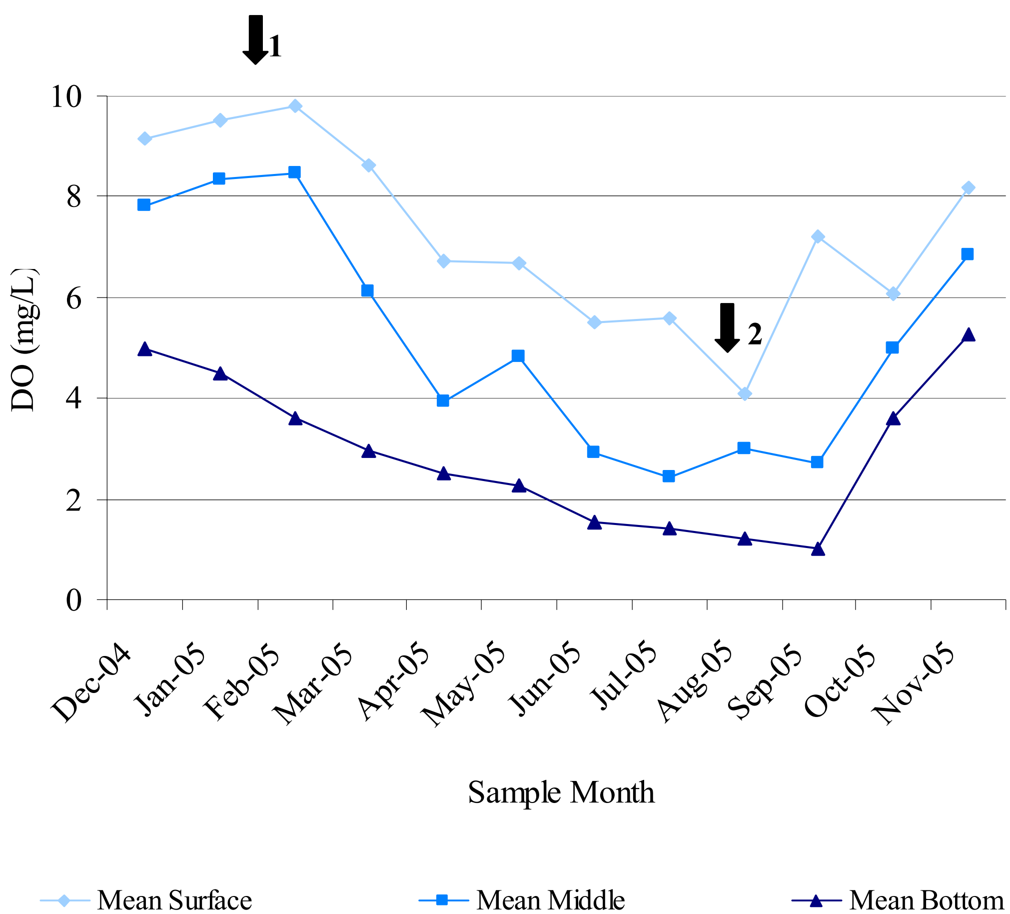

Fig. 3.14. Surface, middle and bottom water dissolved oxygen concentration.

Surface, middle and bottom values for pH are expressed in figure 3.15. Levels decreased through winter (arrow 1) to between 6 and 7, increased through spring (arrow 2), into summer and through autumn. No values were recorded for July/August because the CTD used at that time did not have a pH sensor (arrow 3). Nonetheless, pH most likely remained high between 8 and 9 with a possible peak in late August during the phytoplankton bloom.

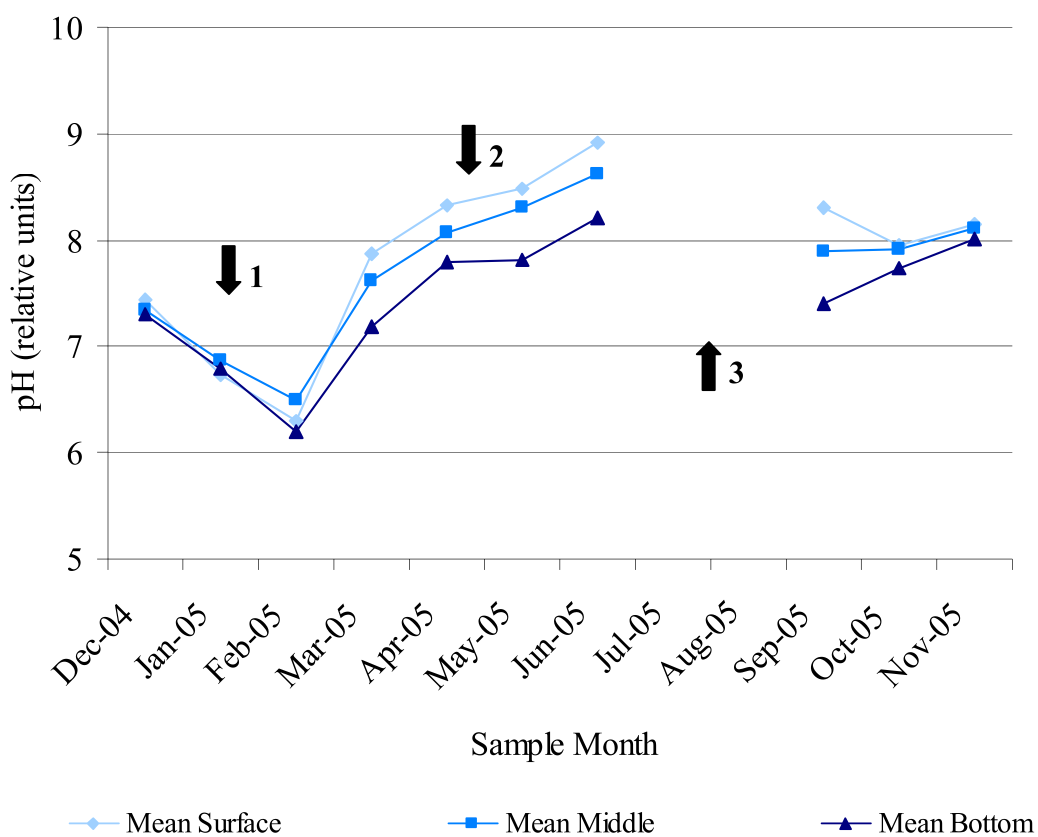

Fig. 3.15. Surface, middle and bottom water pH.

The second MANOVA was also preformed to determine what, if any, seasons were homogeneous, with respect to surface water temperature, salinity, dissolved oxygen and pH ($p < 0.05$). Seasonal means of surface parameters are illustrated in figure 3.16. Seasonally, temperature and salinity increased from winter, into spring and summer (arrow 1), then gave way to a decrease towards autumn (arrow 2). Dissolved oxygen was inversely related to temperature and salinity and decreased from winter to spring (arrow 3), then increased towards summer and into autumn (arrow 4). Levels of pH averaged around 8 throughout the entire sample season, with lowest during winter and highest in summer. Corresponding data for surface, middle and bottom depths are located in Appendix B.

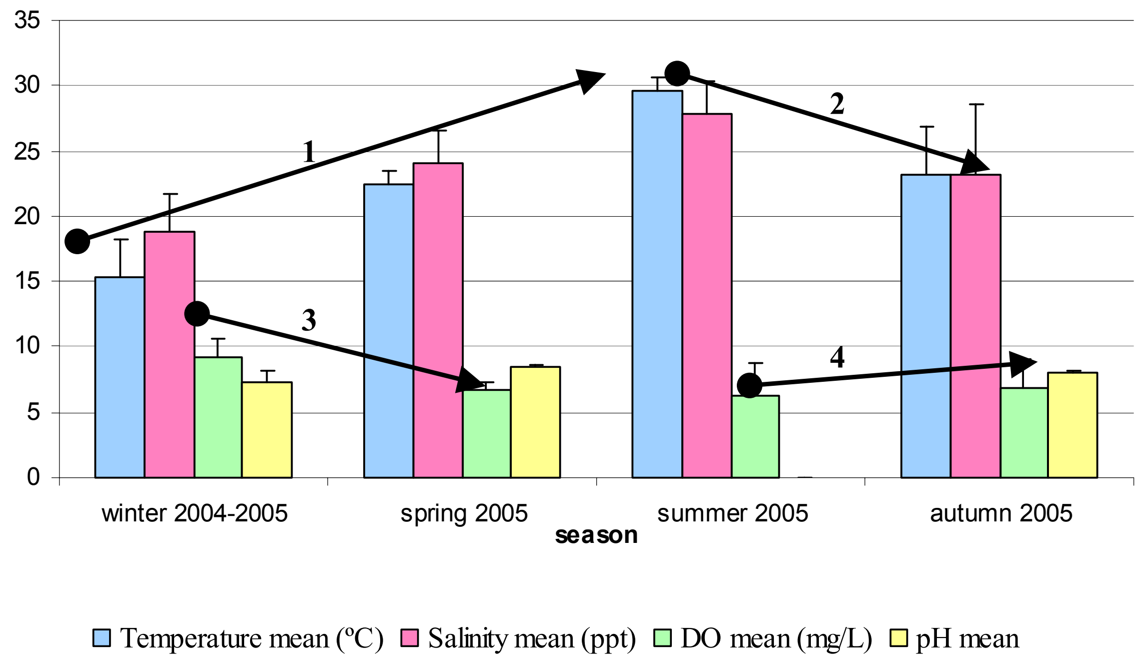

Fig. 3.16. Seasonal comparison of surface water temperature (ºC), salinity (ppt), dissolved oxygen (mg/L) and pH means.

Temperature was statistically homogeneous throughout all seasonal samples, with highest values recorded during summer, lowest in winter and intermediate temperatures occurring in spring and autumn (Table 3.9). Salinity was significantly different between the four seasons with highest quantities in summer and lowest during the winter. Dissolved oxygen was heterogeneous for all seasons sampled, with winter possessing the highest concentrations and summer having the lowest. pH values were highest in summer and lowest during winter. Moderate pH levels existed during spring and autumn and were statistically homogeneous.

There was a significant difference observed between highest and lowest parameters during all seasons. Highest temperature, salinity and pH were recorded during summer, while highest DO occurred in winter. Lowest temperature, salinity and pH were identified during winter with lowest DO taking place during summer. Autumn and spring values were at intermediate levels for all parameters.

Table 3.9
Homogeneous groups for seasons (winter, spring, summer, autumn) according to Bonferroni multiple comparison.

Temperature				
	Summer	Autumn	Spring	Winter
Salinity				
	Summer	Spring	Autumn	Winter
Dissolved Oxygen				
	Winter	Autumn	Spring	Summer
pH				
	Summer	Spring	Autumn	Winter

3.1.3 Transect Hydrology

Seasonal changes in temperature, salinity and dissolved oxygen regimes in the surface and bottom waters along a transect from West Bay (station 12) and the boat channel (stations 10 and 11), through Offatts Bayou (station 9 and 4) and into the Back Bay (station 1) are summarized in figures 3.17 to 3.20. Winter is represented by the 19 January 2005 sample (Fig. 3.17), spring by 12 April 2005 (Fig. 3.18), summer by 19 August 2005 (Fig. 3.19) and autumn by 11 November 2005 (Fig. 3.20). Appendix A contains figures for seasonal surface and bottom pH.

Due to the colder air temperatures during winter, surface water was colder than the bottom water along the Offatts Bayou transect from the open end (station 12) to the blind end (station 1) of Offatts Bayou (Fig. 3.17). An increase in temperature was observed in the bottom waters at the Deep Hole, while the surface remained colder by approximately 4 °C. This temperature increase corresponded to a positive spike of salinity and a negative spike in dissolved oxygen, also in the bottom waters. High salinity bottom water (~21 ppt) flowed in from West Bay, traveled through the boat channel, where it gradually increased, followed by a slight positive spike at the Deep Hole and decrease in the Back Bay. Low dissolved oxygen entered Offatts Bayou from West Bay (station 12) in the bottom waters and immediately decreased at station 11, followed by an increase through station 10 and 9. Surface dissolved oxygen concentrations remained uniform throughout

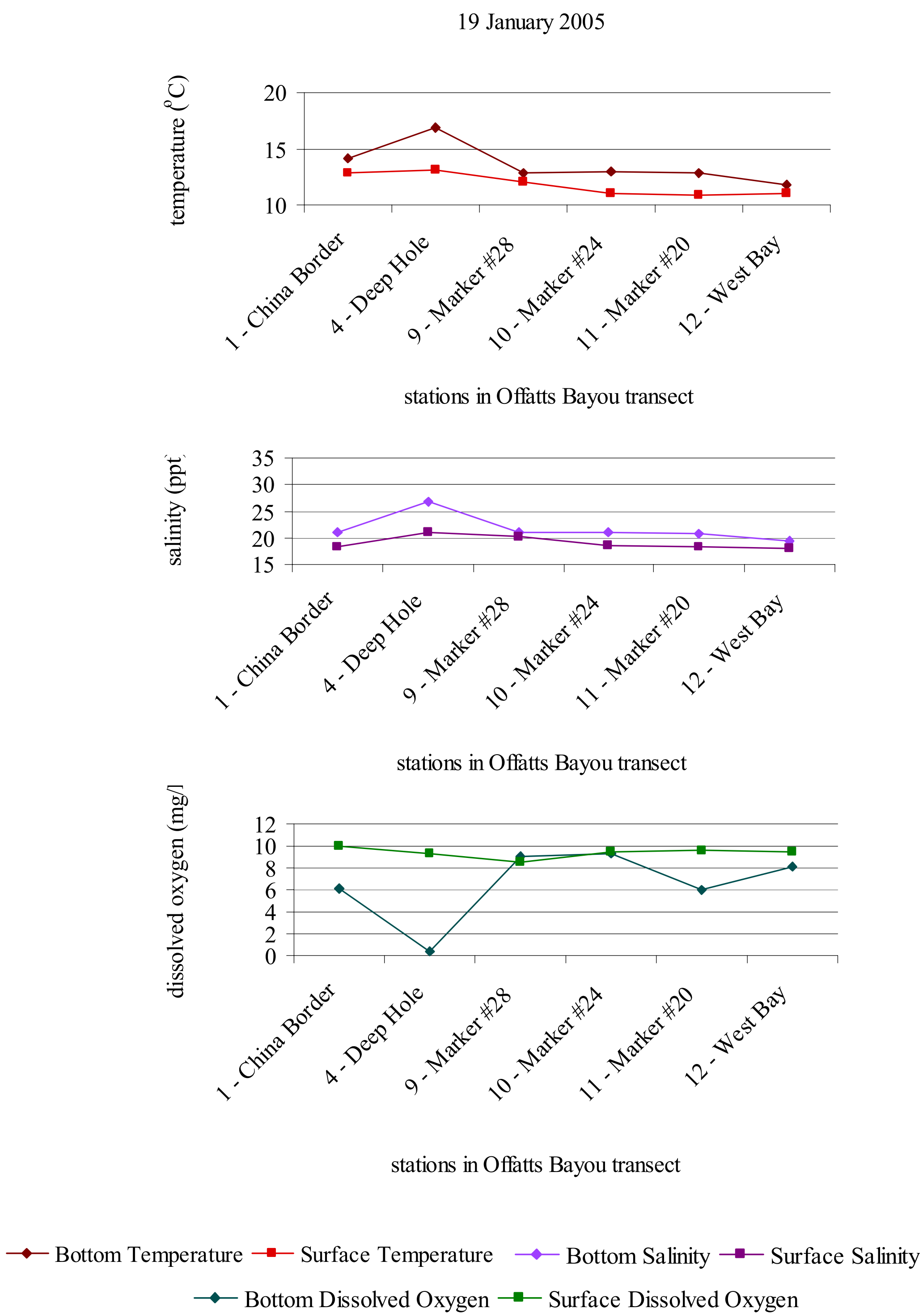

Fig. 3.17. Winter surface and bottom temperature, salinity and dissolved oxygen.

In Spring 2005, surface and bottom water temperatures were relatively similar (~22 °C) throughout the transect from the open end (station 12) to the blind end (station 1) of Offatts Bayou, with only a slight negative deviation at station 4 in the middle of Offatts Bayou (Fig. 3.18). Bottom salinity began at approximately 30 ppt in West Bay, increased to 34 ppt throughout the boat channel and the Deep Hole, then decreased in the Back Bay. Surface salinity increased steadily from roughly 19 ppt in the Back Bay to approximately 26 ppt in West Bay. Dissolved oxygen concentrations in bottom waters began at approximately 5 mg/L in West Bay, decreased through the boat channel to near anoxic conditions at the Deep Hole (1.15 mg/L), then increased in the Back Bay. Anoxic conditions existed in the bottom waters of the Deep Hole due to the lack of mixing which would have brought oxygen rich surface water to the benthos. Surface water dissolved oxygen began at 6.28 mg/L in West Bay, fluctuated between 5 and 6 mg/L throughout the boat channel, then increased to roughly 7.15 mg/L at the Deep Hole and into the Back Bay. Positive spikes in temperature and salinity were again observed at the Deep Hole, which coincided with a negative spike in dissolved oxygen concentrations.

During summer, surface and bottom temperatures were relatively similar throughout the transect, from the open end (station 12) to the blind end (station 1) of Offatts Bayou (Fig. 3.19). High bottom salinities were observed in West Bay, gradually increasing through Offatts Bayou, then decreasing again in the Back Bay. Surface salinities began at approximately 27 ppt in the Back Bay, increased through the

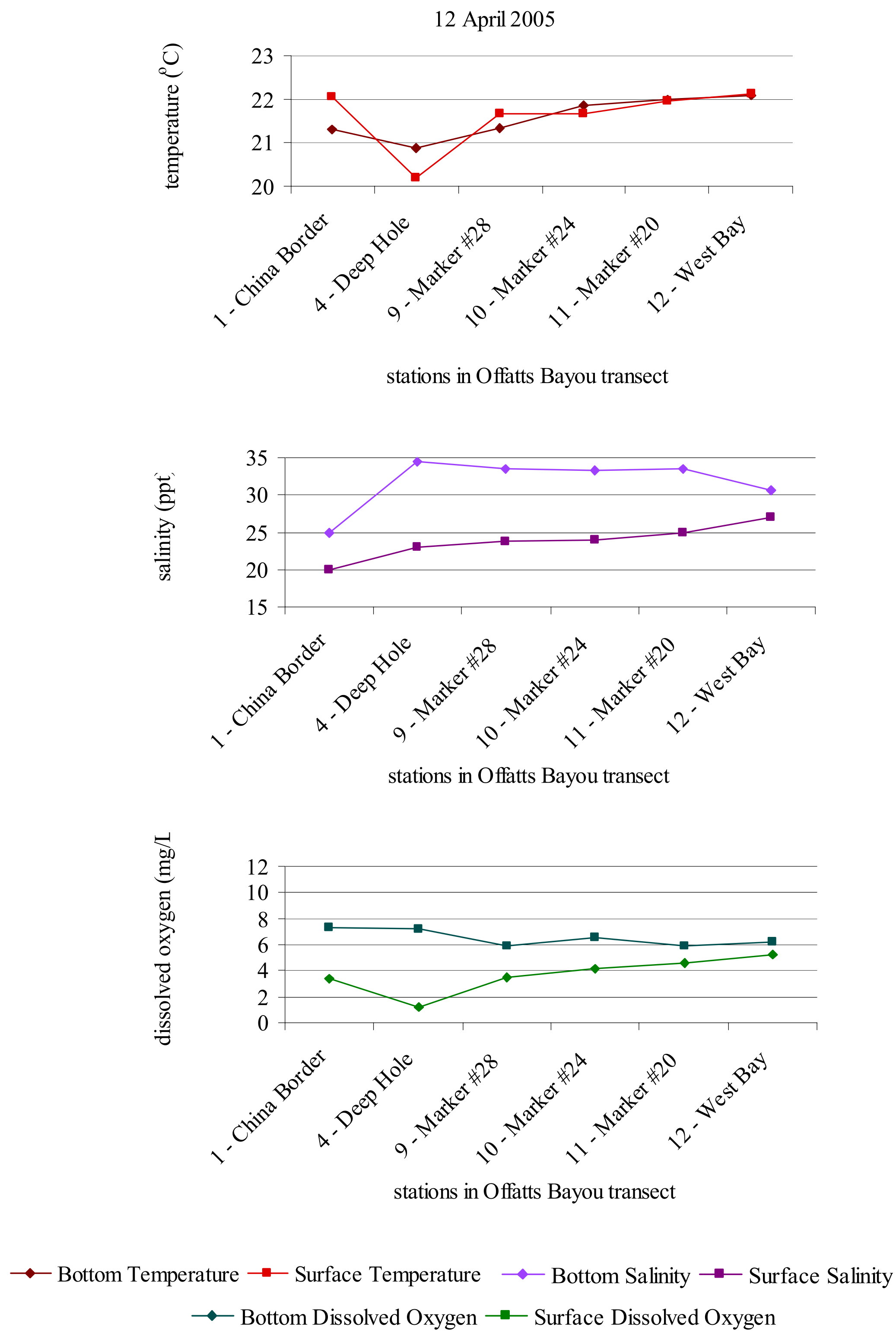

Fig. 3.18. Spring surface and bottom temperature, salinity and dissolved oxygen.

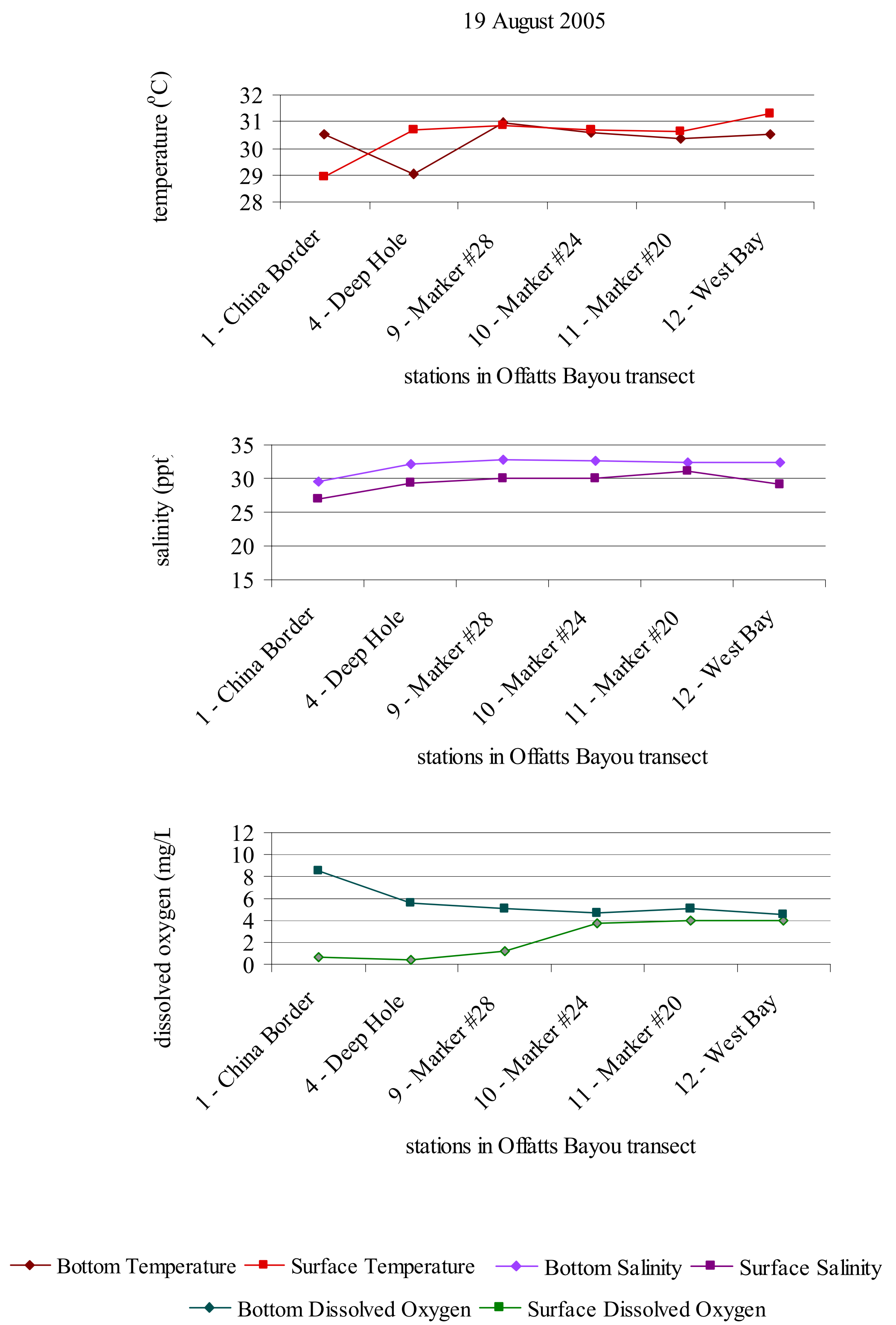

Fig. 3.19. Summer surface and bottom temperature, salinity and dissolved oxygen.

Deep Hole, middle of Offatts Bayou, the boat channel and out into West Bay. Bottom dissolved oxygen concentrations entered from West Bay, remained uniform through the Boat Channel (stations 12, 11 and 10), then decreased to hypoxic conditions throughout Offatts Bayou (station 4 and 9) and the Back Bay (station 1). Dissolved oxygen concentrations in the surface waters were extremely high in the Back Bay (station 1), then decreased and leveled off at the Deep Hole and through the transect towards West Bay.

During autumn, temperatures in the bottom waters began at approximately 24 ºC in West Bay (station 12), increased slightly through the boat channel, decreased dramatically at station 9 and through the Deep Hole then increased in the Back Bay at station 1 (Fig. 3.20). Surface temperatures were relatively stable at roughly 30 ºC throughout the transect. Bottom salinity was relatively constant at 24 ppt throughout the transect with the exception of a minor dip at station 10 in the boat channel. Salinity at the surface corresponded to bottom salinity in West Bay and through the boat channel. At station 9, surface salinity diverged from bottom salinity and decreased through the Deep Hole and Back Bay to 19.6 ppt. Concentrations of dissolved oxygen in both surface and bottom waters flowed similarly with each other from West Bay and through the boat channel. Top and bottom dissolved oxygen concentrations diverged at station 9, where bottom dissolved oxygen decreased to approximately 2.5 mg/L and surface concentrations increased to about 8 mg/L.

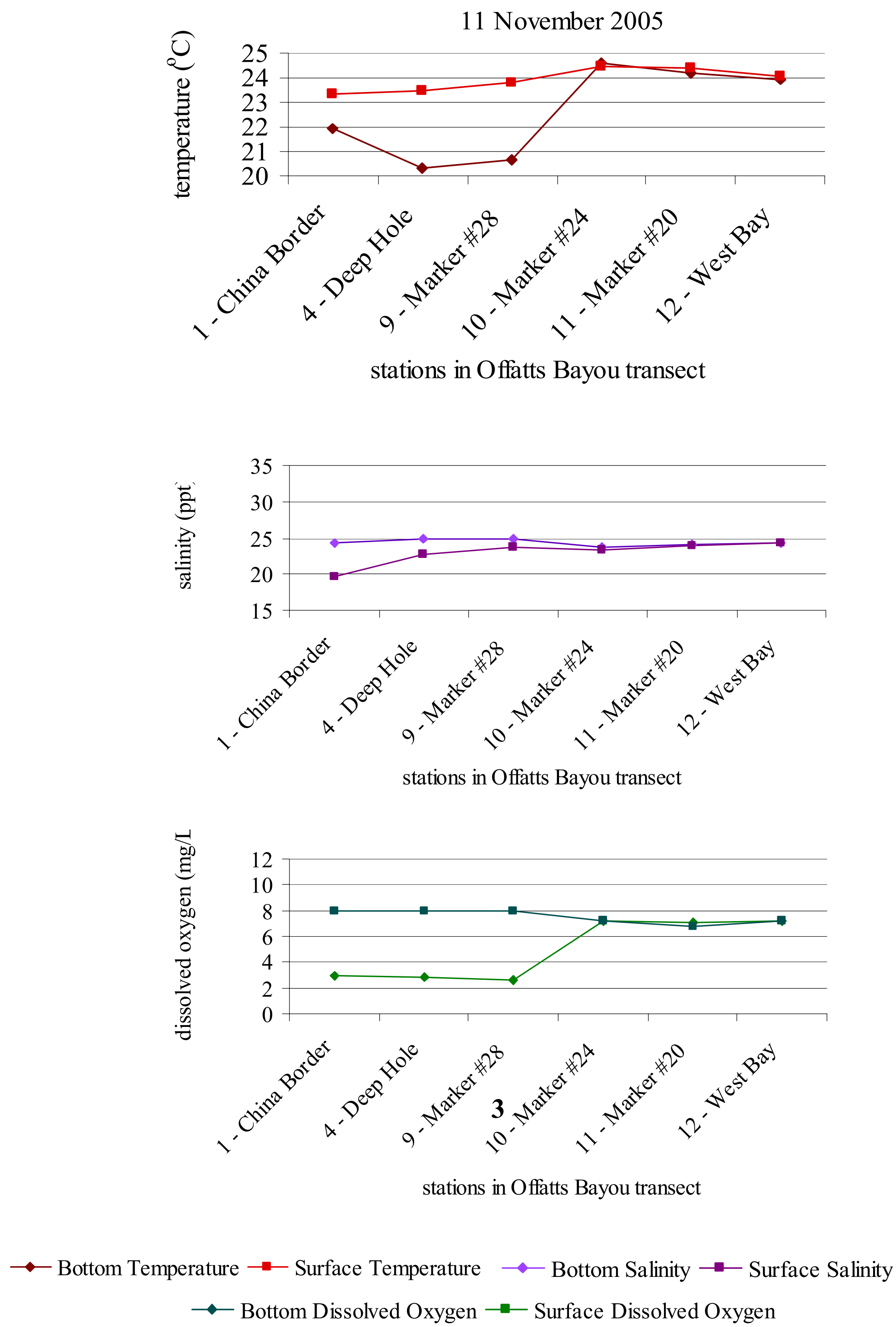

Fig. 3.20. Autumn surface and bottom temperature, salinity and dissolved oxygen

3.2 Phytoplankton Data Analysis

Dominate species are represented in the following figures and were defined as those which occupied greater than 10% of the total abundance of the community. A photographic identification chart is located in Appendix C.

3.2.1 Winter Trends

The phytoplankton community diversity followed specific trends between stations during the winter months. The December 2004 sample was entirely composed of Bacillariophyceae (diatoms), with both pennate and centric forms present (Fig. 3.21). At all stations, except #11, the centric diatom, *Guinardia delicatula,* dominated. Station 1 had a community population consisting of approximately 86% *G. delicatula* and 14% *Thalassiosira pacifica.* Station 3 was comprised of 88% *G. delicatula* 12% *Melosira nummuloides.* Station 5 was almost equally dominated by *Coscinodiscus radiatus* (47%) and *G. delicatula* (53%). Stations 10, 11 and 12 all contained *M. nummuloides* and *G. delicatula* plus *Chaetoceros didymus* (10), *C. radiatus* and *Ditylum brightwelli* (11) and *D. brightwelli* (12). *Ditylum brightwelli* comprised about 22% of the community at station 11 and 30% of the community at station 12.

D. brightwelli transitioned from stations 11/12 in December 2004 to completely dominate the system at all stations, except station 1, in January 2005 (Fig. 3.22). The pennate diatom, *Rhizosolenia pungens,* moved from West Bay back into the middle of Offatts Bayou where it was visible in ⅔ of the stations sampled. An unidentified *Thalassiosira* species was noted in stations 2, 3, 4 and 9. Station 1 was dominated by

Chaetoceros danicus, which was also seen in stations 2 and 8 as a minor representative of the phytoplankton community.

In February, *D. brightwelli* moved into the back regions of Offatts Bayou and was only visible at stations 1 through 4 (Fig. 3.23). A pennate diatom, *Rhizosolenia setigera,* took over as the dominant diatom in the remaining sample stations (Lake Madeline and middle of Offatts Bayou). Due to inclement weather in February 2005, no data was recorded for stations 10 through 12.

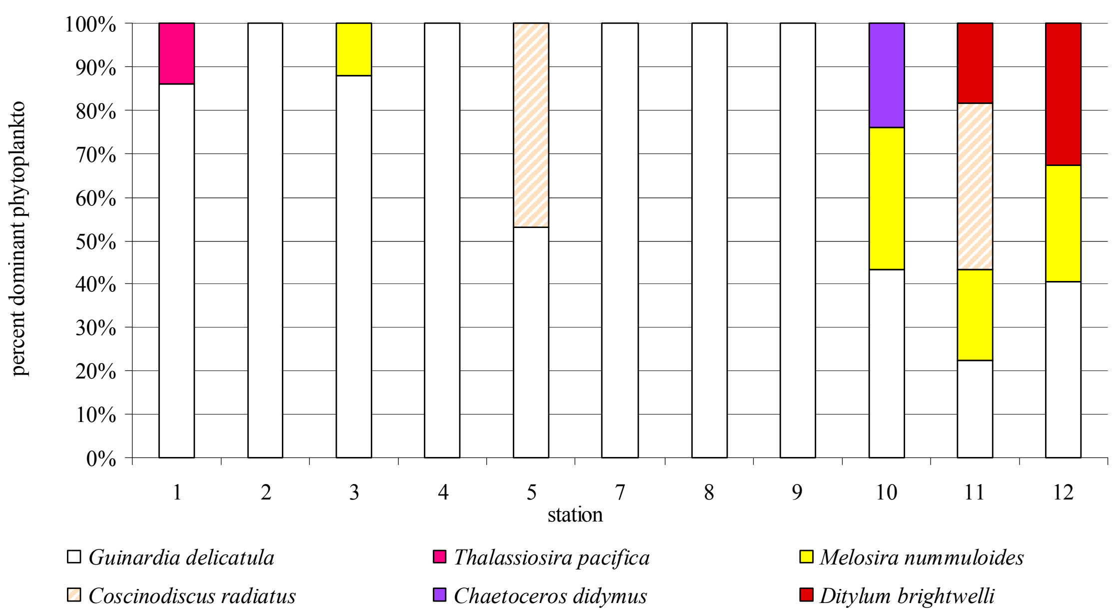

Fig. 3.21. Dominant phytoplankton (%) for 16 December 2004.

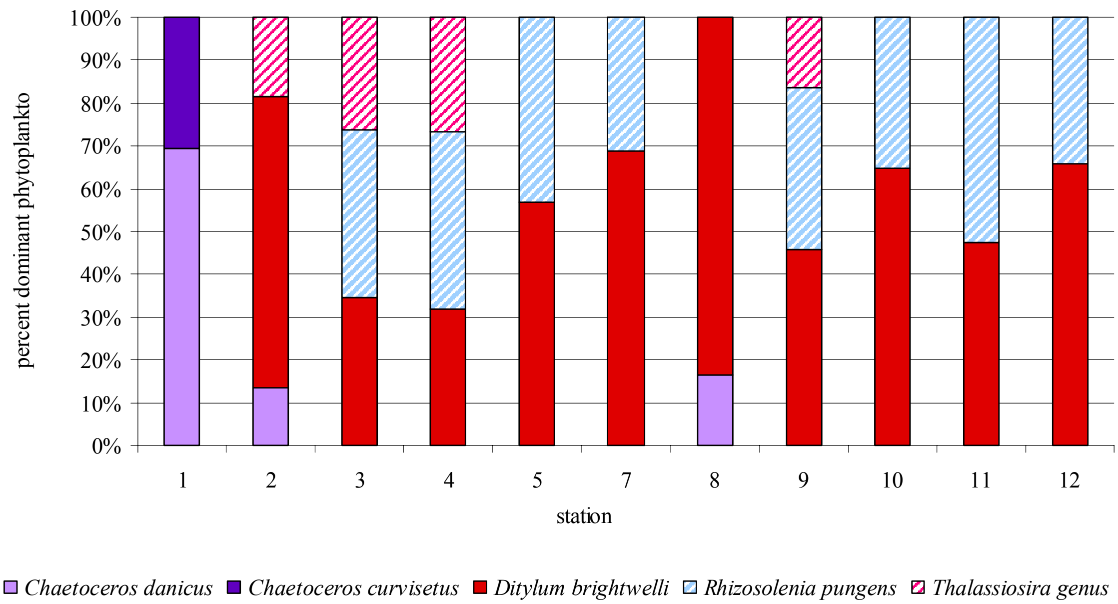

Fig. 3.22. Dominant phytoplankton (%) for 19 January 2005.

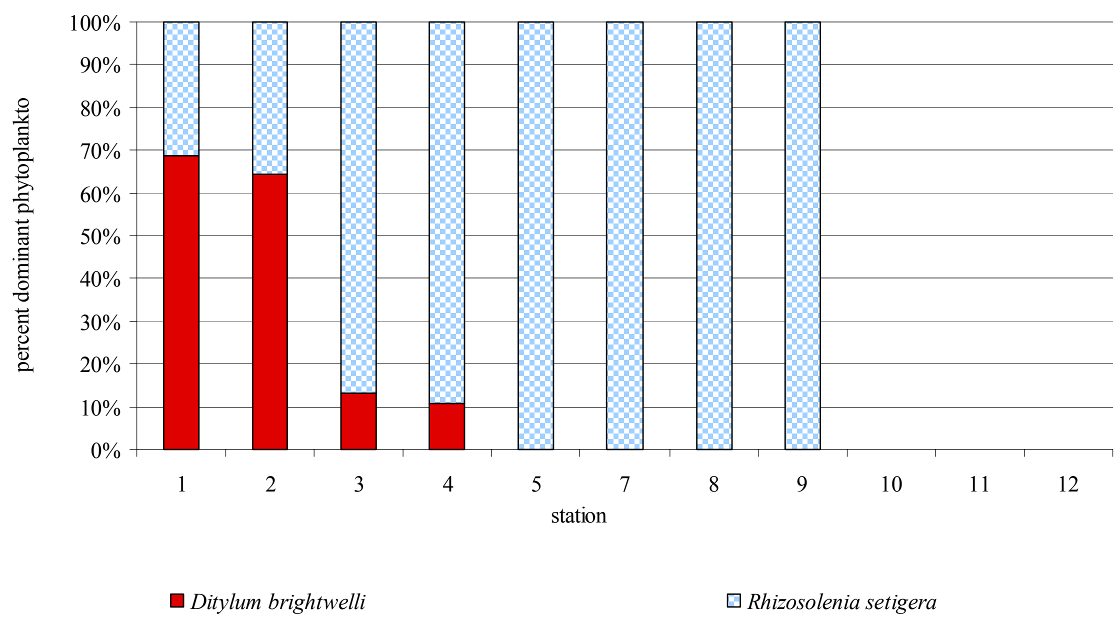

Fig. 3.23. Dominant phytoplankton (%) for 18 February 2005.

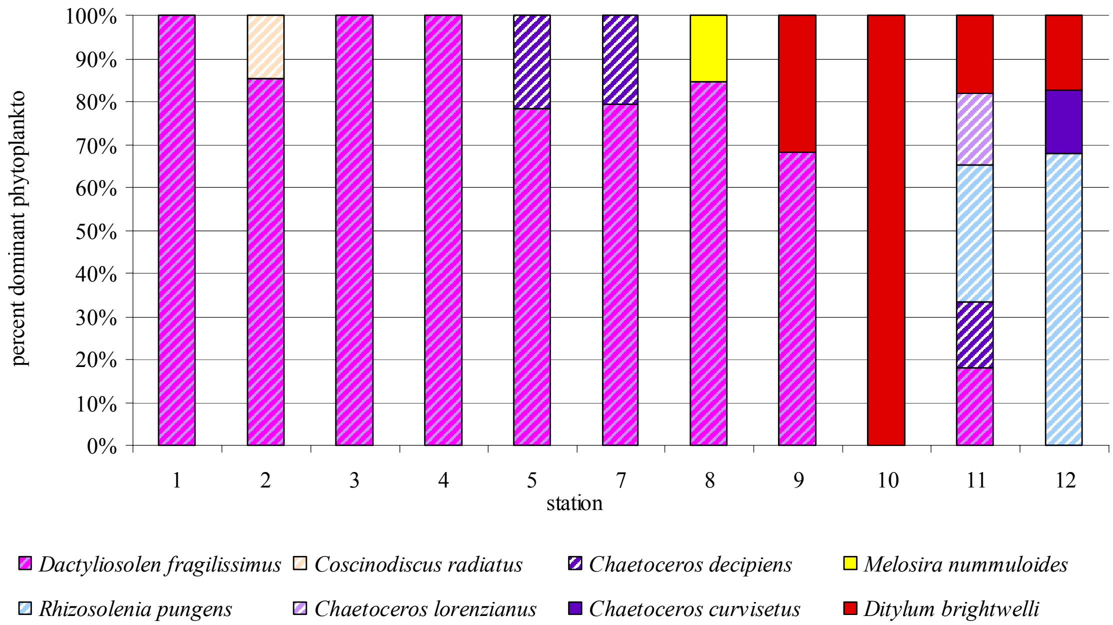

Fig. 3.24. Dominant phytoplankton (%) for 24 March 2005.

In March of 2005, the centric diatom, *Dactyliosolen fragillissimus,* dominated from the middle of Offatts Bayou (station 9), into Lake Madeline (stations 7 and 8) and back into the Back Bay (stations 1 and 2) (Fig. 3.24). Several other diatoms were identified, (*C. radiatus, C. decipiens, M. nummuloides and D. brightwelli),* but in minor percentages. Station 12 contained approximately 69% *R. pungens,* which then transitioned back into station 11 at about 32%. *D. brightwelli* started in West Bay (stations 11 and 12) at 19%, moved inward to completely dominate station 10, then stopped at station 9 with 31%. Station 11 had the greatest diversity with 5 different diatoms (*D. brightwelli, R. pungens, C. decipiens, D. fragillissimus* and *Chaetoceros lorenzianus)*.

The key notable change in winter phytoplankton diversity was the succession of *D. brightwelli* from station to station over a four month period. *D. brightwelli* started out at station 12 (West Bay) in December, moved into all stations (except station 1) during January, proceeded into the Back Bay and out of the open regions of Offatts Bayou in February and finally ended up back out in West Bay in March.

3.2.2 Spring Trends

Spring phytoplankton samples represent one of the two most diverse seasons (the other being autumn) with no visible trends. The temperate and salinity changes from winter to spring within the system furnished numerous phytoplankton species the opportunity to succeed. A notable feature of the phytoplankton community is the appearance of a haptophytes (*Corymbellus aureus)* in almost all stations and a euglenophyte (*Euglenophyta spp A)* in the smaller and enclosed stations (April 2005, Fig. 3.25).

During April 2005, *C. radiatus*, a centric diatom, constituted the bulk of the phytoplankton community at stations 1, 2, 3, and 10 (Fig. 3.25). Station 4 was dominated by *C. decipiens* while Station 5 was dominated by an unidentified *Chaetoceros* species. Station 7 and 8, even though they were in close proximity of each other, were highly populated by two very different phytoplankton; a haptophyte at station 7 (*C. aureus)* and a centric diatom at station 8 (*D. brightwelli)*. Stations 9, 11 and 12 contained a large percentage of *Rhizosolenia imbricata*, with small quantities of *C. radiatus* and *D. brightwelli*. The most abundant species in West Bay (stations 11 and 12) was *R. imbricata*, which then made its way backward into the further reaches of

Offatts Bayou (stations 3 and 9). *R. imbricata* transitioned from West Bay into the Back Bay during the period between the April and May 2005 samplings.

In May, the haptophyte, *C. aureus,* became the dominating phytoplankton in most stations (Fig. 3.26). Stations 10, 11 and 12, in the West Bay and Boat Channel, still showed a variety of phytoplankton species. A *Euglenophyta spp A* could be seen in station 2 (~ 28%). *C. radiatus* has transitioned out of Offatts Bayou and into West Bay during May, except at a minor percentage at station 5 (~ 12%).

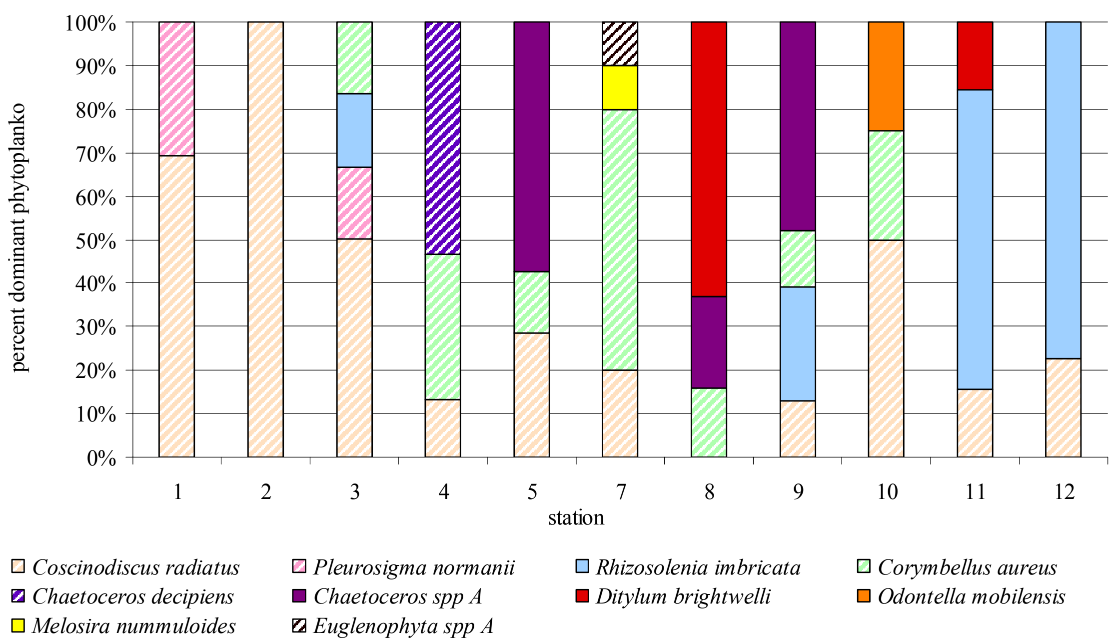

Fig. 3.25. Dominant phytoplankton (%) for 12 April 2005.

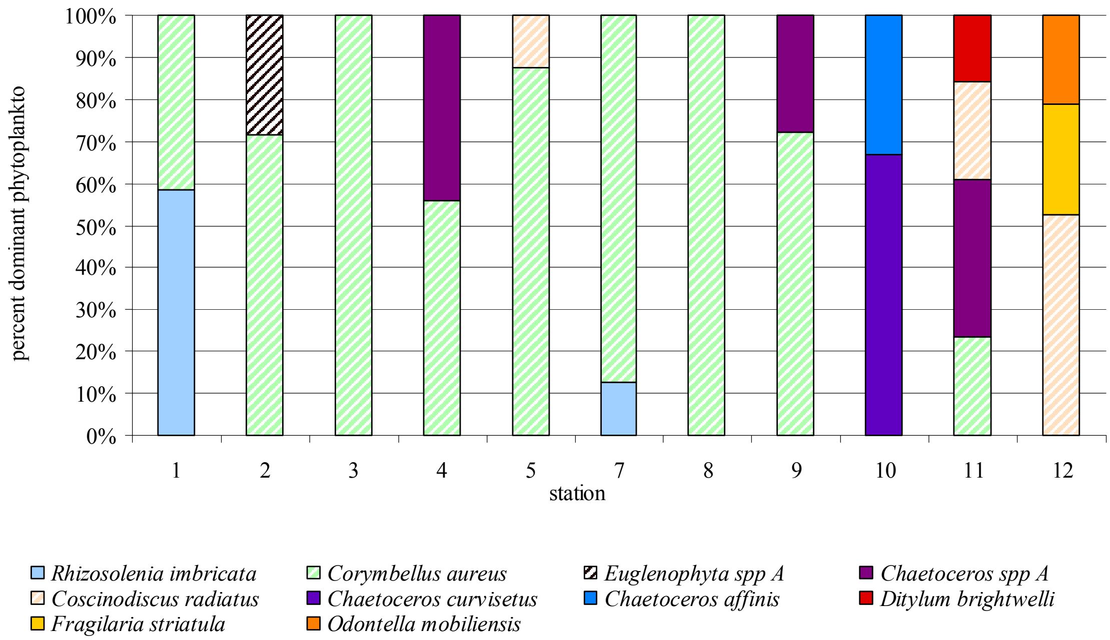

Fig. 3.26. Dominant phytoplankton (%) for 11 May 2005.

3.2.3 Summer Trends

The early summer (June) phytoplankton population in 2005 was comprised of a mixed bacillariophyte and haptophyte assemblage (Fig. 3.27). Throughout June, the haptophyte, *C. aureus,* dominated all stations within Offatts Bayou and Lake Madeline. New phytoplankton species, not seen in the winter and spring months, also appeared during June in Offatts Bayou; station 1 (*Skeletonema menzelli)*, station 5 (*Chaetoceros affinis),* and station 7 and 8 (*Navicula directa, Striatella unipuncta*) then disappeared by the July sampling. The West Bay regional stations (stations 12 and 11) were dominated by the *Chaetoceros spp A* during the month of June.

The June to July 2005 timeframe reflected the transitional zone from a mixed community to complete dominance of Offatts Bayou by *C. aureus* (Figs. 3.27, 3.28).

During the summer bloom from July, through August and into early September, the phytoplankton community was 99% dominated, at almost all stations throughout Offatts Bayou, by the small haptophyte, *C. aureus* (Figs. 3.27, 3.28 and 3.29). During early September (Fig. 3.29), station 7 had approximately 12% *Euglenophyta spp A* and station 12 had remnants of *R. setigera* and *C. spp A.*

In late September, after Hurricane Rita, the Offatts Bayou system displayed a transitional phase from C. *aureus* domination to a large diversity of phytoplankton (Fig. 3.30). *C. radiatus* dominated at stations 1, 2 and 5, while also in stations 10 and 11 as minor percentages of the community composition. *C. aureus* dominated 100% of the sample in Stations 3, 4, 7 and 8, but was also a small contributor at stations 5 and 9. *Chaetoceros spp. A* dominated at stations 9, 11 and 12, but was also visible in stations 1 and 10. *Odontella mobilensis* appeared in stations 10 and 12.

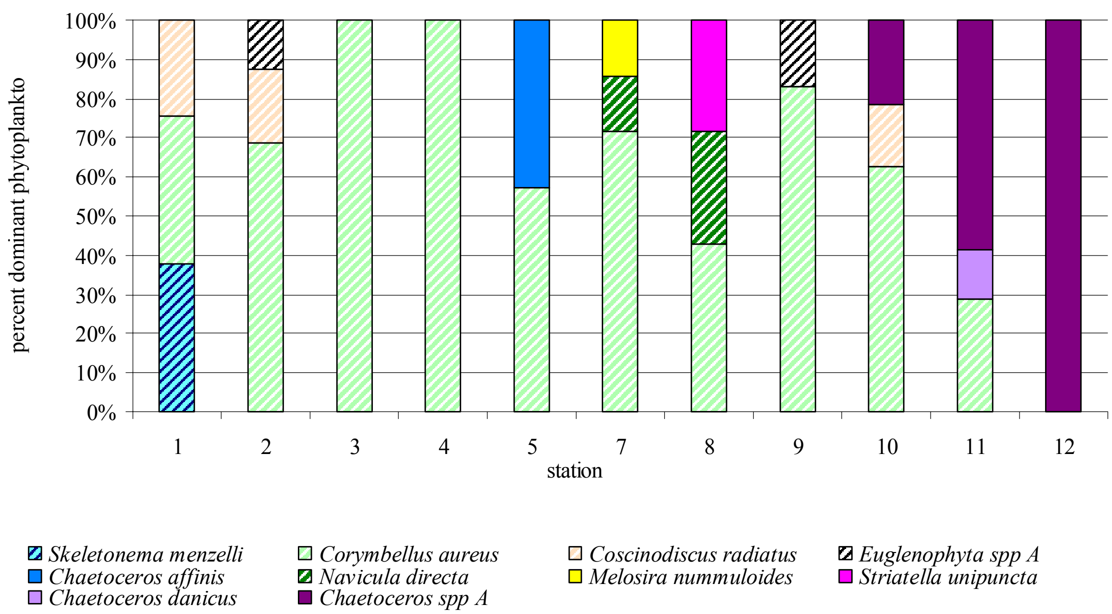

Fig. 3.27. Dominant phytoplankton (%) for 15 June 2005.

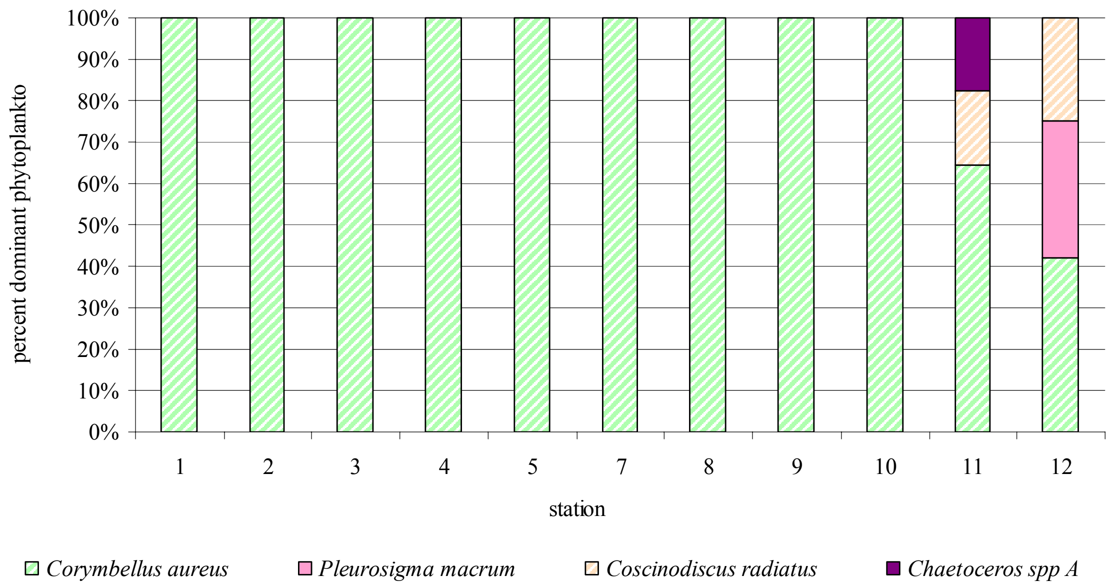

Fig. 3.28. Dominant phytoplankton (%) for 21 July 2005.

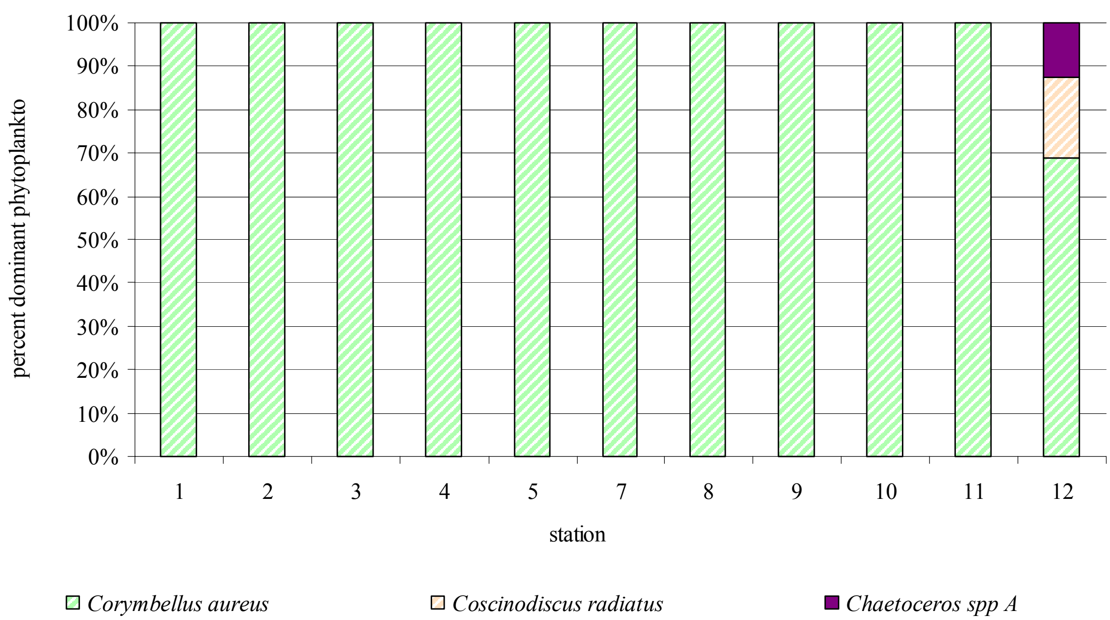

Fig. 3.29. Dominant phytoplankton (%) for 19 August 2005.

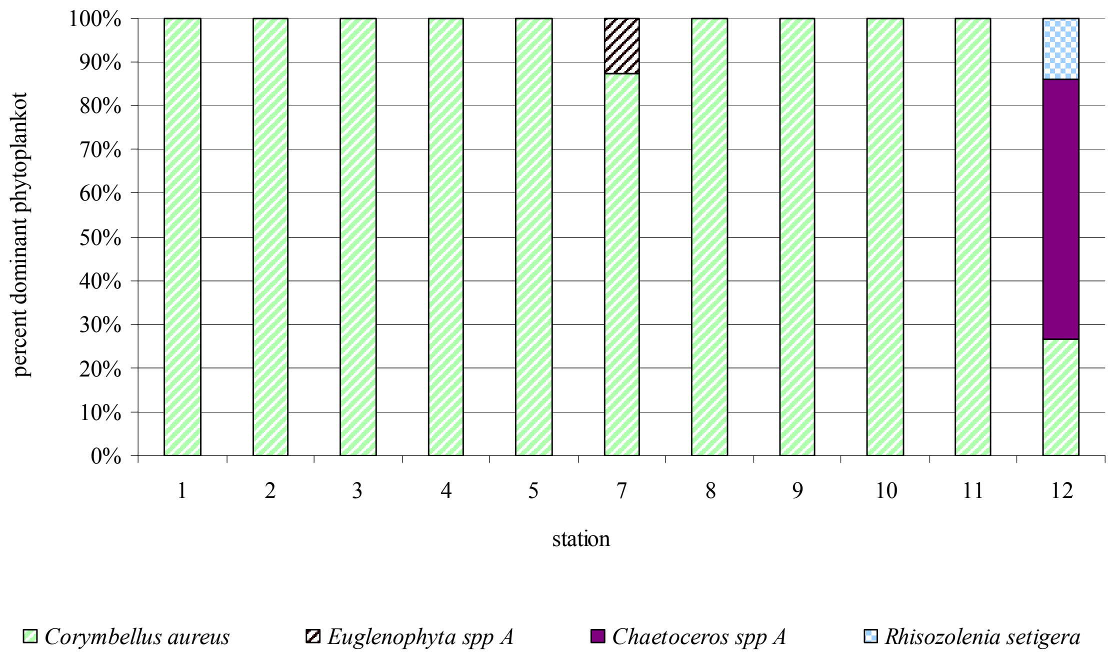

Fig. 3.30. Dominant phytoplankton (%) for 15 September 2005.

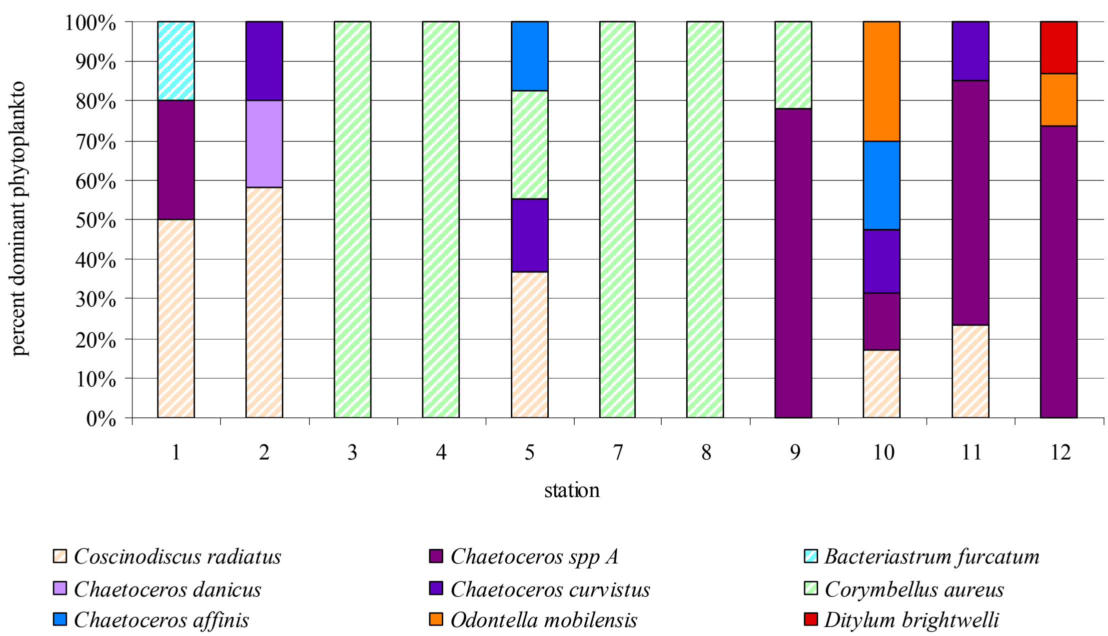

Fig. 3.31. Dominant phytoplankton (%) for 29 September 2005.

3.2.4 Autumn Trends

Autumn (2005) was the second season with a highly diverse phytoplankton community that was dominated by a mixed bacillariophyte assemblage. In October, *Chaetoceros spp A* and *O. mobilensis* had transitioned into the middle and back areas of Offatts Bayou and into Lake Madeline and co-dominated at stations 1, 2, 3, 4, 5, 7, 8 and 9 (Fig. 3.32). *Lithodesmium undulatum* constituted 100% of the phytoplankton community at station 10 and co-dominated in stations 11 and 12 with *Chaetoceros spp A*. *D. brightwelli* reappeared in the phytoplankton community at station 7 (~17%), *C. radiatus* dominated at station 9 (~11%) and *Bacteriastrum hyalinum* appeared for the first time at station 12 as a negligible contributor to the population.

In November 2005, all stations were dominated by a suite of 3 species within the *Chaetoceros* genus (Fig. 3.33). *C. spp A* remained in the back areas of Offatts Bayou (from October), dominating stations 1 and 2. October domination by *C. spp A* gave way to *Chaetoceros spp B* in West Bay (stations 11 and 12), middle of Offatts Bayou (stations 3, 9 and 10) and Lake Madeline (stations 7 and 8). *Chaetoceros curvisetus* co-dominated at most stations (⅔ of the stations). *S. menzelli* reappeared in the Offatts Bayou phytoplankton community at Station 5, representing approximately 13% of the population.

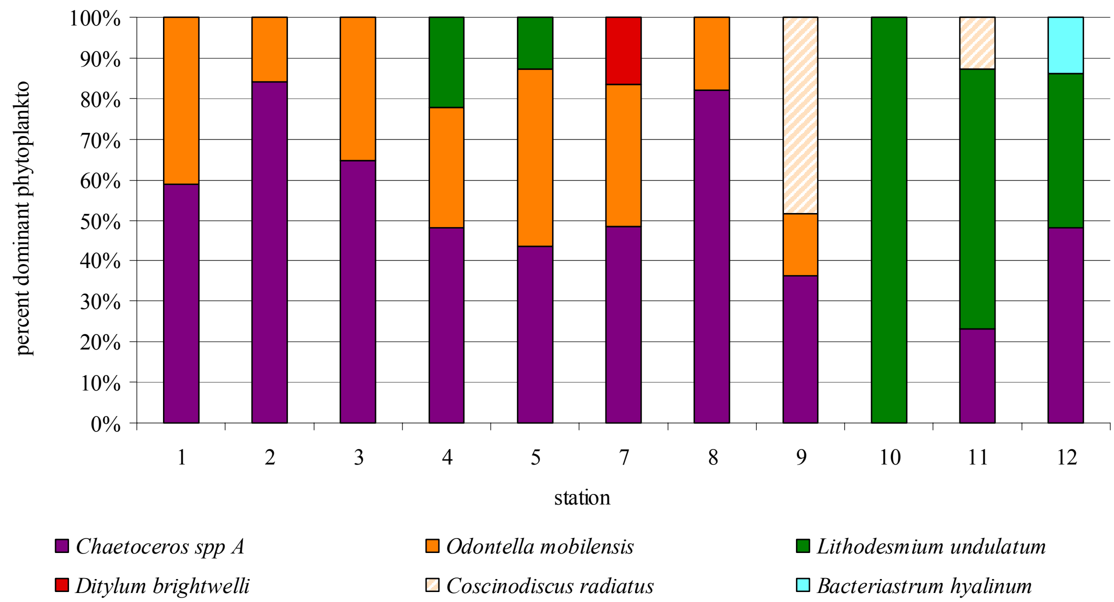

Fig. 3.32. Dominant phytoplankton (%) for 19 October 2005.

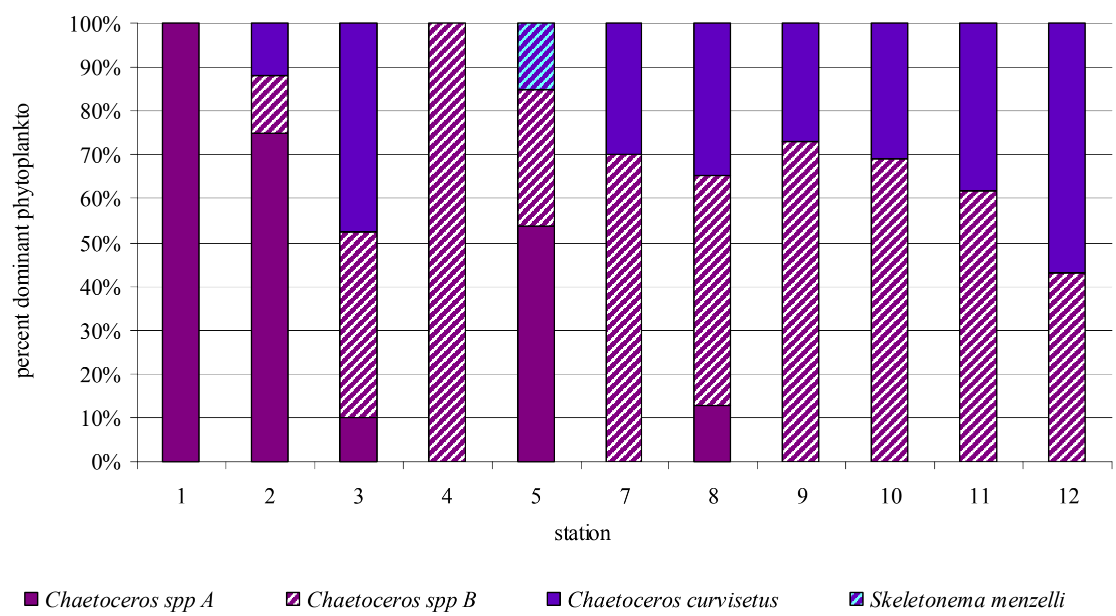

Fig. 3.33. Dominant phytoplankton (%) for 11 November 2005.

3.2.5 Phytoplankton Species

Figure 3.34 depicts the annual successional pattern between algal taxa in Offatts Bayou. The Bacillariophyta group dominated (100%) from December 2004 through March 2005. In April 2005, percentages of Bacillariophyta decreased to approximately 82% and the first Haptophyta arrived, contributing to roughly 18% of the community composition at. Euglenophyta species were visible in April through June 2005, but contributed a relatively minor percentage (~ 3%) to the community. Throughout May and June 2005, Haptophyta (~ 60%) and Bacillariophyta (~ 40%) were present in almost equal percentages. July, August and early September 2005 was completely dominated by Haptophyta, contributing almost 100% to the phytoplankton

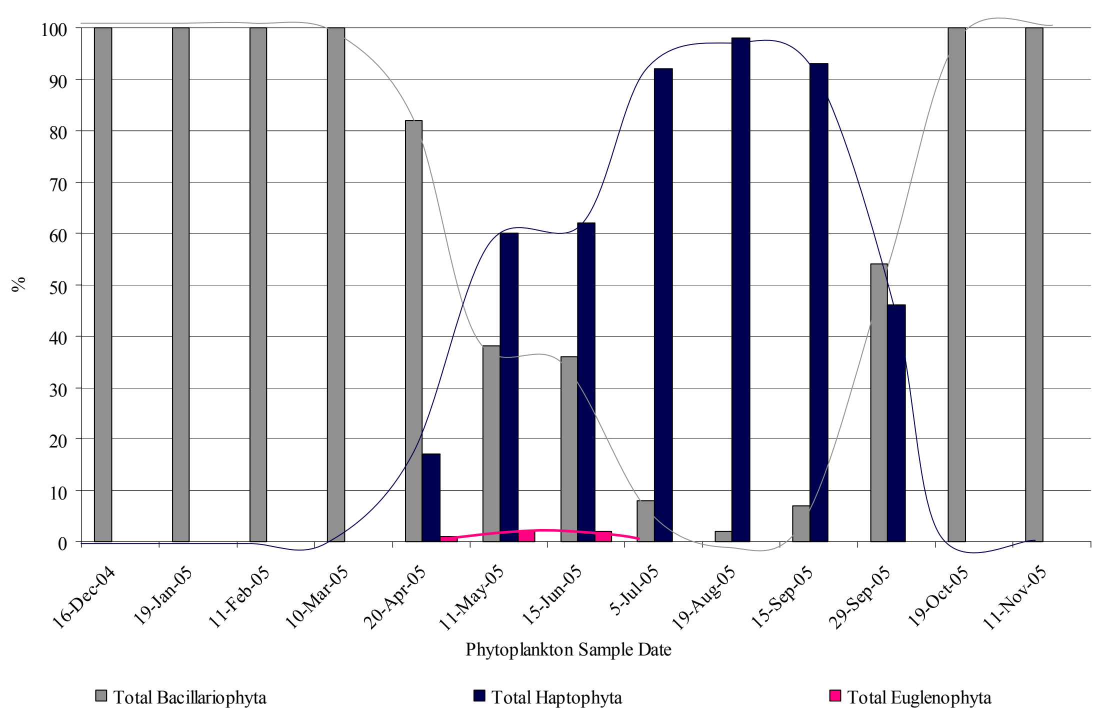

Fig. 3.34. Dominant phytoplankton (%) taxa changes by sample date

population. Late September 2005 represented the transition from Haptophyta back to Bacillariophyta domination with almost equal percentages of species (~ 50% each). Bacillariophyta represented 100% of the phytoplankton community composition in October and November, 2005.

Table 3.10 contains an inventory of those dominant species encountered over the 1 year period from December 2004 to November 2005 (> 10% of total sample). A total of thirty one algal species belonging to Bacillariophyta, Haptophyta and Euglenophyta were identified as the dominant forms in the phytoplankton tows at all stations from December 2004 to November 2005. Twenty six individuals were identified to species

Table 3.10.
Dominant phytoplankton species occurring in the Offatts Bayou region. This is not a comprehensive list. Classification was accomplished according to Identifying Marine Phytoplankton (Tomas, 1997).

Phytoplankton		
Bacillarophyta - centric diatom		**Bacillarophyta - pennate diatom**
Guinardia delicatula		*Thalassiosira pacifica*
Coscinodiscus radiatus		*Thalassiosira cf.*
Ditylum brightwelli		*Melosira nummuloides*
Chaetoceros danicus		*Rhizosolenia pungens*
Chaetoceros didymus		*Rhizosolenia setigera*
Chaetoceros curvisetus		*Rhizosolenia imbricata*
Chaetoceros decipiens		*Pleurosigma normanii*
Chaetoceros lorenzianus		*Pleurosigma macrum*
Chaetoceros affinis		*Odontella mobilensis*
Chaetoceros spp. A		*Skeletonema menzelli*
Chaetoceros spp. B		*Navicula directa*
Dactyliosolen fragillissimus		*Striatella unipuncta*
Bacteriastrum furcatum		*Lithodesmium undulatum*
Bacteriastrum hyalinum		*Fragilaria striatula*
Euglenophyta		**Haptophyta**
Euglenophyta spp. A		*Corymbellus aureus*

level, and four to genus. Diatoms were the most significant with respect to the number of species and abundance in the phytoplankton community; centric and pennate diatoms were almost equally dominant in their appearance in plankton tows. Remaining phytoplankton individuals in the community were represented by various species of dinoflagellates, cyanobacteria, and unknown golden and green coccids.

3.3 Chlorophyll a, Phaeophytin a and Phytoplankton Abundance Analysis

Monthly and seasonal chlorophyll *a* (chl *a*) and phaeophytin *a* (phaeo *a)* concentrations were measured as a proxy for phytoplankton biomass and abundance within the Offatts Bayou and Lake Madeline regions (Table 3.11). The temporal distributions of chl *a* and phaeo *a* in the surface waters of Offatts Bayou and Lake Madeline showed definite monthly and seasonal trends (Table 3.11, 3.12). In addition, a stepwise regression analysis revealed that temperature, dissolved oxygen concentrations and pH had the most significant effects on chl *a* concentrations ($p < 0.05$).

Low chl *a* and phaeo *a* were observed from the end of December 2004 into May 2005, at times with lowest temperatures and pH and highest concentrations of dissolved oxygen (Table 3.11). During low chl *a* concentrations in the winter months, the phytoplankton community was abundant, but not to the degree that was observed during the summer season. The dominate phytoplankton community consisted of a maximum mean concentration of 14×10^6 individuals per liter in December 2004, then slowly declined through the rest of winter (January, February and March 2005) to an annual minimum mean concentration of 4.2×10^4 individuals per liter (April 2005) for the entire sample period. The concentration remained low through May and June, giving way to a dramatic increase in July, which was the beginning of the summer *Corymbellus aureus* bloom. Highest values of chl *a* and phaeo *a* occurred during August when temperatures, pH and abundances were highest and dissolved oxygen concentrations were reduced in surface waters. Phytoplankton abundance increased to the annual maximum mean population in August (83.1×10^6 cells/L), then declined to 42.5×10^6 cells/L through September. The phytoplankton community was composed entirely of diatoms during October and November 2005 and continued to decrease during the cooler temperatures and fresher waters.

Lowest chl *a* (0.002 µg/L) and phaeo *a* (0.0009 µg/L) clearly transpired in spring 2005 during periods of decreased dissolved oxygen (6.7 mg/L) and abundance (6.7×10^5 cells/L) (Table 3.12). The highest seasonal mean concentrations of chl *a* (0.0117 µg/L) and phaeo *a* (0.0105 µg/L) occurred in summer 2005 during highest temperatures, pH (assumed) and abundances (41.5×10^6 cells/L), along with a significantly reduced dissolved oxygen (5.5 mg/L). The large standard deviation on chl *a* and phaeo *a* for summer 2005 are present because of the large range of values, resulting from the substantial algal bloom in August that greatly increased the biomass of the phytoplankton population...not due to error. Winter (10.4×10^6 cells/L) and autumn (7.5×10^6 cells/L) mean dominate abundances, chl *a* (0.0027 and 0.0030 µg/L, respectively) and phaeo *a* (0.0016 and 0.0025 µg/L, respectively) were intermediate.

Table 3.11.
Monthly means and standard deviations (S.D.) of temperature (T), dissolved oxygen (DO), chl *a,* phaeo a, dominate (DC/L) and total (TC/L) cell counts per liter. Highest values are in bold and lowest values are italicized.

Month	Mean T (°C)	Mean DO (mg/L)	Mean pH	Mean Chl *a* (µg/L)	Mean Phaeo *a* (µg/L)	Mean DC/L	Mean TC/L
Dec-04	15.4	9.1	7.4	0.0031	0.0020	14.8 x 10^6	18.9 x 10^6
Jan-05	13.4	9.5	6.7	0.0022	0.0012	11.2 x 10^6	13.3 x 10^6
Feb-05	*12.7*	**9.7**	6.5	0.0032	0.0014	11.8 x 10^6	12.3 x 10^6
Mar-05	17.9	8.6	7.9	0.0023	0.0015	3.8 x 10^5	5.7 x 10^5
Apr-05	21.9	6.7	8.3	*0.0016*	*0.0008*	*4.2 x 10^4*	*5.0 x 10^4*
May-05	23.3	6.7	8.5	0.0025	0.0012	1.3 x 10^6	1.4 x 10^6
Jun-05	28.7	5.5	9.3	0.0035	0.0020	1.1 x 10^6	1. 2 x 10^6
Jul-05	30.7	5.6	not recorded	0.0104	0.0088	39.0 x 10^6	3919 x 10^6
Aug-05	**31.1**	*4.2*	not recorded	**0.0225**	**0.0213**	**83.1** x 10^6	**83.1** x 10^6
Sept-05	29.6	7.2	8.6	0.0085	0.0060	42.9 x 10^6	43.2 x 10^6
Oct-05	24.6	6.1	8.0	0.0030	0.0028	8.1 x 10^6	9.3 x 10^6
Nov-05	21.1	8.2	8.2	0.0031	0.0021	6.9 x 10^6	7.3 x 10^6
Month	T S.D. (°C)	DO S.D. (mg/L)	pH S.D.	Chl *a* S.D. (µg/L)	Phaeo *a* S.D. (µg/L)	DC/L S.D.	TC/L S.D.
Dec-04	2.1	0.5	0.3	0.0024	0.0024	10.2 x 10^6	12.5 x 10^6
Jan-05	1.3	1.1	0.3	0.0023	0.0017	9.3 x 10^6	10.6 x 10^6
Feb-05	2.4	0.8	0.3	0.0034	0.0038	10.1 x 10^6	10.3 x 10^6
Mar-05	2.2	0.7	0.3	0.0026	0.0024	2.6 x 10^6	3.8 x 10^6
Apr-05	0.4	0.4	0.1	0.0010	0.0005	4.4 x 10^4	5.5 *x 10^4*
May-05	0.4	2.4	0.1	0.0012	0.0006	7.9 x 10^5	7.8 x 10^5
Jun-05	0.5	0.5	0.1	0.0040	0.0041	1.1 x 10^6	1.1 x 10^6
Jul-05	0.5	0.8	not recorded	0.0132	0.0134	34.3 x 10^6	34.2 x 10^6
Aug-05	0.8	1.0	not recorded	0.0260	0.0261	39.6 x 10^6	39.6 x 10^6
Sept-05	0.8	1.7	0.3	0.0104	0.0103	78.7 x 10^6	78.6 x 10^6
Oct-05	3.2	1.1	0.1	0.0022	0.0018	5.2 x 10^6	6.0 x 10^6
Nov-05	3.0	0.3	0.1	0.0014	0.0008	6.0 x 10^6	6.1 x 10^6

Table 3.12.
Seasonal means and standard deviations (S.D.) of temperature (T), dissolved oxygen (DO), chl *a*, phaeo a, dominate (DC/L) and total (TC/L) cell counts per liter. Highest values are in bold and lowest values are italicized.

Season	Mean T (°C)	Mean DO (mg/L)	Mean pH	Mean Chl *a* (µg/L)	Mean Phaeo *a* (µg/L)	Mean DC/L	Mean TC/L
winter 2004-2005	*15.3*	**9.2**	*7.3*	0.0027	0.0016	10.4 x 10^6	12.6 x 10^6
spring 2005	22.5	6.7	8.4	*0.0020*	*0.0009*	*6.7 x 10^5*	*7.1 x 10^5*
summer 2005	**30.2**	*5.5*	**not recorded**	**0.0117**	**0.0105**	**41.5 x 10^6**	**41.6 x 10^6**
autumn 2005	23.2	6.9	8.0	0.0030	0.0025	7.5 x 10^6	8.3 x 10^6
Season	T S.D. (°C)	DO S.D. (mg/L)	pH S.D.	Chl *a* S.D. (µg/L)	Phaeo *a* S.D. (µg/L)	DC/L S.D.	TC/L S.D.
winter 2004-2005	2.9	1.5	0.8	0.0026	0.0026	8.2 x 10^6	9.3 x 10^6
spring 2005	1.1	0.6	0.1	0.0012	0.0006	4.171 x 10^5	4.172 x 10^5
summer 2005	0.9	1.1	not recorded	0.0174	0.0181	28.3 x 10^6	38.4 x 10^6
autumn 2005	3.6	2.1	0.2	0.0019	0.0059	5.6 x 10^6	6.1 x 10^6

Seasonal chl *a,* phaeo *a* and abundances were calculated per station (Appendix C) and exhibited a distinct spatial pattern across Offatts Bayou and Lake Madeline. Chl *a* and phaeo *a* concentrations and abundances varied both as a function of location within Offatts Bayou and Lake Madeline and season. Figures 3.35 to 3.40 represent distributions of chl *a,* phaeo *a* and abundances for winter and summer 2005.

During winter, a trend of high to moderate concentrations of chl *a* and phaeo *a*, but intermediate phytoplankton abundance were seen at the isolated stations 7 and 8 in Lake Madeline (Figs. 3.35 to 3.37). Low to intermediate concentrations of chl *a,* phaeo *a* and abundances were visible in the West Bay (station 12), the boat channel (stations 10 and 11) and the Middle of Offatts Bayou (station 9). In the Back Bay, stations 1 and 2 exhibited low to intermediate quantities of chl *a* and phaeo *a*, while abundances were low to moderate. Concentrations of chl *a* and phaeo *a* varied from low to moderate and abundances from moderate to high at stations 3, 4 and 5 in the back region of Offatts Bayou. During the summer season, stations in West Bay, the boat channel and the Back Bay revealed low to intermediate concentrations of chl *a*, phaeo *a* and abundance of phytoplankton (Figures 3.38 to 3.40). Concentrations of chl *a* and phaeo *a* were high in Lake Madeline (station 7 and 8), while abundances were intermediate to moderate. Stations 4 and 5 in the back regions of Offatts Bayou, displayed intermediate concentrations of chl *a*, phaeo *a* and cell abundances.

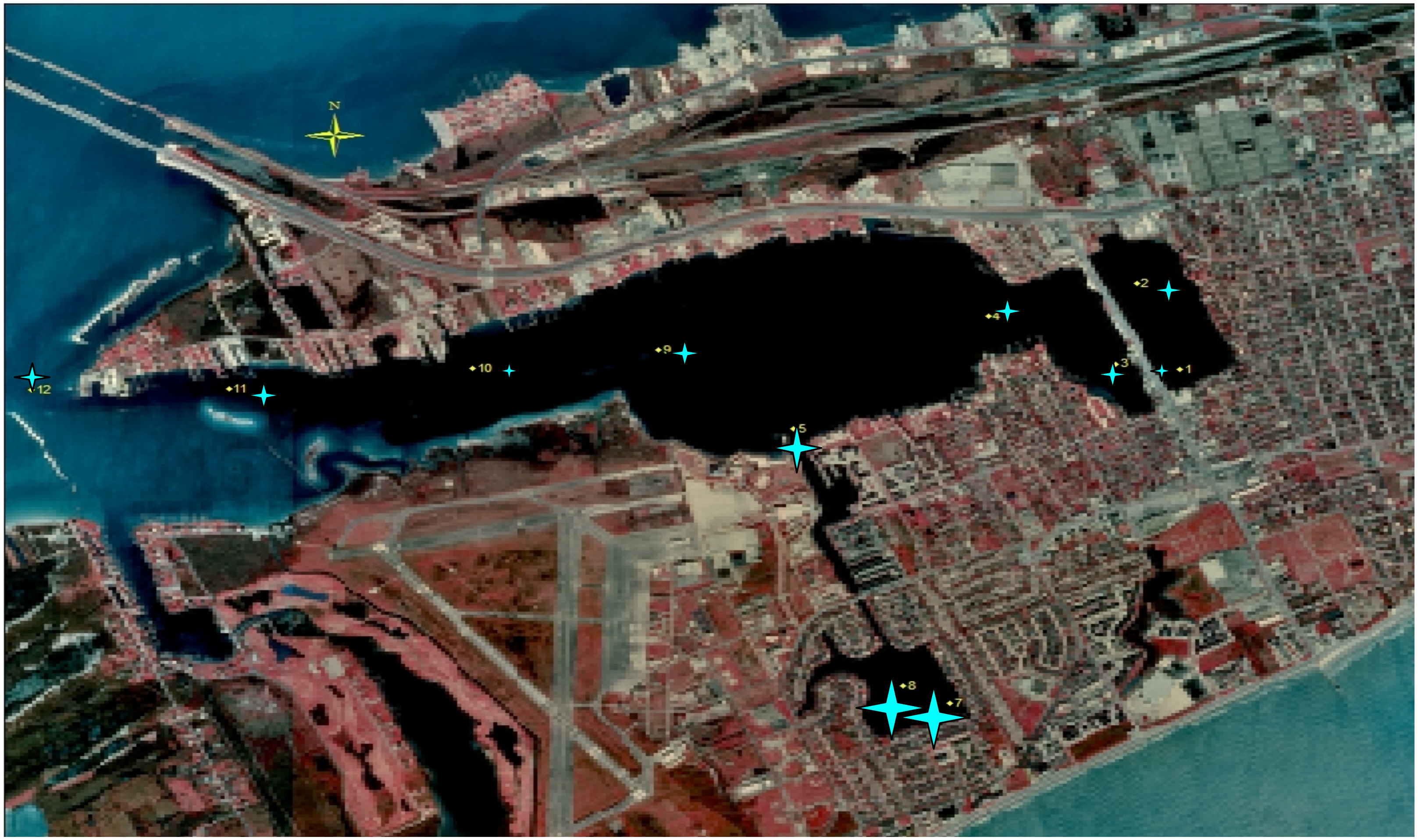

Fig. 3.35. Offatts Bayou and Lake Madeline chlorophyll *a* (µg/L) map for winter. (December 2004, January, February and March 2005)

≤ 0.00150 (L), = 0.001501 to 0.0030 (I), = 0.00301 to 0.0060 (M), >0.0060 (H)

Fig. 3.36. Offatts Bayou and Lake Madeline phaeophytin *a* (µg/L) map for winter. (December 2004, January, February and March 2005)

≤ 0.00120 (L), = 0.001201 to 0.0032 (I), = 0.003201 to 0.0048 (M), > 0.0048 (H)

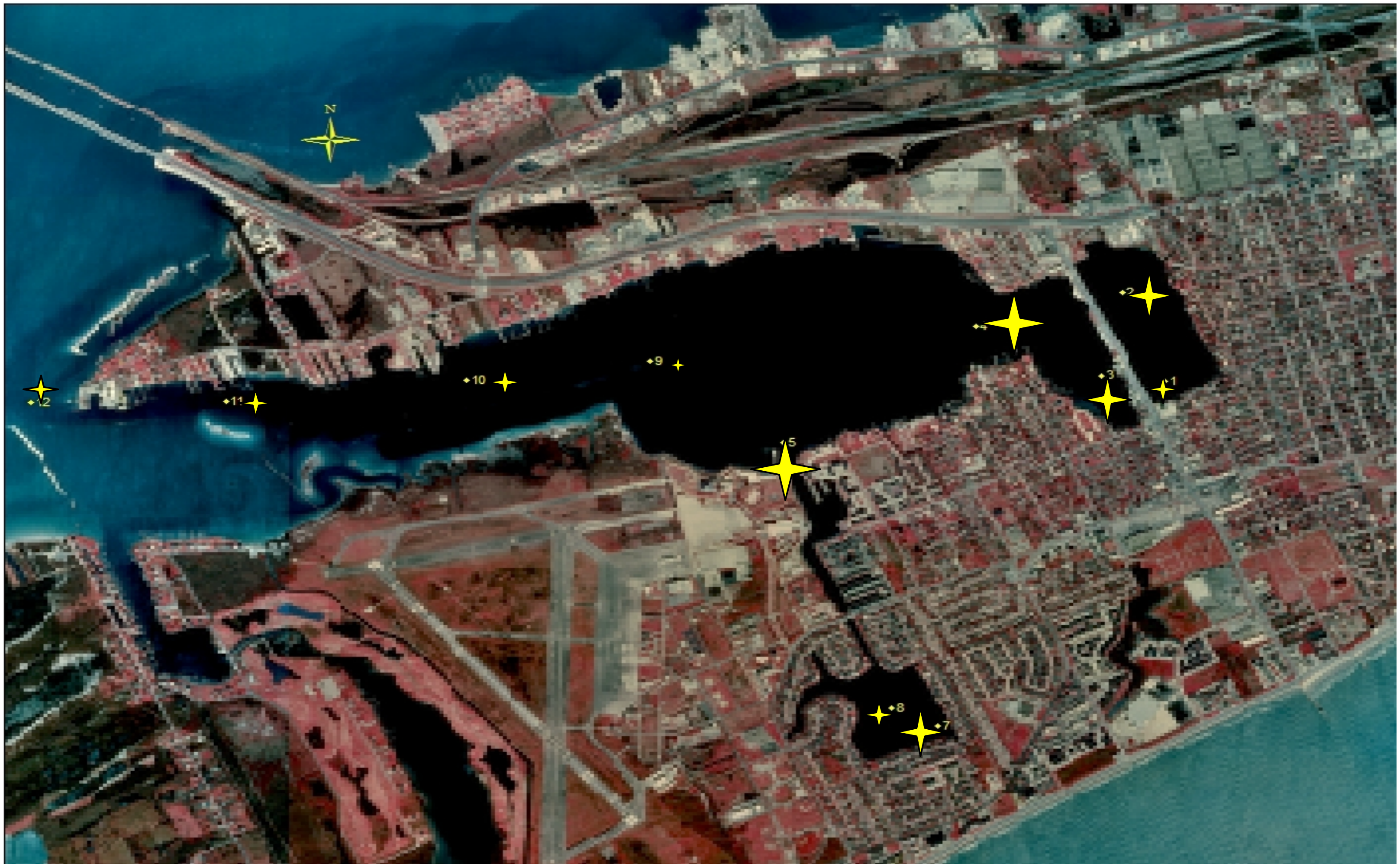

Fig. 3.37. Offatts Bayou and Lake Madeline abundance (cells/L) map for winter. (December 2004, January, February and March 2005)

$\leq 5 \times 10^6$ /liter (L), $> 5 \times 10^6$ to 10×10^6 /liter (I), $> 10 \times 10^6$ to 15×10^6 /liter (M), $> 15 \times 10^6$ /liter (H)

Fig. 3.38. Offatts Bayou and Lake Madeline chlorophyll *a* (µg/L)map for summer. (June, July, August, September 2005)

≤ 0.0063 (L), = 0.00631 to 0.0126 (I), = 0.01261 to 0.0189 (M), > 0.0189 (H)

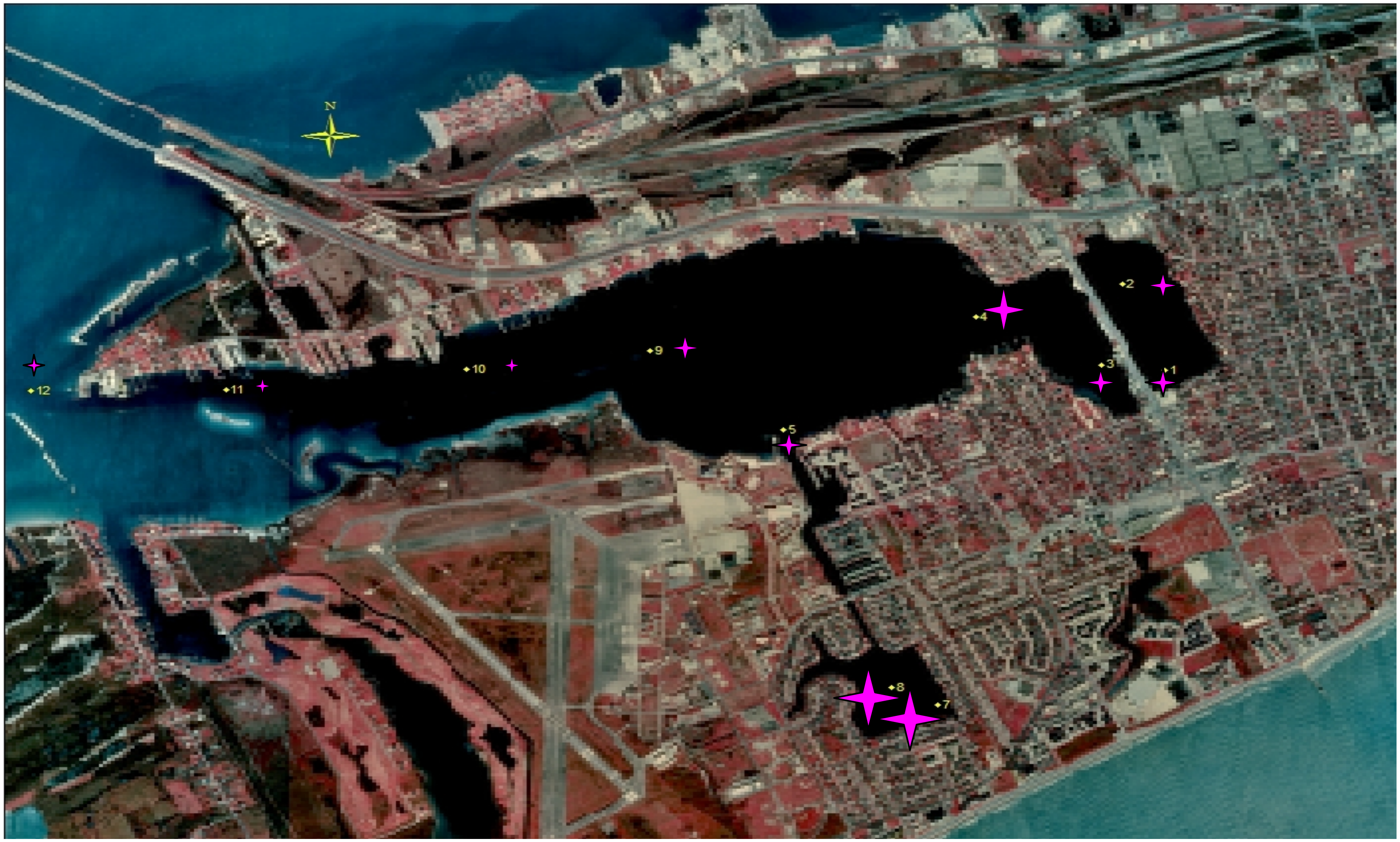

Fig. 3.39. Offatts Bayou and Lake Madeline phaeophytin *a* (µg/L) map for summer. (June, July, August, September 2005)

≤ 0.0063 (L), = 0.00631 to 0.0126 (I), = 0.01261 to 0.0189 (M), > 0.0189 (H)

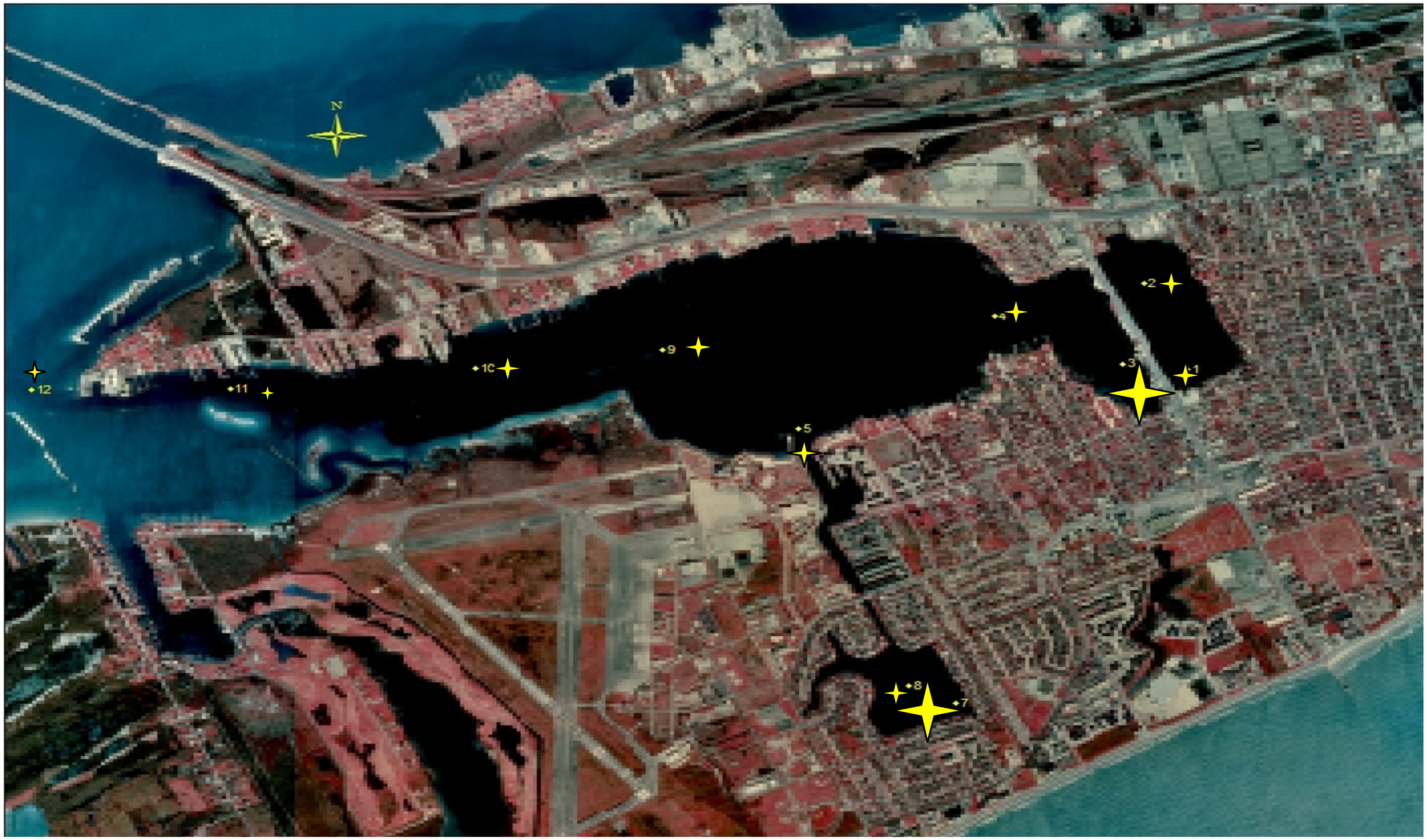

Fig. 3.40. Offatts Bayou and Lake Madeline abundance (cells/L) map for summer. (June, July, August, 15 September 2005)

$\leq 30 \times 10^6$ /liter (L), $> 30 \times 10^6$ to 60×10^6 /liter (I), $> 60 \times 10^6$ to 90×10^6 /liter (M), $> 90 \times 10^6$ /liter (H)

3.4 Statistical Analysis of Phytoplankton Biomass

A stepwise regression analysis was preformed to determine which independent variable or variables (temperature, salinity, dissolved oxygen, pH or seasons) had the most influence on the dependent variable, chl *a* concentration, throughout the sample year. An examination of the data revealed temperature, dissolved oxygen and pH to be the best predictors for annual or seasonal chlorophyll *a* concentration changes (model 3: $r^2 = 0.198$, $p < 0.05$). There was a 44.5% ($p = 0.05$, $R = 0.445$) correlation between chl *a* and the best fit model with parameters temperature/dissolved oxygen/pH.

The three variables, temperature, dissolved oxygen and pH were the first, second and third best predictors, respectively, for seasonal changes in phytoplankton biomass (chl *a)*. The best fit equation that expressed the relationship between the dependent variable and best predictor factors was:

$$\text{Chl } a = -0.009 + (0.001 * \text{temperature}) + (0.001 * \text{dissolved oxygen}) + (-0.001 * \text{pH})$$

Temperature, dissolved oxygen and pH were therefore the "cause" variables and the most important factors for assessing the habitat preference of the phytoplankton and should be the main parameters measured in future experimental studies in this region.

3.5 Meteorological and Tidal Data Analysis

There were four relatively large rain and wind events with greater than 2 inches of precipitation and greater than 20 km h^{-1} winds during the 2004-2005 sample year, (Fig. 3.41, 3.42, Table 3.13). On 21 December 2004 (blue arrow), precipitation in the amount of 2.39 cm was recorded, along with a mean temperature of 18 °C (Figs 3.41 and 3.42). At this time also, winds blew out of the southeast at a speed of 21 km h^{-1} (Figs 3.43 and 3.44). The next rain storm occurred on 2 March 2005 (pink arrow), with measured mean temperature at 10 °C and a precipitation of 2.84 cm. Winds blew from the northeast at 26 km h^{-1}. On 23 September 2005, during Hurricane Rita (green arrow), Offatts Bayou suffered maximum sustained wind speed of 63 km h^{-1} and a maximum gust of 89 km h^{-1} out of the northeast (white arrow, Fig. 3.42). During this time, precipitation was gauged at 3.4 cm and mean temperature was 26 ˚C. The final rain event of the 2004-2005 sample year occurred on 1 November 2005 (yellow arrow) and deposited 1.93 cm of rain to the system with a mean temperature of 13 ˚C and mean wind speed of 29 km h^{-1}.

Table 3.13
Major storm events during the 2004 - 2005 sample year. Included are corresponding precipitation, mean wind speed and mean temperature.

Date	precipitation (cm)	Mean wind speed (km h^{-1})	Mean temperature (°C)
21-Dec-04	2.39	21	18
2-Mar-05	2.84	26	10
23-Sep-05	3.4	34	26
1-Nov-05	1.93	29	13

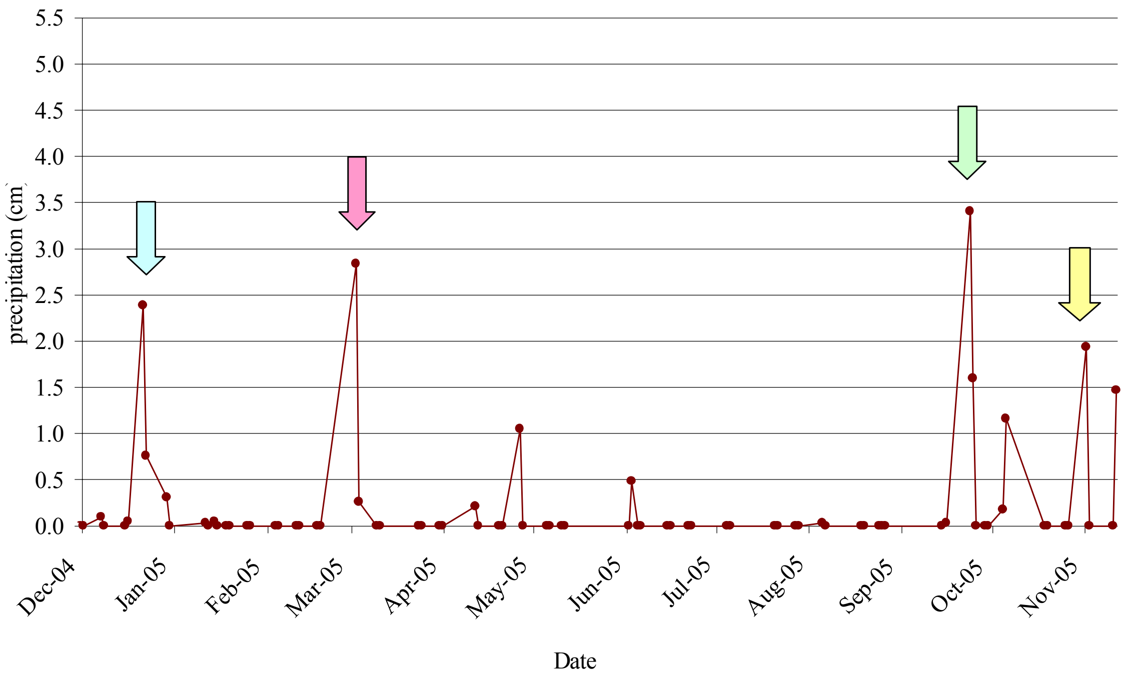

Fig. 3.41. 2004 - 2005 total precipitation (cm) and corresponding rain events. (blue = 21 Dec 2004, pink = 2 Mar 2005, green = 23 Sep 2005, yellow = 1 Nov 2005)

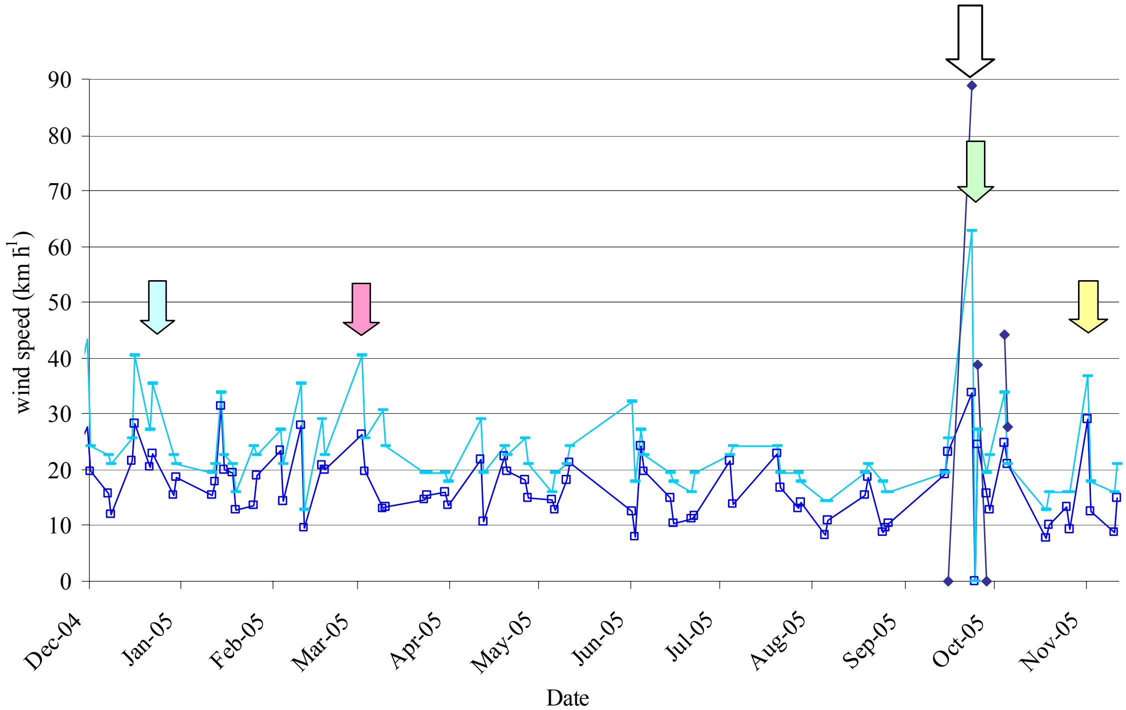

Fig. 3.42. 2004 - 2005 wind speeds (km h^{-1}). (maximum sustained speed = light blue, mean wind speed = medium blue, maximum gust = dark blue; blue arrow = 21 Dec 2004, pink arrow = 2 Mar 2005, green arrow = 23 Sep 2005, yellow arrow = 1 Nov 2005, white arrow = maximum gust on 23 Sept 2005).

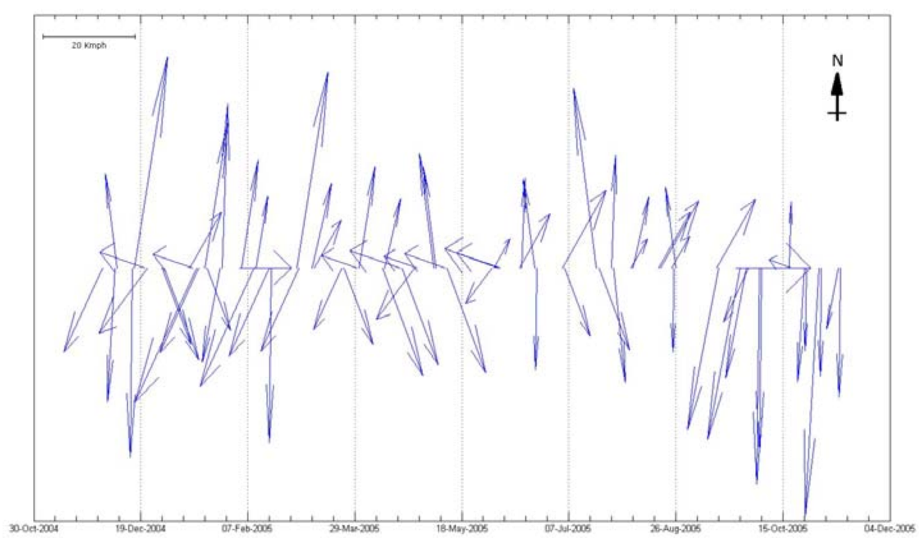

Fig. 3.43. 2004 - 2005 wind direction. Arrows indicate direction wind is blowing from.

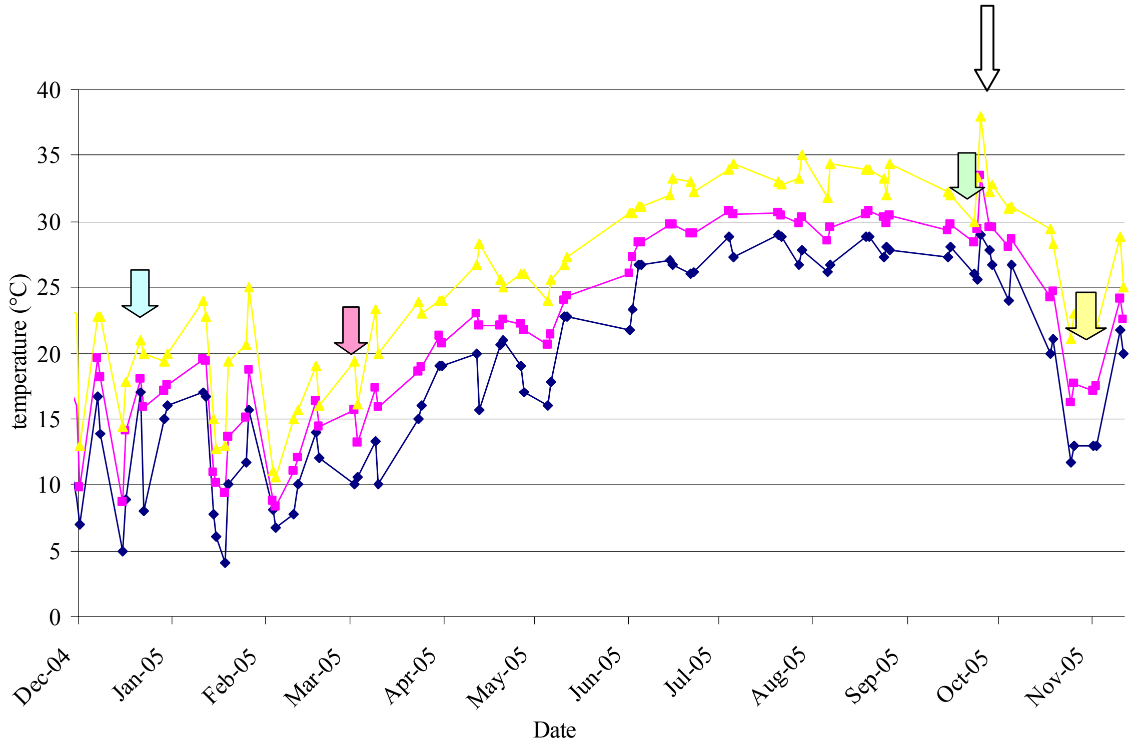

Fig. 3.44. 2004 - 2005 minimum, mean and maximum air temperatures (°C). (minimum temperature = dark blue, mean temperature = pink, maximum temperature = yellow; blue arrow = 21 Dec 2004, pink arrow = 2 Mar 2005, green arrow = 23 Sep 2005, white arrow = Hurricane Rita (24 Sep 2005), yellow arrow = 1 Nov 2005).

Meteorological data for Offatts Bayou was highly variable over the 2004 - 2005 sample year (Appendix D), which reflected low precipitation rates and higher than normal air and surface water temperatures (Fig. 3.14). Throughout the entire 2004-2005 sample period, surface water temperatures directly reflected changes in air temperature by approximately 3 °C. In the winter months, air (< 15 °C) and water (< 20 °C) temperatures were low, then gradually increased through spring. In June, air and surface temperatures were between 25.5 to 28.5 °C, then progressively increased to the maximum in July, August and September (~ 27.5 = air, ~ 30.5 = water). Air and water temperatures dramatically decreased by 5 to 10 °C between September and autumn (October and November).

Table 3.14
Monthly comparison of air temperature vs. surface water temperature means and salinity vs. precipitation means. Highs are in **bold** and lows are *italicized.*

Month	mean air temperature (°C)	mean surface water temperature (°C)	mean surface water salinity (ppt)	mean precipitation (cm)
Dec-04	11.9	15.4	21.0	0.4
Jan-05	11.1	13.4	19.3	*0.0*
Feb-05	*9.8*	*12.7*	18.1	*0.0*
Mar-05	14.1	17.9	*16.1*	0.4
Apr-05	18.9	21.9	23.7	0.2
May-05	19.8	23.3	24.6	*0.0*
Jun-05	25.5	28.7	25.5	0.1
Jul-05	**28.1**	30.7	28.3	*0.0*
Aug-05	27.7	**31.1**	29.3	*0.0*
Sept-05	27.2	29.6	**29.8**	0.7
Oct-05	19.4	24.6	25.0	0.2
Nov-05	16.9	21.1	20.5	**0.9**

Monthly comparison of mean annual salinity and mean annual precipitation is also described in Table 3.14. There was very little precipitation input to the system and salinity was fairly stable throughout the sample year. Salinity means however, did follow similar monthly trends as surface and air temperature means. Salinity decreased through winter to its minimum in March, then gradually increased through spring and summer to its maximum in July, August and September. October and November represented a decrease back to winter salinity levels. Precipitation rates in April and

September had no affect on salinity levels, while March, October and November rainfall may have had a slight impact on the salinity concentration.

Warmer air temperatures and less precipitation were observed during the 2004-2005 study period in Offatts Bayou as compared to NOAA's normalized 30-year data from 1971-2000 for the Galveston Bay region (Table 3.15). During the 2004-2005 sample period, highest air temperatures were observed in August and lowest in December. NOAA's data reflected the highest air temperature in both July and August and the lowest in January. January represented the month with the greatest air temperature (5.9 ˚C) difference between the sample period and NOAA's normalized data. The annual average air temperature was 1˚C higher during the 2004-2005 study period (22.4 ˚C) than NOAA's 30-year normalized average (21.4 ˚C). During the 2004-2005 sample period highest precipitation was recorded in July (10.2 cm), while the lowest was in June (0.6 cm). NOAA's normalized data indicated highest precipitation levels in August (10.7 cm) and lowest in April (6.5 cm). The greatest difference in precipitation rates occurred in the month of June (9.7 cm). February (0.4 cm) and November (0.6 cm) had the least difference in rainfall between the study period and NOAA's data. The annual average precipitation rate was 2.6 cm less during the 2004-2005 study period (6.7 cm) than NOAA's 30 year normalized average (9.3 cm).
or if the data matched NOAA's normalized data trend.

Table 3.15.
Comparisons between temperature and precipitation rates during the study period (2004 - 2005) and NOAA's normalized data (1971 - 2000). (NOAA, National Weather Service Forecast Office). Highest values are in **bold** and lowest are *italicized*.

sample month	2004-2005 sample year temperature (C°)	NOAA temperature normals (C°)	2004-2005 sample year precipitation (cm)	NOAA precipitation normals (cm)
Dec-04	*13.9*	14.5	6.7	9.0
Jan-05	14.6	*8.7*	5.5	10.4
Feb-05	15.3	14.4	7.0	6.6
Mar-05	17.6	17.8	10.0	7.0
Apr-05	21.6	21.1	4.7	*6.5*
May-05	24.8	24.9	6.7	9.4
Jun-05	29.3	27.9	*0.6*	10.3
Jul-05	30.1	**29.1**	**10.2**	8.8
Aug-05	**30.3**	**29.1**	2.5	**10.7**
Sep-05	29.2	27.3	9.9	14.6
Oct-05	23.3	23.4	6.4	8.9
Nov-05	19.3	18.6	9.8	9.2
Average	22.4	21.4	6.7	9.3

Tidal data was obtained from NOAA CO-OPS for the specific days in which phytoplankton tow measurements were undertaken (Appendix D). Galveston Bay, including the Offatts Bayou region, is considered a microtidal environment with tidal influence at approximately 0.65 m (Ward, 1991). Comparisons between tidal heights and phytoplankton community changes revealed there was no interaction between tidal effects and changes in phytoplankton abundances or diversity and that there was no sufficient water exchange between Offatts Bayou and West Bay to be a factor in phytoplankton dynamics. This is consistent with findings by Gunter (1941). He established that even after a storm tide in mid December 1940, there was a very slow interchange between Offatts Bayou and West Bay waters as represented by little change in salinity values recorded before and after the storm.

3.6 Bathymetry of Offatts Bayou

The bathymetry of Offatts Bayou and the adjacent Lake Madeline and Back Bay is represented below in figure 3.45. West Bay (left side) and the boat channel into the middle of Offatts Bayou was fairly shallow with depths between 4 - 5 meters. Water depth continued to increase through the middle of Offatts Bayou to the Deep Hole, where 9 meters was the average measured. Depths at stations 1 and 2 in the Back Bay ranged from 4 to 6 meters, while the Lake Madeline stations were between 4 and 8 meters deep. Offatts Bayou bathymetry is consistent with section 3.1.3 of the fluctuations in surface and bottom temperature and salinity values and dissolved oxygen concentrations along the transect from West Bay, through Offatts Bayou and into the Back Bay and Lake Madeline.

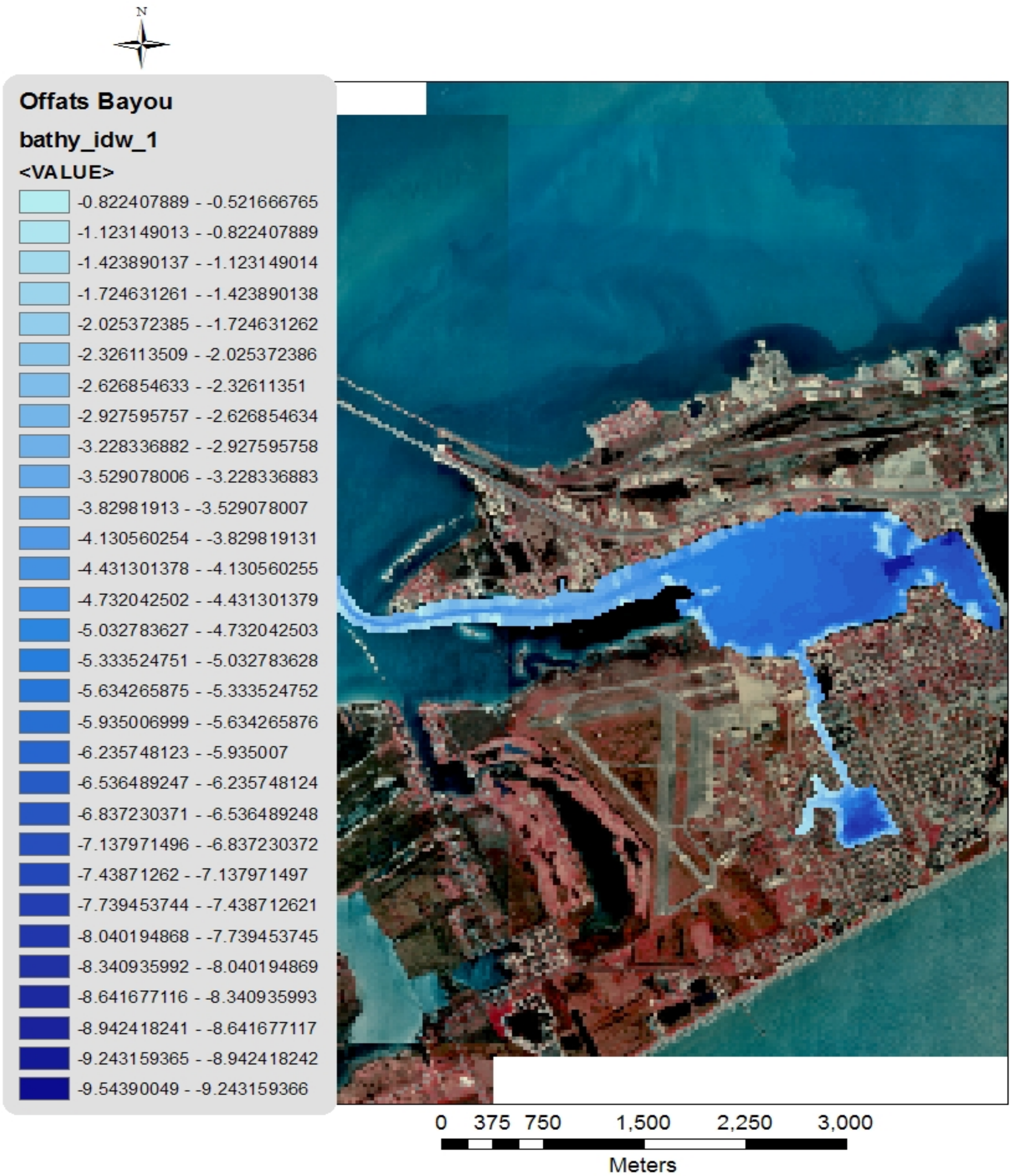

Fig. 3.45. Bathymetry of Offatts Bayou. (Courtesy of Andrew McInnes – Texas A&M University at Galveston)

4. DISCUSSION

4.1 Temporal Patterns of Abiotic Factors and Phytoplankton Community Dynamics

4.1.1 Patterns of Abiotic Factors

Hydrological parameters measured and studied in detail in Offatts Bayou over a one year period included the following: water temperature, salinity, dissolved oxygen and pH. These hydrological factors revealed a significant seasonal variation that impacted phytoplankton community composition and biomass in Offatts Bayou. In addition, regional resources (see methods section) were used to obtain air temperature, wind effects, precipitation and tidal variations for the system.

Air temperature and precipitation normals calculated by NOAA for the past 30 years (1971-2000), revealed that the Galveston Bay Estuary region was typically wetter and cooler in the past than in the 2004-2005 sample year. Consequently, the hotter and drier trend observed during the 2004-2005 sample period in Offatts Bayou did not match NOAA's 30-year normalized data. Thus, seasons were defined based on a MANOVA performed on surface water temperature, salinity and dissolved oxygen data ($p < 0.05$). These seasonal ranges were applied to the data analysis and the interpretation of patterns observed in Offatts Bayou as part of this study.

Surface water temperature, salinity and pH variances have been shown to be significant factors that affect phytoplankton dynamics (growth, reproduction, distribution, metabolism and photosynthetic capability) on an annual basis depending on seasonal trends of the region under study (Smayda, 1980; Day *et al.*, 1989; Izaguirre *et* *al*., 2001; Hinga, 2002). Decreased temperatures, salinities and pH were observed during winter and autumn, along with intermediate concentrations of diatoms (Figure 3.16; Appendix C-Table 2). Additionally during winter, dissolved oxygen and was found to be higher than all other seasons. These findings followed a well established pattern in which higher solubility of oxygen in colder waters during winter months can cause increased dissolved oxygen levels. During intermediate temperatures, salinities and pH in spring, transitional trends of phytoplankton abundance and diversity were observed (Figures 3.1b, 3.25 and 3.26). Throughout the summer period while temperatures, salinities and pH increased, the highest seasonal concentrations of phytoplankton abundance were measured (Appendix-Table 1, Appendix C-Table 2). The seasonal trend in environmental parameters and phytoplankton dynamics observed during the sample year in Offatts Bayou has also been seen in various marine ecosystems.

Regional and daily variations in wind speed and direction and insolation have previously been shown to strongly influence phytoplankton distribution in aquatic ecosystems (Bondarenko *et al*., 1996) and may impact circulation and stratification-destratification patterns. Vertical mixing mechanisms, such as wind effects, play a role in the redistribution of phytoplankton biomass throughout the water column, which directly affect the variability in phytoplankton community composition and abundances (Lucas *et al*., 1999a; Cloern, 1991). Wind speeds and directions were shown to be variable before and during sampling days (Figures 3.42 and 3.43). Wind resuspension of sediments likely played a role in the vertical and horizontal distribution of algae and nutrients in Offatts Bayou, given the shallowness of some sample stations within the inlet. Phytoplankton samples collected from surface waters in well mixed and/or turbulent marine systems often contain pennate benthic diatom forms that are thought to be transported up to the surface through wind induced resuspension (Margalef, 1978). The intermittent presence of benthic diatoms in the collected winter, spring and autumn surface water samples from Offatts Bayou supports the finding that resuspension of bottom sediment events did occur. Water conditions were windier prior to the February phytoplankton sampling than during other winter samplings. These conditions most likely contributed to the initial high abundance of the benthic diatom *Rhizosolenia setigera* in the February plankton tow (Figure 3.23).

There is little detailed information available on the stratification status of Galveston Bay. Nothing, however, was known about the stratified vs. mixed conditions in Offatts Bayou prior to this research, hence relative stratification indices were calculated for temperature, salinity, dissolved oxygen and density (Figures 3.2 to 3.11). Relative stratification, in terms of temperature, salinity and dissolved oxygen distributions, revealed that the Offatts Bayou system was controlled by physical factors, such as wind induced mixing and exchange with West Bay, at the opening of the embayment (station 12) and along the boat channel (Stations 11, 10, and 9) where the water column was shallow and well mixed. In Lake Madeline (station 7 and 8) and the Back Bay (stations 1 and 2), temperature, salinity and dissolved oxygen stratification indices indicated various stages of stratification and mixing that were controlled by a mixture of physical and biological processes, which varied seasonally. For example, prior to the late August fish kill in Lake Madeline (station 8), the dissolved oxygen stratification index indicated a slightly mixed water column (Figure 3.6). A strong oxycline was established at station 8 when the rate of oxygen consumption exceeded the mixing rate, which resulted in anoxia in bottom waters potentially contributing to the fish kill in late August (Figure 3.1c). These mixing and consumption trends were most likely the result of the samples taken early in the morning shortly after increased respiration (consumption of oxygen) had occurred during the night. At other periods during the summer, calm winds occurring over long periods of time in Lake Madeline and the other isolated regions, resulted in less horizontal and vertical mixing, which lead to increased stratification in the enclosed regions. The resulting stratification was reflected in the relatively high concentrations of dissolved oxygen at the surface and hypoxic conditions in the bottom waters (Figure 3.1c). The physical and biological factors controlling temperature, salinity and dissolved oxygen distributions in Offatts Bayou also affected phytoplankton abundance and diversity on a spatiotemporal basis.

4.1.2 Phytoplankton Patterns

In Texas estuaries, phytoplankton dynamics are characterized by blooms that are highly variable, both spatially and temporally and exhibit a wide range of seasonal patterns. From a temporal perspective, Offatts Bayou displayed seasonal differences in phytoplankton composition and abundance with the highest phytoplankton standing crop occurring in the warmer months from July to September (Table 3.11). In the Offatts Bayou region, the seasonal succession of the phytoplankton community was reflected by the transition from a dominance of diatoms in autumn, winter and spring to haptophytes in summer (Figure 3.34). This is consistent with Cloern's (1996) paper, in which he states that each season will be dominated by a different phytoplankton species. Although Offatts Bayou's location on the Texas Gulf coast seemed to possess a modest range of seasonal water temperature fluctuations as compared to other temperate marine systems, its impact on the phytoplankton community cannot be overlooked (Figures 3.1 a-c). The temperature range during the sample year was the principal driver for cold water species during winter and warmer water haptophytes during summer (Figures 3.21 to 3.33). Compared to Zotter's (1979) identification of 59 alga species in the Galveston Bay estuary, the Offatts Bayou study revealed only 30 dominate species throughout the study period.

Diatoms are known to have maximal growth rates at lowered salinities and temperatures, as seen in previous studies along the Texas coastline (Stevens, 1960; Zotter, 1979; Buskey and Schmidt, 1992) and in other regions of the world (Smayda and Hitchcock, 1977; Zielinski and Gersonde, 1997; Gayoso, 1999). Zotter's (1979) examination of three sites in the upper and lower parts of Galveston Bay revealed that diatoms were more dominant in the autumn and winter months than in the summer and spring, which is consistent with the seasonal phytoplankton community succession observed in this study in Offatts Bayou (Figure 3.34). The diatom phytoplankton abundance increased during the colder and less saline winter (15.3 °C, 18.7 ppt) and autumn (23.2 ºC , 23.2 ppt) then decreased during the warmer and more saline summer (30.2 ºC, 28.3 ppt). During winter 2004-2005, the phytoplankton community was entirely composed of Bacillariophyta (diatoms), of which, approximately 50% were pennate (5 species) and 50% were centric (9 species) forms with pennate species dominating only in February. *Guinardia delicatua* (centric) dominated in December (Figure 3.21), while *Ditylum brightwelli* (centric) dominated in January (Figure 3.22). *Rhizosolenia setigera* (pennate) was most prevalent in February (Figure 3.23) and *Dactyliosolen fragillissimus* (centric) in March (Figure 3.24). During the autumn season, numerous species of *Chaetoceros* genera were identified as the dominating phytoplankton in the Offatts Bayou system. These diatoms are common estuarine species which are known to occur in other parts of Galveston Bay and in systems throughout the world.

It has been reported that communities dominated by diatoms become photoinhibited more easily from increased irradiance levels during late spring and summer months than other phytoplankton taxa (Platt and Denhan, 1980), while haptophytes have the ability to live in a range of temperatures and salinities (Jordan and Chamberlain, 1997). The first representatives of Euglenophytes (*Euglenophyta spp A)* and Haptophytes *(Corymbellus aureus)* appeared in early spring when diatoms were beginning to decrease in abundance in the warmer surface waters. The haptophyte, *C. aureus,* became the dominant algal form by late spring in response to the increase in surface water temperature and salinity. The high summer phytoplankton abundance corresponded to an algal bloom of *C. aureus,* which peaked in August. During late August, a large fish kill occurred in Lake Madeline, which was most likely associated with the *C. aureus* bloom and will be discussed in further detail in section 4.4.

Changes in biomass and diversity can be related to events, such as extreme storms, that affect the phytoplankton community. Such an event occurred on 24 Sept 2005 when Hurricane Rita hit the Texas Gulf Coast with wind gusts of over 90 km h^{-1} (discussed in section 4.3). Sampling after the hurricane (29 September) revealed a turnover in the phytoplankton community from haptophyte dominance to a 50/50 mix of haptophytes and bacillarophytes. Representatives of the *Chaetoceros genus* (*C. curvisetus and C. spp. A and B*) were the dominating species in the Offatts Bayou region during autumn. A large *Pseudo-nitzschia* spp. community was observed in the autumn samples, but it could not be identified to species level and was not included as a dominant species.

Minor quantities of euglenophyta, cyanobacteria, dinophyta and chlorophyta were seen periodically throughout the year. For example, in the 2004-2005 study, less than 10 cells of the dinoflagellate *Gonyaulax* spp. were noted throughout the study period. This is not consistent with a bloom of *Gonyaulax* that occurred in 1949 and was responsible for the fish kill in Offatts Bayou (Connell and Cross, 1950). The difference in the *Gonyaulax* spp. community abundance between the 1949 example and the 2005 study period is consistent with the assumption that temporal fluctuations in abiotic parameters often affect phytoplankton community dynamics, not only on a seasonal level, but also annually (Boynton *et al.,* 1982, Stockwell *et al.*, 1989)

Corymbellus aureus, which bloomed during the summer months, was found to congregate in groups of approximately 25 cells and had flagella to aid in surface water buoyancy and movement. *C. aureus*, a species of the Haptophyceae, was first identified in the colder English Channel waters off the Cornish coast (Green, 1979) and is typically associated with coastal or oceanic ecosystems in the Atlantic or Mediterranean regions of the world (Tomas, 1997). This is the first recorded occurrence of *C. aureus* in Offatts Bayou and Galveston Bay, and there is no evidence that it was previously documented anywhere along the Gulf Coast. It is thought that since *C. aureus* was only observed during the warmer months that the low temperatures experienced during winter and autumn was too cold for this Mediterranean species. One possible explanation for the intense bloom of *C. aureus* in the summer months was due to less competition from other phytoplankton, such as the diatoms.

It is quite probable that diatoms could have dominated during the summer in Offatts Bayou, regardless of the increase in temperature and salinity, if not for the possibility that haptophytes may have utilized one of several mechanisms to outcompete the diatoms. One of these is a mechanism called allelopathy. This process occurs when haptophytes living under an N or P deficient environment release extracellular substances that hinder the development and growth of other phytoplankton (Granéli and Johansson, 2003). Indirect measurements (personal observations) of large volumes of extracellular material on the filter, in the phytoplankton tow net and on the surface of the water suggest that allelopathy may have occurred. N-limited conditions existed during winter in Offatts Bayou (Quigg *et al.*, 2006) and thus could very well have been present during summer of 2005. If allelopathy was responsible for the decrease in diatom concentrations during summer, then it may have been a stronger controlling mechanism than the high summer temperature, salinity or nutrient levels. Another possible mechanism for the decrease in diatom population was the increased abundances of zooplankton (personal observation). This would have resulted in an increase in grazing pressure and a reduction of edible diatoms, leaving *C. aureus* to dominate.

Santschi (1995) reported that the chl *a* maximum typically occurs in March to April in Galveston Bay and that the bay experiences phytoplankton blooms in the spring. This was not the case for the Offatts Bayou embayment in 2004-2005. The phytoplankton bloom occurred during the summer months, along with increased temperatures and chl *a* concentrations. Temperature and dissolved oxygen concentrations were correlated to chl *a* ($p < 0.05$; R = 0.445), while salinity changes in Offatts Bayou were of less importance. These findings corresponded to an earlier study in the Indian River Lagoon, Florida, in which temperature was positively correlated to chlorophyll *a* (Phlips *et al.*, 2002). Phlips *et al.* (2002) measured elevated chlorophyll *a* concentrations in field samples in summer, along with increased temperatures.

Differences between phytoplankton blooms in Santschi's (1995) study for Galveston Bay and the present study for Offatts Bayou suggest that there may have been a temporal delay in responses of phytoplankton communities in Offatts Bayou due to differing abiotic factors between years and/or regions. This is also consistent with the finding that the 2004-2005 Offatts Bayou sample season was drier and hotter than in the past 30 years (1971-2000) (Table 3.16). An additional factor delaying the response in phytoplankton blooms may have been the flushing rate of Offatts Bayou. The flushing rate of Galveston Bay, as interpreted by Santschi (1995) is between 40 and 88 days. Since Offatts Bayou is isolated, microtidal and has an abnormal bathymetry with reduced circulation, the flushing rate may be even more reduced. The diminished flushing rate in Offatts Bayou most likely decreased the introduction of fresh nutrients from Galveston Bay into the system for continued phytoplankton growth, as compared to the continual recycling of resident nutrients through the phytoplankton community.

4.2 Spatial Patterns of Abiotic Factors and Phytoplankton Community Dynamics

4.2.1 Abiotic Patterns across Offatts Bayou

Hydrological patterns (T, S, DO, pH) were examined to determine if spatial differences existed between sampling stations along a transect from the West Bay, through Offatts Bayou, into Lake Madeline and the Back Bay. Stations #1, 4, 8, 9 and 12 were chosen in particular to explain the major patterns observed in Offatts Bayou as a whole system (Figure 2.1). Station 1 was one of the most sheltered sections of the Offatts Bayou system, located near 61st street, in the Back Bay. This part of Offatts Bayou was relatively shallow (~ 4m) and protected from extreme wind conditions. Station 4 was located at the blind end of Offatts Bayou and is referred to as the "Deep Hole" because it is greater than 9 meters in depth. A bathymetric survey of Offatts Bayou (Figure 3.45) revealed this was the deepest section of the embayment and produced interesting water column hydrography throughout the study period. In the summer months, station 4 became hypoxic at 2.5 to 3.5 meters below the surface and then anoxic between 3.5 and 4.5 meters in depth below the surface. In winter, station 4 exhibited a much deeper mixed water column, becoming hypoxic at about 4.5 meters, then anoxic around 5 meters below the surface(Figures 3.1 a-d, Appendix A). Two sampling stations were located in Lake Madeline; of these, station 8 was located in the center of Lake Madeline and chosen for its depth (~7 m). The mid section of Offatts Bayou was covered by three stations (9, 10 and 11); the following discussion will focus on station 9, which was chosen because it is located in the middle of Offatts Bayou, is approximately 5 meters in depth and not significantly different from station 10 and 11 ($p < 0.05$). Station 12 is located in the waters of West Bay (just outside of Offatts Bayou).

On an annual basis, stations 9 and 12 were often more mixed than 1, 4 and 8. Differences occurred because stations 9 and 12 were less sheltered and most likely subjected to greater wind effects and stronger West Bay input currents than all other stations (Figure 2.1). Thus, stations 9 and 12 remained oxygenated throughout their water column during the sample year. Conversely, dissolved oxygen concentrations in Lake Madeline (station 8) and stations in the interior section of Offatts Bayou (stations 1 and 4), which were more enclosed, received less wind effects and lowered current strength, remained stratified at varying degrees throughout the sample year (Figures 3.2, 3.4 and 3.6).

Following the dredging and subsequent creation of Offatts Bayou during the early part of the twentieth century, a poor circulation pattern developed (U.S. Corp of Engineers, 1971) and as a consequence, a significantly increased residence time of waters occurred. During the 2004-2005 study, the dominant circulation pattern throughout Offatts Bayou and Lake Madeline was regulated by a density gradient and to a lesser extent by currents and wind stress. As seen in the water column data, bottom water, was dense (colder and saltier) and entered Offatts Bayou from West Bay (station

12), traveled through the boat channel (stations 11, 10, 9), then dispersed outward into the wider middle section (station 9 and 5), the back regions (stations 4, 3, 2 and 1) and Lake Madeline (stations 7 and 8) (Figures 3.17 to 3.20). Less dense (warmer and fresher) water flowed out of Lake Madeline and Offatts Bayou into West Bay along the surface.

The impact on the Offatts Bayou circulation by abiotic factors is evident in the distribution of temperature and salinity levels throughout the embayment. Seasonal surface temperature and salinity fluctuation levels were controlled by physical factors, such as insolation and wind effects. Subsequently, temperature was homogeneous (statistically) throughout Offatts Bayou while insolation was evenly distributed across the Offatts Bayou embayment ($p < 0.05$). Salinity was statistically heterogeneous across the Offatts Bayou region throughout the sample year ($p < 0.05$) due to an overall lack of water circulation between Offatts Bayou and West Bay. Salinity levels were generally higher at the mouth of Offatts Bayou where seawater from Galveston Bay flowed in. In Lake Madeline and the other isolated sections of Offatts Bayou, where circulation was reduced, salinities dropped, but not to the level that might be predicted if there were significant freshwater inputs.

Since Offatts Bayou circulation was greatly reduced, stratification – destratification events were attributed to winds, through their influence on wave generation and subsequent resuspension of sediments, fluctuations in temperature and salinity that resulted in density changes and the level of insolation that the water received throughout the year. For example, the relative salinity stratification index in

Lake Madeline, during March 2005, increased by approximately 5 fold above the average (0.3 → 1.5) (Figure 3.6) and station 1 had a 3 fold increase (0.2 → 0.6) (Figure 3.2). The index indicated an increase in the salinity stratification of the water column which correlated with a rain event that introduced approximately 3 cm of precipitation to the system and lowered the salinity (Figure 3.41).

In Offatts Bayou, an important factor in determining the dissolved oxygen water column profile was the stratification of density, calculated from changes in top to bottom temperature and salinity measurements. As seen in the numerous water column profiles in Offatts Bayou (Figure 3.1a-d), if the water column had a high degree of density stratification, then dissolved oxygen concentrations (> 2 mg/L) remained above the shallow pycnocline, with hypoxia or anoxia below the phycnocline. For example, the Deep Hole was extremely stratified in July with anoxia developing 2.5 meters below the surface, when temperatures and salinities were high and no to little wind effects (Figures 3.5 and 3.42). Conversely, in December during colder, less saline and windier conditions, the water column was less stratified at this location, with anoxia developing at 6.5 meters below the surface (Figures 3.5 and 3.42). Stratification - destratification patterns, similar to those present in Offatts Bayou, occur throughout the Gulf coastal estuaries, such as Galveston Bay and San Antonio Bay (Monbet, 1992).

4.2.2 Phytoplankton Patterns across Offatts Bayou

Several patterns of phytoplankton community abundance and biomass developed and were influenced by a wide range of abiotic and biotic mechanisms at play in Offatts Bayou. Phytoplankton biomass and community composition within a mass of water can be altered by changes in population abundance (mortality or production), predator-prey interactions and settling out to the benthos or resuspension into the water column (Cloern, 1996). Those individuals displaced by horizontal movement of water masses are characterized by wind forces, tidal action and horizontal gradients of density (Fischer *et al.*, 1979) which had the ability to move phytoplankton from one region of a bay or estuary to an adjacent one.

The first pattern that was examined was in Lake Madeline (station 8); a deep, isolated water body. During winter, the colder and fresher surface water displayed high concentrations in chlorophyll *a* and low abundance levels. This pattern reflected the diatom community that generated large quantities of chlorophyll *a* in order to capture as much sunlight as possible during levels of low irradiance. Throughout summer in Lake Madeline, high chlorophyll *a* and moderate phytoplankton abundance, consisting of a haptophyte dominated community (100%), indicated that there were different mechanisms affecting the community. During the August identification sampling, there was a significantly larger population of zooplankton (personal observation) than in other seasons or at other stations. The zooplankton were most likely preying upon small phytoplankton, with the exception of the large (clusters of ~ 25 cells) haptophyte, *C. aureus*, thereby decreasing the algal diversity. Allelopathy is another mechanism that haptophytes utilize to control and possibly deter other algal cells from living in the surface waters with them.

In the blind end regions (stations 1 and 4) during winter, chlorophyll *a* concentration was at an intermediate level and abundance was extremely high. The high diatom concentrations were due both to increased mixing that brought cells up from the bottom sediment and adaptations, such as chain forming and spines that increased the surface area of the diatom and aided in surface water buoyancy. In summer, both chl *a* and phytoplankton abundances were intermediate to moderate, but higher than during winter. This trend resulted from the increase in phytoplankton, namely *C*, *aureus*, during the hotter, more saline and increasingly stratified water conditions.

During both winter and summer in West Bay (station 12) and the boat channel (station 9), chlorophyll *a* and abundance levels were the lowest observed throughout the entire region. It is believed that the high rate of horizontal and vertical mixing re-circulated the phytoplankton throughout the water column, thus not allowing the community to remain at the surface for any prolonged amount of time. It is also possible that the resuspended matter in the water column limited light to the phytoplankton, which decreased algal processes and abundances. This second scenario is consistent with the model described by Cloern (1996) in which a shallow, highly turbulent system brought resuspended sediments up into the water column, thereby limiting light availability and reducing abundance of phytoplankton in the surface waters.

The seasonal succession of algal groups were similar at all the sampling stations during the study, but species composition of the phytoplankton were very different between stations at certain periods during the year. At the most restricted (in terms of circulation) and isolated stations in Offatts Bayou (1 and 8), dominate species richness was relatively low (one to two dominate species) all year, except for the months of April, June and November. These months were the transitional periods that incurred the most changes in temperature and salinity, resulting in various opportunistic alga taking advantage of water conditions. In the more open stations 4, 9 and 12, species diversity varied from one to four, but were generally greater than that seen at stations 1 and 8 in any given month. The presence of periodic benthic diatoms (pennate forms) in surface waters during winter and autumn supported the notion that phytoplankton were being resuspended via vertical mixing in the more open stations. These findings were supported by a second model described by Margalef (1978), which predicted pennate diatoms at the benthos being stirred up into the water column and surface waters during periods of intense mixing. This process was previously shown for other shallow marine systems similar to Offatts Bayou (Lucas *et al.*, 1999; Cloern, 1991). The results of the Offatts Bayou study revealed that the distribution of phytoplankton is not uniform, but varies over temporal and spatial scales.

4.3 Effects of Hurricane Rita

Hurricane related winds have the potential to cause large fluctuations in the environment when they pass through as area, such as resuspending sediments laden with benthic organisms (Cahoon and Cooke, 1992) and light limited phytoplankton (Zeeman, 1985). During periods of intense hurricane winds, sediment and nutrient resuspension result in highly productive waters, an increased benthic diatom population in surface waters in some locations (Fogel *et al.,* 1999) and the development of vertical stratification afterwards (Paerl *et al.*, 2001).

Hurricane Rita (2005) made landfall east of Galveston Island on 24 September 2005 at approximately 0300 (C.S.T.). Before this date, water conditions in Offatts Bayou were summer - like with high temperatures and salinities. Dissolved oxygen was low and the haptophyte, *Corymbellus aureus*, dominated the phytoplankton community throughout the Offatts Bayou embayment.

Hurricane Rita's strong sustained wind forcing of 62 km h^{-1}, wind gusts to 90 km h^{-1} and little precipitation (~ 2 cm) in the vicinity of Galveston Bay impacted the water quality and phytoplankton community in Offatts Bayou (Figures 3.41 and 3.42). The data collected before and after Hurricane Rita demonstrated that even though Galveston Island was on the "clean side" of the hurricane, the small, shallow and protected inlet of Offatts Bayou sustained marked impacts in phytoplankton species succession and biomass increases (Figures 3.30 and 3.31). Previous studies on the influence of Hurricane Gordon (1994) (Fogel *et al.*, 1999) and Hurricanes Dennis, Floyd and Irene (1999) (Paerl *et al.*, 2001) revealed resuspension patterns and stratification events resulted in high productivity (increased chl *a*) after the hurricanes past. The resuspension of surface sediments rich in nutrients and benthic microbes produced a turbid, yet productive water column in a region in which a hurricane has passed, resulting in biomass and productivity changes. An increased assemblage of phytoplankton was observed in the Offatts Bayou embayment after Hurricane Rita. This was not concurrent with an increased chl *a* concentrations (Figure 3.). In fact, chl *a* measured after the hurricane was decreased, at most stations, relative to that measured before the hurricane. Chl *a* concentrations at station 4 were similar during both

September samplings (pre and post Hurricane Rita). The increase in chl *a* observed only at stations 3, 7 and 8 most likely reflected the horizontal displacement of surface waters by the strong northwesterly winds associated with Hurricane Rita. The system shifted from being a haptophyte dominated community before the hurricane to an almost 50/50 haptophyte/bacillarophyte assemblage after its passage. Since there was only one benthic diatom (*Odontella mobilensis*) present in the surface waters following Hurricane Rita, it is believed that horizontal movement of water masses was the most contributing factor for displacing phytoplankton into Offatts Bayou and Lake Madeline from West Bay. However, there were numerous species of large, heavy centric diatoms, (*C. radiatus,* four *Chaetoceros spp, B. furcatum and D. brightwelli*), which may have settled on the sediment surface during the summer water column stratification, that were then resuspended after the hurricane. Thus, both horizontal and vertical mixing mechanisms could be attributed to the increased phytoplankton abundance throughout Offatts Bayou after Hurricane Rita.

As a result of low precipitation rates from the hurricane, there was no significant change in salinity (Figure 3.41). Temperatures fluctuated during the hurricane but returned to pre-Hurricane Rita levels by the sampling period on 29 September 2005 (Figure 3.44). Post hurricane surface dissolved oxygen concentrations remained similar to pre hurricane concentrations from West Bay and along the boat channel. At stations 9 and 4, along the inner regions of Offatts Bayou, there was an increase of 3 to 5 mg/L after Hurricane Rita passed through. This was most likely caused by the mixing in the water column and subsequent increased diatom biomass.

4.4 August Fish Kill

From early in Galveston's history, there have been reports of algal blooms and fish kills occurring in Offatts Bayou (Gunter, 1942; Connell and Cross, 1950). Despite the problems associated with phytoplankton blooms cause, they do not always result directly in fish kills (Hallegraeff *et al*, 2003). Other factors such as reduced and prolonged low dissolved oxygen, high organic matter loads and high concentrations of H_2S are known to contribute to fish kills.

Fish kills related to low dissolved oxygen concentrations have been seen across the United States coastal regions and are not a new phenomenon for Galveston Bay. Following Tropical Storm Frances's (1998) high rainfall on the Texas Gulf coast, waters containing low dissolved oxygen concentrations were pushed into Galveston Bay, resulting in massive fish kills in the East and West Bays (Lester *et al.*, 2002). An example of a fish kill from outside the Gulf Coast resulted from a bloom of *Heterosigma* in Hood Canal (WA), during September 2000, which caused the massive deaths of dead starfish, crabs, shrimp and oysters, along with starry flounder, gunnels, and greenlings (Connell *et al*., 2001). The fish kill was thought to be a result of low oxygen with *Heterosigma* cell abundances ranging between 3×10^5 to 2.7×10^8 cells per liter (Connell *et al*., 2001).

A large fish kill in Offatts Bayou during the late summer of 2005, consisted of fry (1000's) and adult (100's) menhaden (*Brevoortia patronus*), stripped mullet (<50) (*Mugil cephalus*) and ribbon fish (1) (*Trichiurus lepturus*) (Appendix E). This occurred at a time where there was also high phytoplankton abundance corresponding to a bloom of *C. aureus*. This was associated with extremely low dissolved oxygen concentrations in the water column, calm winds and high temperatures. The bloom was especially prevalent in Lake Madeline, where hypoxic conditions existed from the water's surface down to 4 meters, after which the water column was anoxic. *C. aureus* manufactured significant quantities of extracellular byproducts (personal observation). The exudates observed in this study were almost gelatinous in nature and clogged water sample filters and phytoplankton tow nets. The ratio of phaeo *a* relative to chl *a* in the water column in August was used as a proxy for the production of exudates and the change in the phytoplankton bloom's state. Chl *a* measurements represent the living or newly dead cell of phytoplankton, while phaeo *a* represent the breakdown of the chl *a* pigment when the phytoplankton cells are stressed due to grazing or senescence. The ratio of chl *a*/phaeo *a* was reduced during the summer months as compared to the rest of the year. The resulting ratio indicated that about half of the chl *a* measured was actually phaeo *a* and that there was a high degree of phytoplankton death occurring during the August fish kill. *C. aureus* is not known to produce a toxin (Green, 1979) and so the fish kill was not likely attributed to toxin production, but rather related to the ambient water conditions and the high organic matter loading due to the declining bloom.

An odor of sulfide was also recognized in the regions where *C. aureus* was present in extremely high concentrations (personal observation), especially Lake Madeline. However, it is unknown if the sulfide odor was the result of algal degradation or if it diffused out of the bottom sediment during the mixing process. DMSP, a metabolic precursor to dimethylsulfide (DMS), is produced in significantly larger amounts by flagellated phytoplankton, particularly haptophytes. Thus, it is quite possible that high concentrations of DMS were present during the summer bloom of the flagellated *C. aureus.* However, there has been no research accomplished on *C. aureus* to determine if it is a producer of DMS (Moestrup, 1979). *Emiliania huxleyi,* a haptophyte, has long been recognized as an important producer of large concentrations of DMS (Burkill *et al.*, 2002; Quigg and Wardle, 2005). It is also possible that *C. aureus* released DMS when degraded by bacteria and/or was grazed upon by zooplankton, based on such finding for *E. huxleyi* (Dacey and Wakeham, 1986). DMS and sulfide concentrations, which have been shown to depress respiratory and circulatory functions, resulting in respiratory arrest, apnea and death in fish (Torrans and Clemens, 1982).

In addition, as the bacteria began to degrade the dead fish, more dissolved oxygen was removed from the water column and more fish appeared at the surface from probable suffocation. Maximum reductions of dissolved oxygen were reached in Lake Madeline bottom waters during the period of the fish kill (Aug 25 to 26).

The peak phytoplankton bloom in August was associated with extremely low dissolved oxygen concentrations in the water column, calm winds, and high temperatures. The summer bloom was especially prevalent in Lake Madeline, where hypoxic conditions existed from the water's surface to 4 meters, after which the water column went anoxic.

5. CONCLUSIONS

Phytoplankton communities are dynamic and composed of a wide variety of species that exhibit successional temporal and spatial patterns in response to abiotic and biotic seasonal shifts. The interactions of various chemical (water temperature, salinity, pH, dissolved oxygen concentrations), physical (insolation, freshwater input, storm events and wind speed and direction) and biological (predator-prey interactions, physiological competition) regimes were major determinants in the dynamics, diversity, succession and distribution of phytoplankton in Offatts Bayou.

In order to address questions and concerns about the water quality and phytoplankton community composition in Offatts Bayou, a series of null hypotheses were tested:

H_1: There is no significant seasonal difference in surface, middle and bottom water hydrological parameters (T, S, DO_2, pH).

The initial hypothesis proposed that there was no significant seasonal difference between surface, middle and bottom water hydrological parameters (temperature, salinity, dissolved oxygen and pH). The findings in this study did not support the hypothesis (MANOVA, $p < 0.05$). The significant results demonstrated that (1) temperature was homogeneous throughout the water column (2) there was a significant difference between salinity, dissolved oxygen and pH in the three water levels, (3) a density driven circulation pattern (colder, more saline water on the bottom, and warmer, fresher at surface) existed in Offatts Bayou and flowed inward at the bottom from West Bay and out at the surface and (4) seasonal trends were observed.

H_2: There is no significant monthly and seasonal change in surface phytoplankton diversity related to variability in hydrological parameters (T, S, DO_2, pH).

The second null hypothesis was rejected and showed that phytoplankton diversity did change in response to fluctuations in hydrological parameters. Phytoplankton tows were carried out once per month and statistically analyzed for patterns on a monthly and seasonal basis. When sampling first started in the colder and less saline winter, there was a high diversity of Bacillarophyta. At this time, there was also a high concentration of dissolved oxygen, in relation to the rest of the sample year. The community composition changed in late spring when temperatures, salinities and pH began to increase and dissolved oxygen decreased. At this time, the first Euglenophyta and Haptophyta appeared. Throughout the summer, haptophyte mean cell concentrations increased to bloom conditions, while dissolved oxygen concentrations and diatoms were reduced. Autumn reflected a decrease in temperature, salinity and pH, while DO_2 and diversity of the diatom community increased.

H_3: There is no significant seasonal change in the surface phytoplankton biomass and abundance related to variability in hydrological parameters (T, S, DO_2, pH).

The third hypothesis, no significant seasonal change in the surface phytoplankton biomass and abundances is related to variability in hydrological parameters (T, S, DO_2, pH) was rejected. Chlorophyll *a* concentration is an index of phytoplankton biomass and it is the most common property used to characterize marine productivity. In Offatts Bayou, chl *a* concentrations followed very similar trends as phytoplankton abundance; increase in the summer and decrease in autumn, winter and spring. Temperature, dissolved oxygen concentrations and pH (to a lesser degree) were recognized as the leading factors in the seasonal fluctuations of chl *a* during the sample period ($p < 0.05$). These findings are plausible given phytoplankton seasonal succession relied heavily on temperature changes in the surface waters of the Offatts Bayou region. Dissolved oxygen concentrations were also linked to both the temperature of the surface waters and the species of phytoplankton present. The findings are important for future research endeavors on phytoplankton changes in Offatts Bayou related to temperature changes associated with global warming.

H_4: The water column in Offatts Bayou is not stratified based on seasonal and spatial differences between values (T, S, DO_2, density) of surface and bottom water.

The final hypothesis, the water column in Offatts Bayou is not stratified based on seasonal and spatial differences between values (T, S, DO_2, density) of surface and bottom water, was rejected. A relative stratification index was utilized for temperature, salinity and dissolved oxygen and a stratification density index revealed that a combination of stratification-destratification events occurrede during seasons throughout Offatts Bayou. Overall, there was mixing at most stations in the winter and stratification during the summer. Relative temperature and salinity stratification indices showed that all stations were mixed throughout the year, with only minor stratification episodes during the year. For dissolved oxygen concentrations, those stations (10, 11 and 12) close to West Bay, where winds and currents were more prevalent, were mixed throughout all seasons sampled during the year. Stations within Offatts Bayou that were sheltered and not influenced by local mixing (1, 2, 7, and 8) experienced dissolved oxygen stratification more often. Stations 1 and 2 (Back Bay) were less stratified in the winter than in the summer and station 7 and 8 (Lake Madeline) were stratified year round, but to a lesser degree in winter, spring and autumn. The remaining stations in the open portion of Offatts Bayou (4, 5 and 9) experienced a range of dissolved oxygen stratification statuses throughout the year and throughout their water column. Station 4 was stratified throughout the year, with greatest stratification observed in July and late September (after Hurricane Rita). Station 5 was mixed throughout winter and autumn and slightly stratified during spring and summer. Station 9 was mixed during early winter and autumn, but slightly stratified in late winter, spring and summer. Stratification vs. mixed conditions of the water column are significant for research on phytoplankton vertical migration, oxycline and/or pycnocline impacts on the phytoplankton community, consumption rates, mixing rates, anoxic and hypoxic conditions and fish kills.

Offatts Bayou is a complex component of the Galveston Bay estuary. Long term monitoring of Offatts Bayou is essential for tracking, recording and assessing various human impacts to phytoplankton distribution, abundance, and productivity as well as impacts to higher trophic levels such as the fish and humans. The mechanisms dominating changes in phytoplankton dynamics and community composition in Offatts Bayou and the adjoining Galveston Bay estuary are complex and the factors vary spatially and temporally. These issues are not unique to the Galveston Bay estuary, but represent a deficiency in awareness of phytoplankton dynamics in all aquatic systems. The following ideas represent possible future research directions:

1. Light penetration should be measured through the water column (Secchi disk) to resolve influences of light availability on phytoplankton production relative to those parameters measured in the present study (T, S, DO, pH). This would allow researchers to determine if light is more important to phytoplankton successional patterns in Offatts Bayou than temperature, salinity, dissolved oxygen or pH.
2. Live phytoplankton samples should be observed and counted, in addition to preserved samples. This will help to identify phytoplankton species that do not preserve well, such as small flagellates.
3. Samples for nutrient analysis should be collected at each station during hydrolab samplings, to observe seasonal trends in nutrient fluxes. This will help to understand where nutrients are entering and when greatest quantities are present. Identifying these problematic areas will assist resource managers and reduce future phytoplankton blooms and potential marine mortality.
4. Additional phytoplankton tows should be accomplished at each meter level of the water column to define which phytoplankton occur below the pycnocline during

stratification periods. It would also have been beneficial in this study to determine which benthic species were being resuspended into the water column during high wind events.

5. Plankton tows should be accomplished on zooplankton to study predator-prey relationships between zooplankton and phytoplankton. This would help determine zooplankton abundances and seasonal succession patterns relative to phytoplankton patterns.

6. Continued collection of hydrological variables and phytoplankton communities will provide data for developing a long term library for future researchers to compare fluctuations in Galveston Bay and Offatts Bayou.

7. In many shallow systems, the biomass of benthic microalgae often exceeds that of the phytoplankton in the overlying waters. Thus, collections from the microphytobenthos would allow for a direct comparison of the abundance of benthic and suspended phytoplankton.

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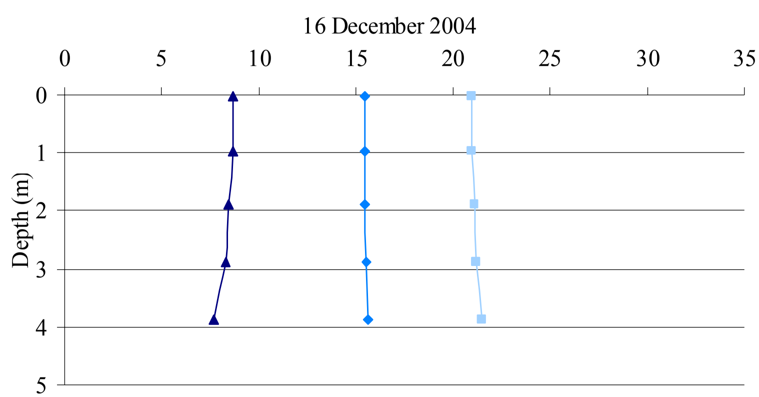
APPENDIX A

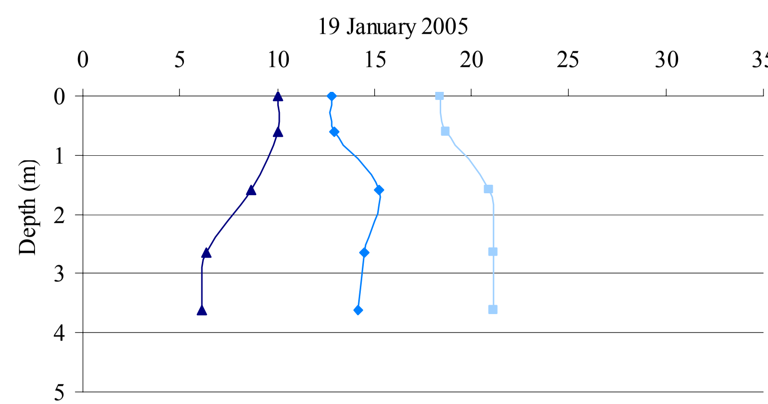
WATER COLUMN PARAMETER AND STRATIFICATION DATA

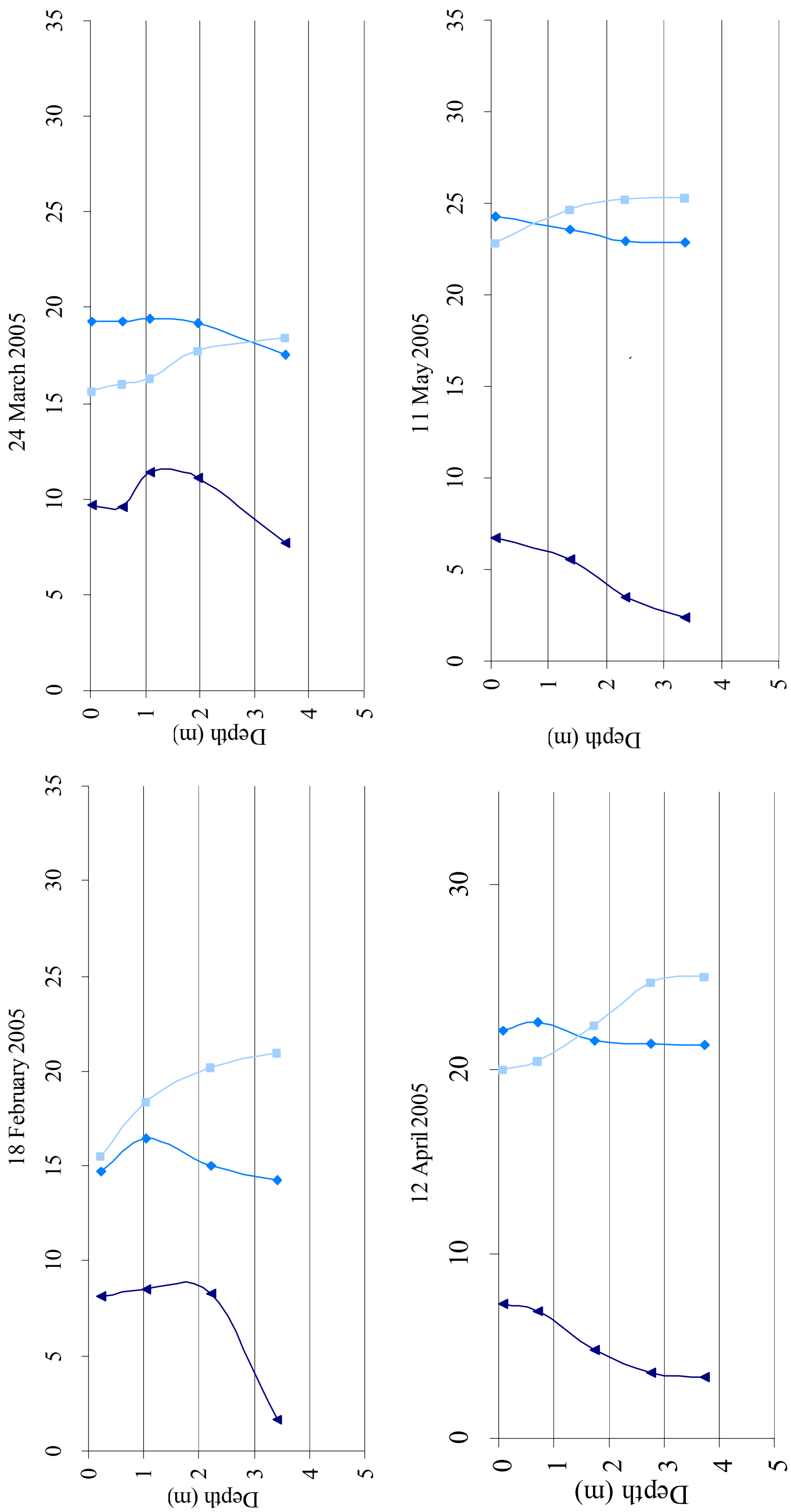
Water Column Parameter Data

Temperature (°C)
Salinity (ppt)
Dissolved Oxygen (mg/L)

Station 1:



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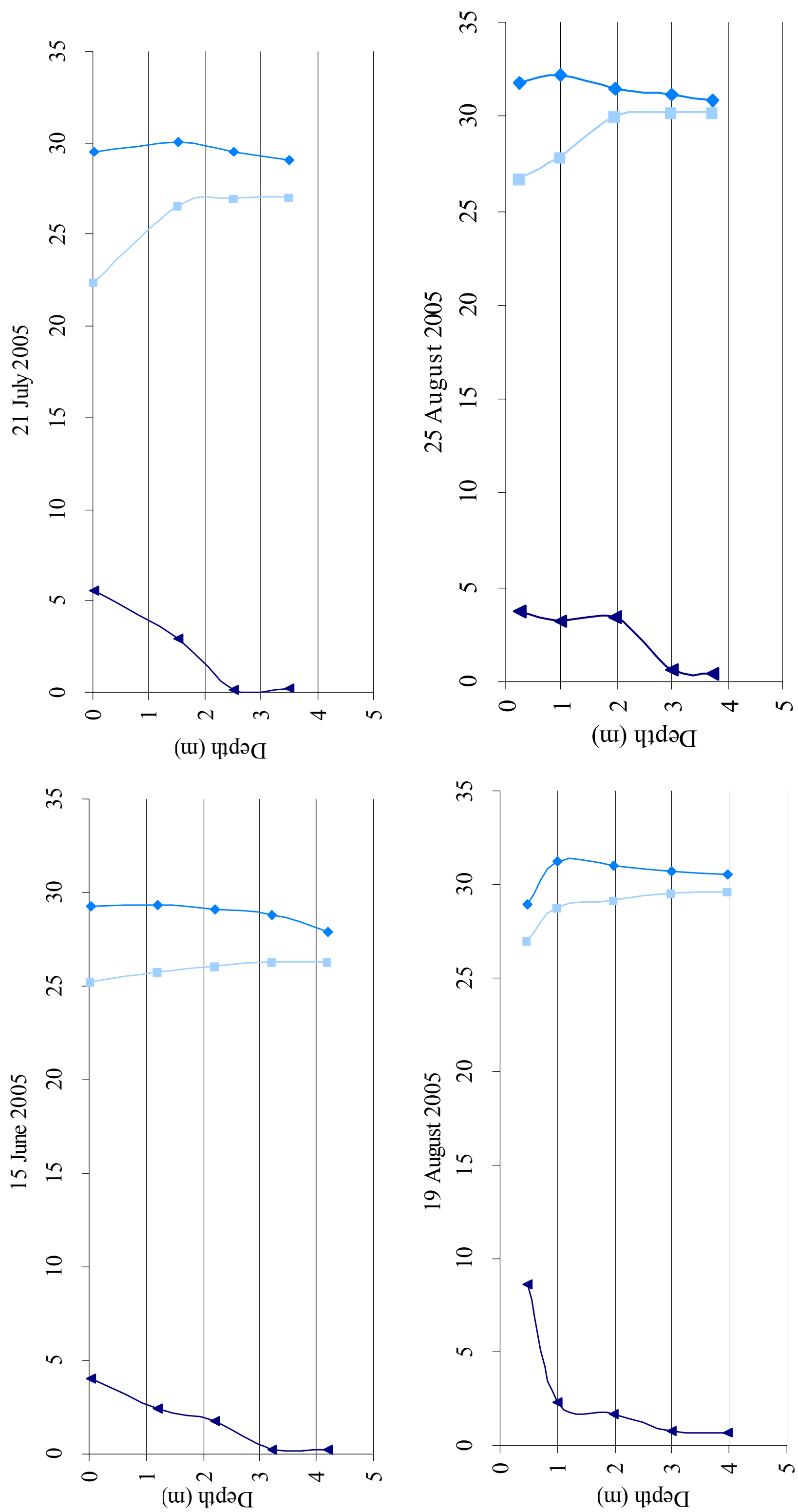
11 May 2005
18 February 2005
12 April 2005
Depth (m)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15 June 2005
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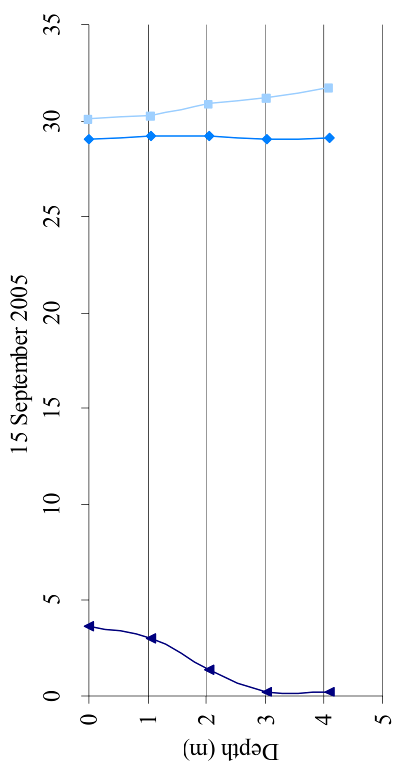
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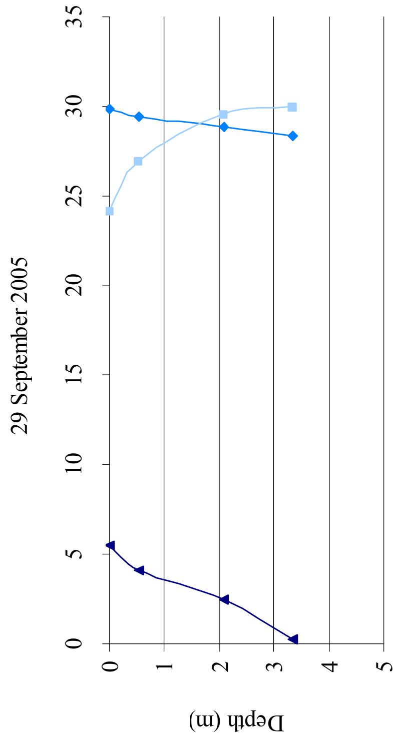
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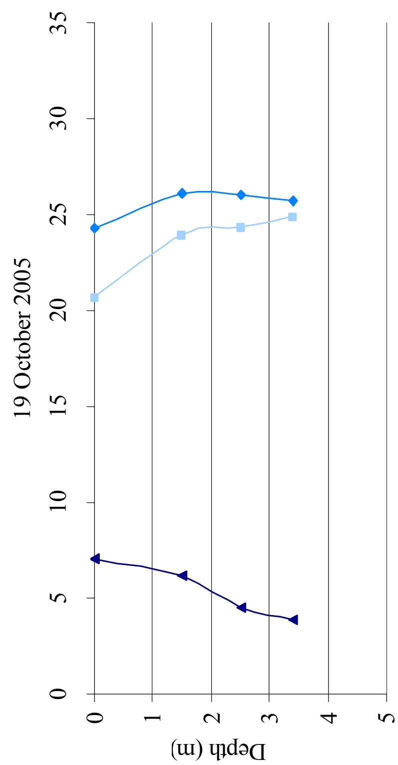
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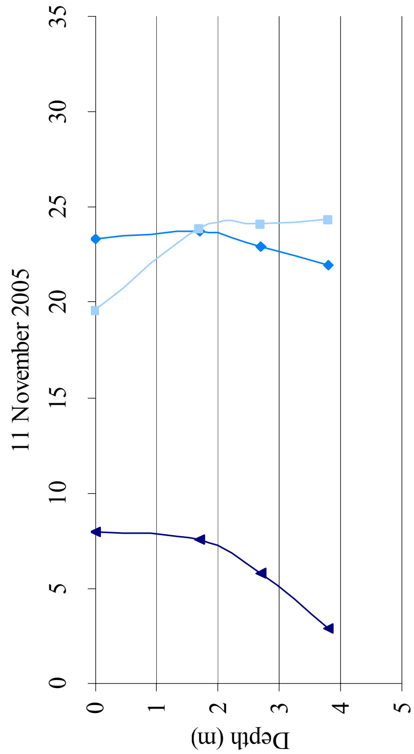
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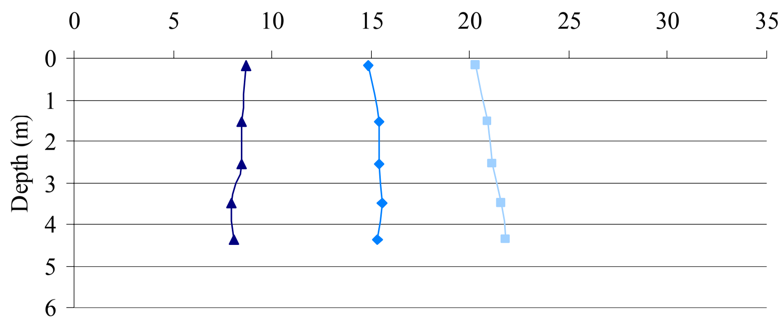

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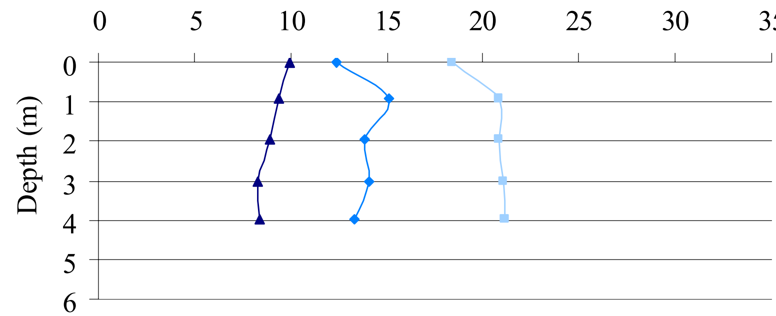

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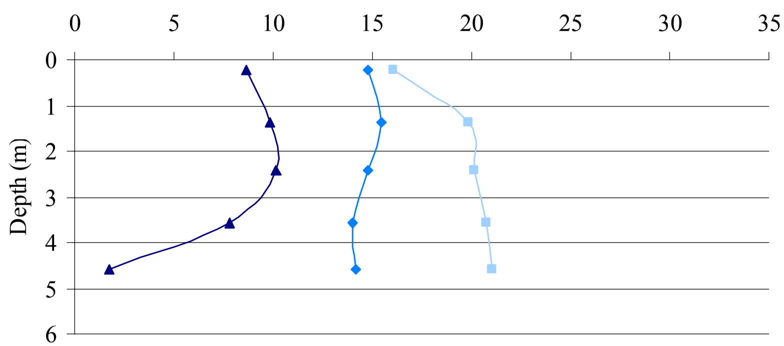

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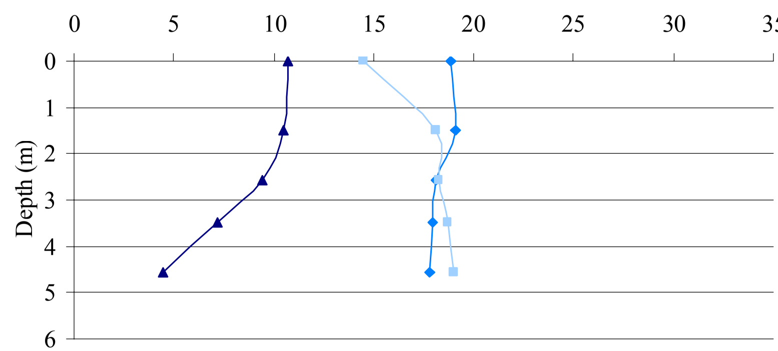

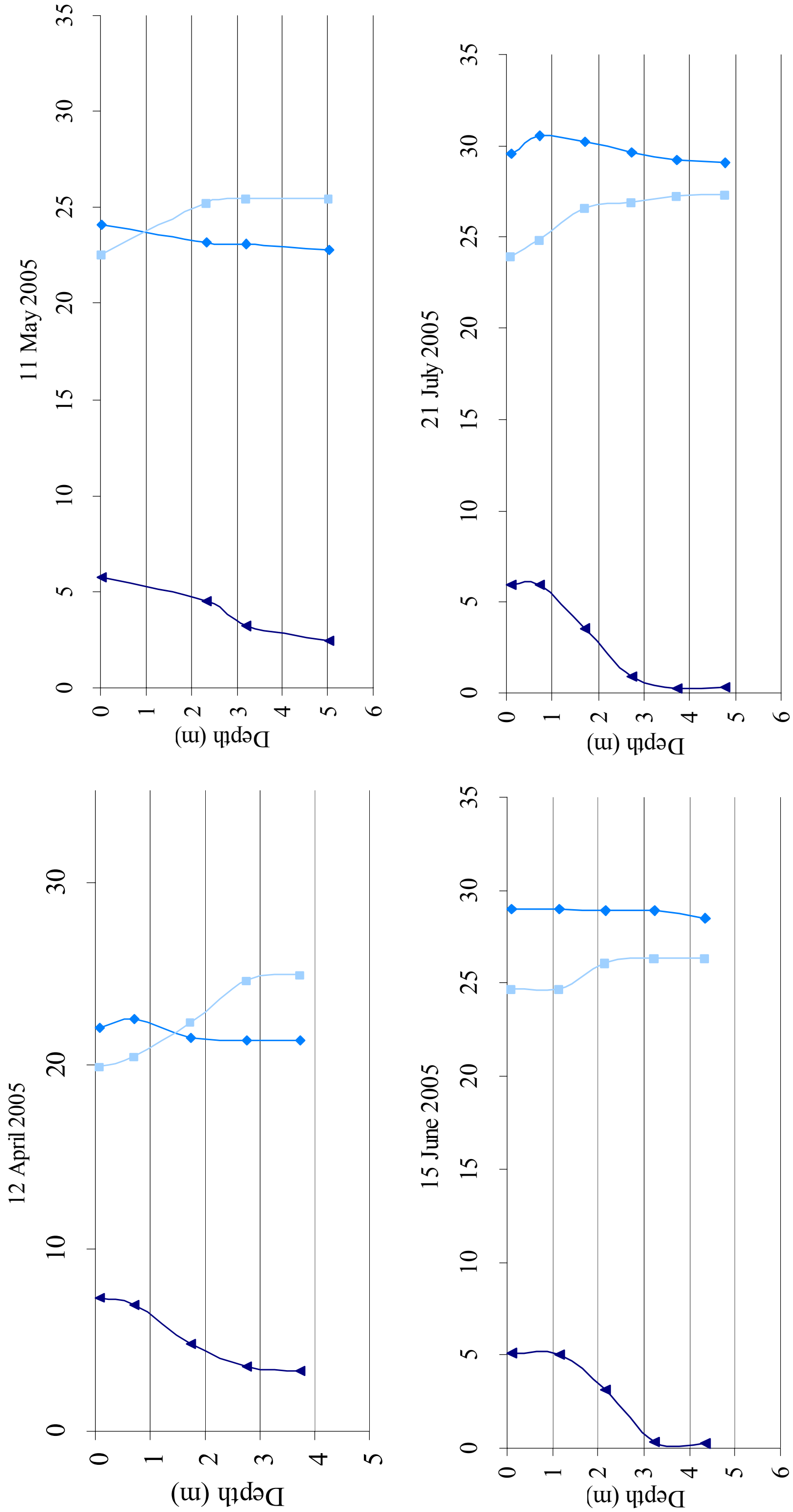
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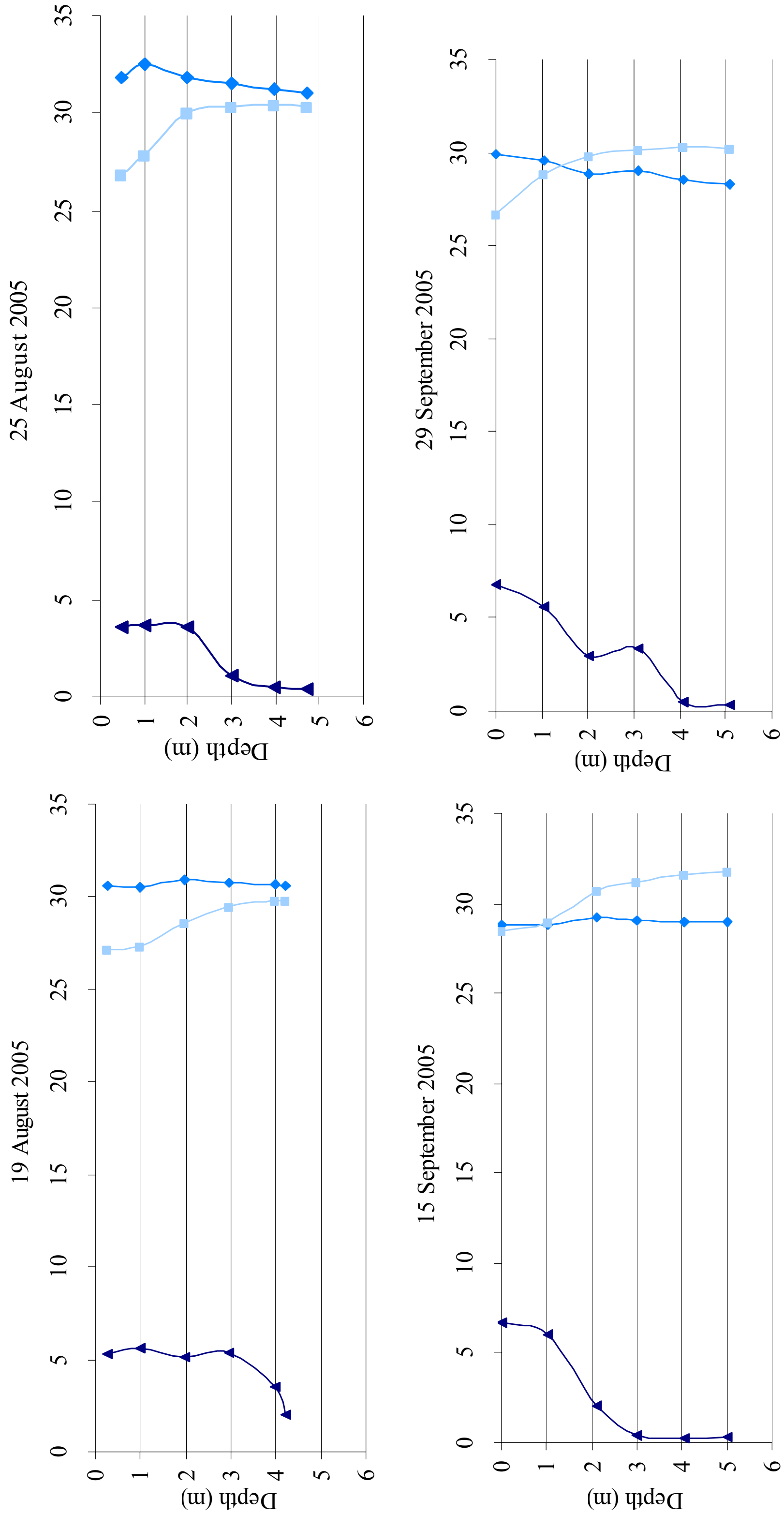
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Depth (m)
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29 September 2005
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Depth (m)
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Depth (m)
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15 September 2005
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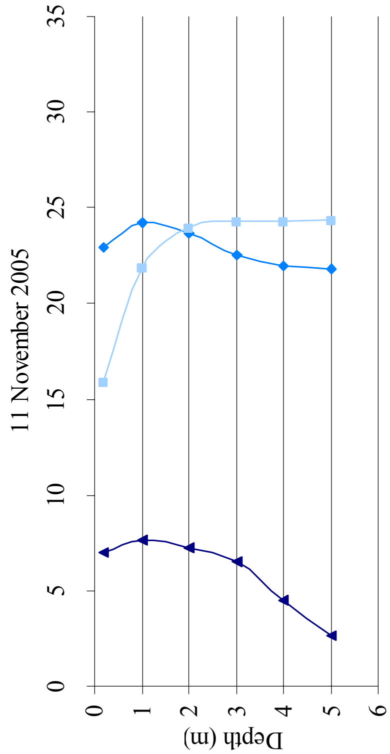
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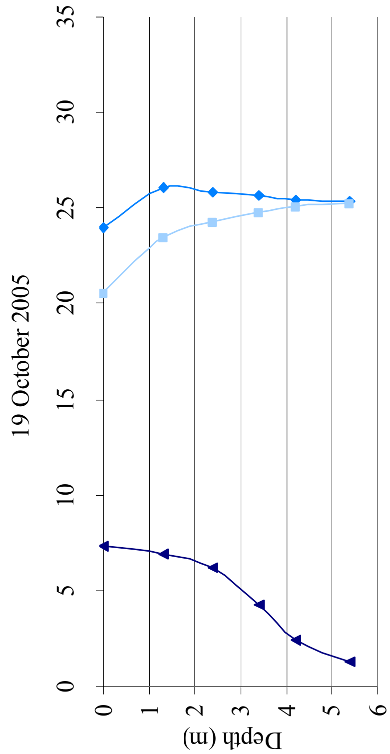
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Depth (m)

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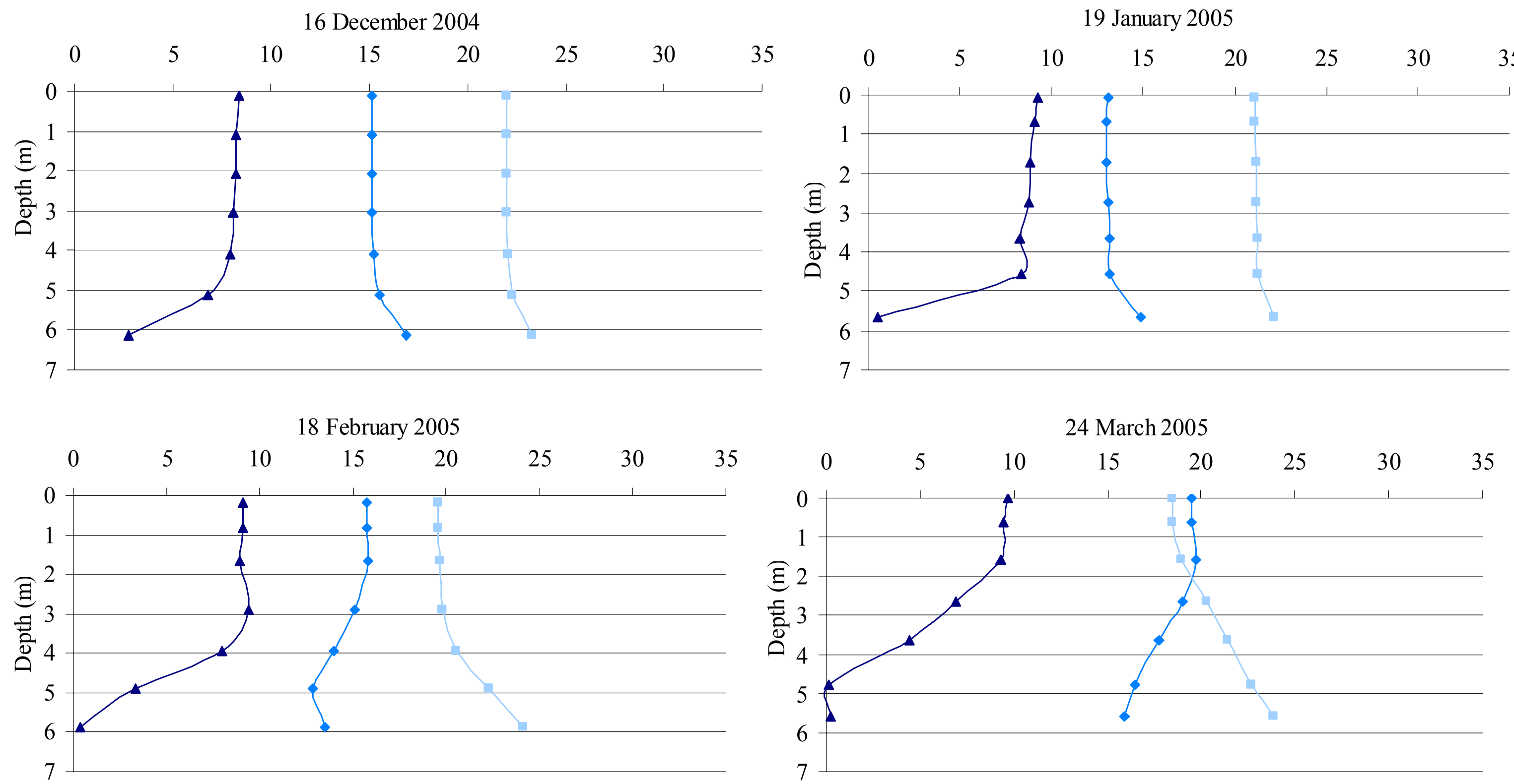
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19 January 2005
18 February 2005
24 March 2005
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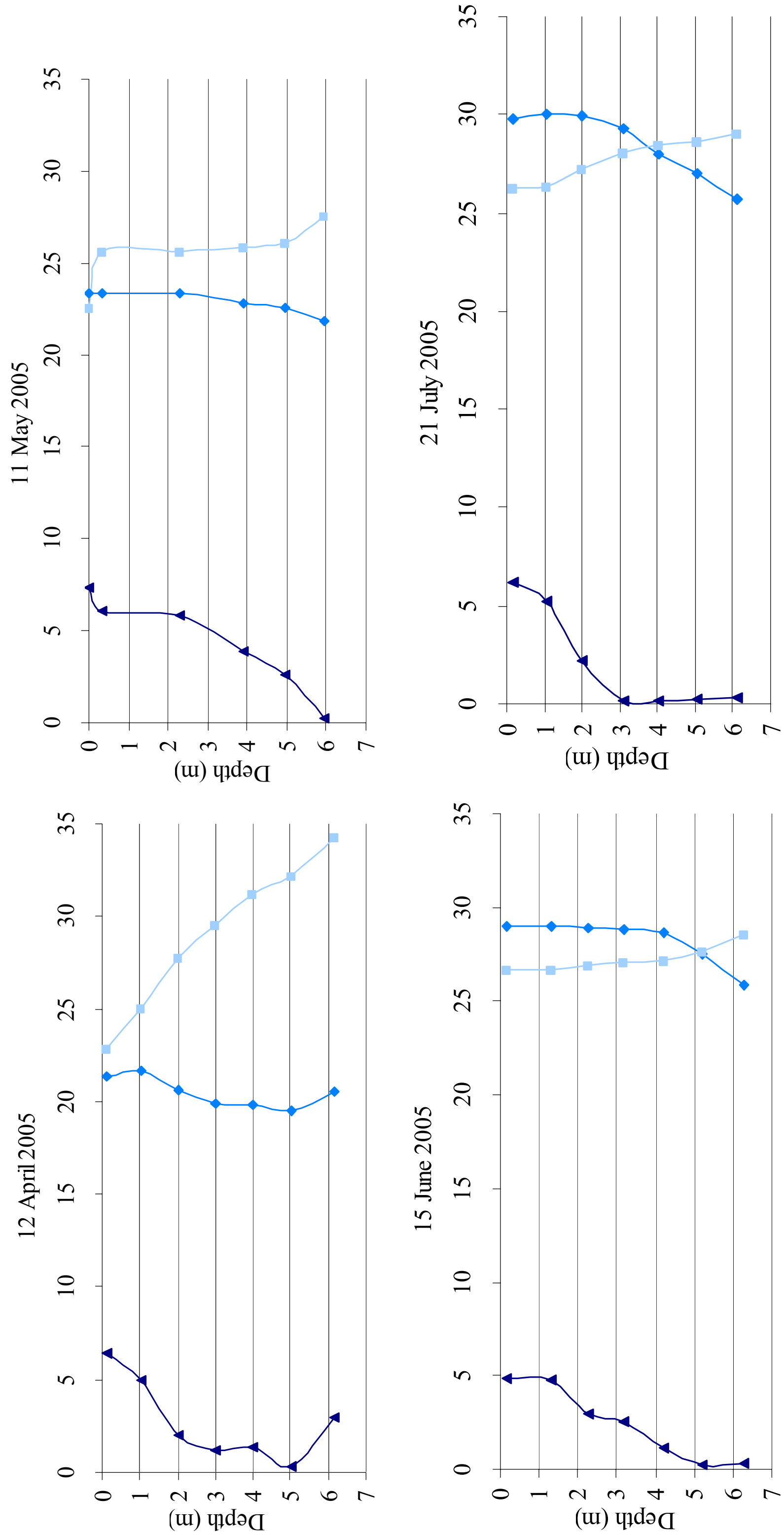
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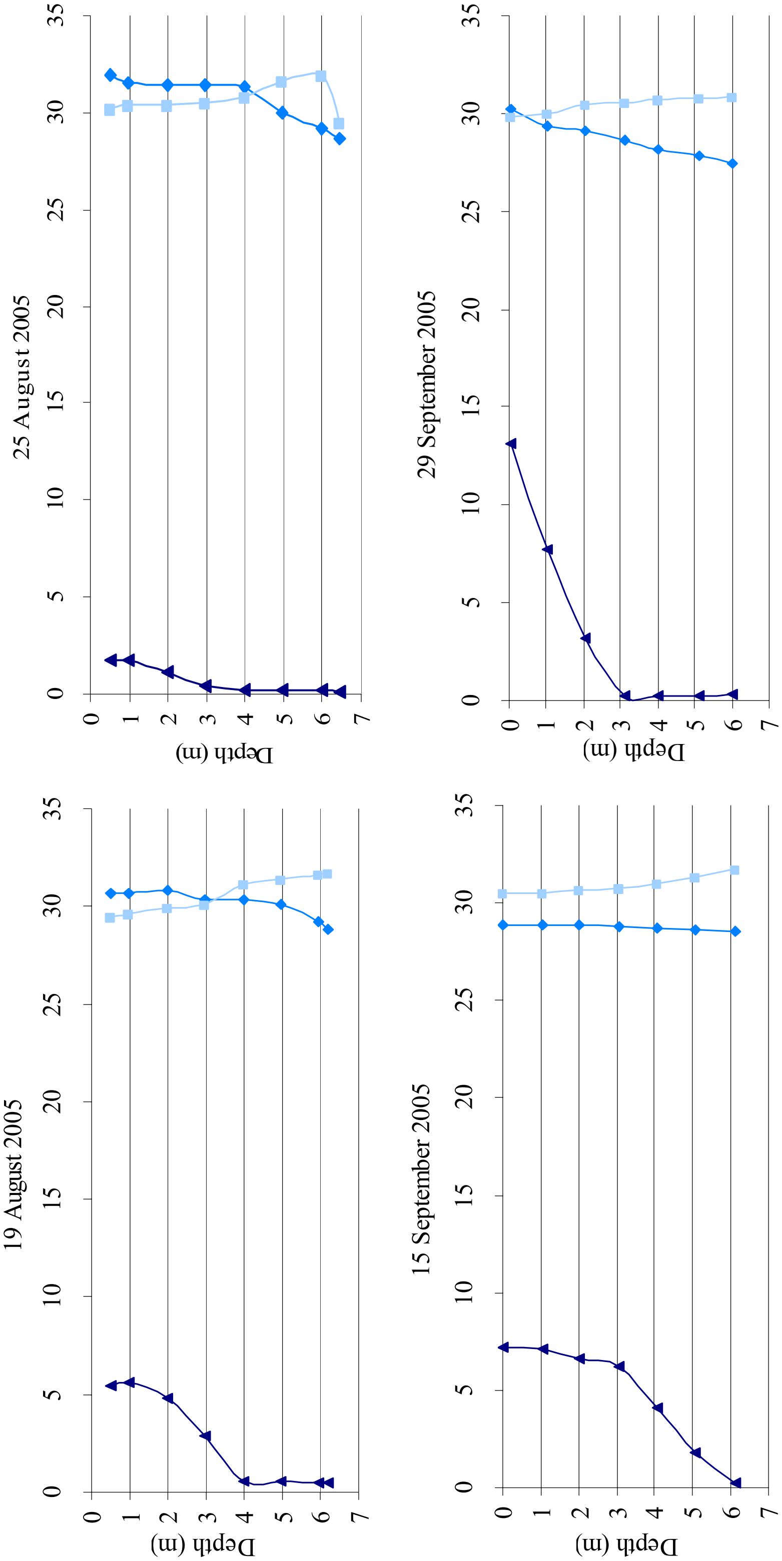

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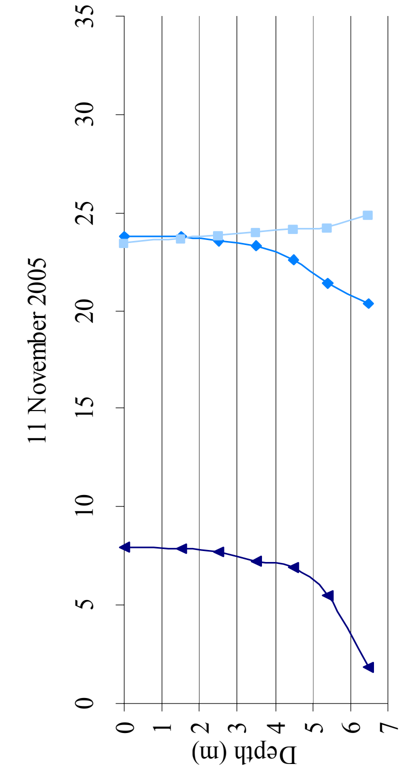
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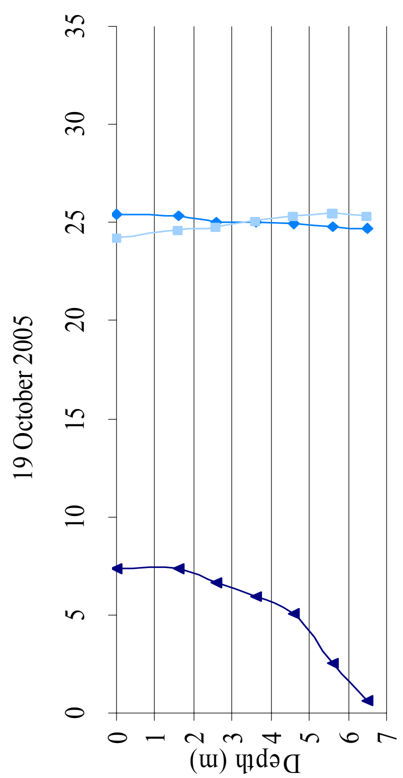
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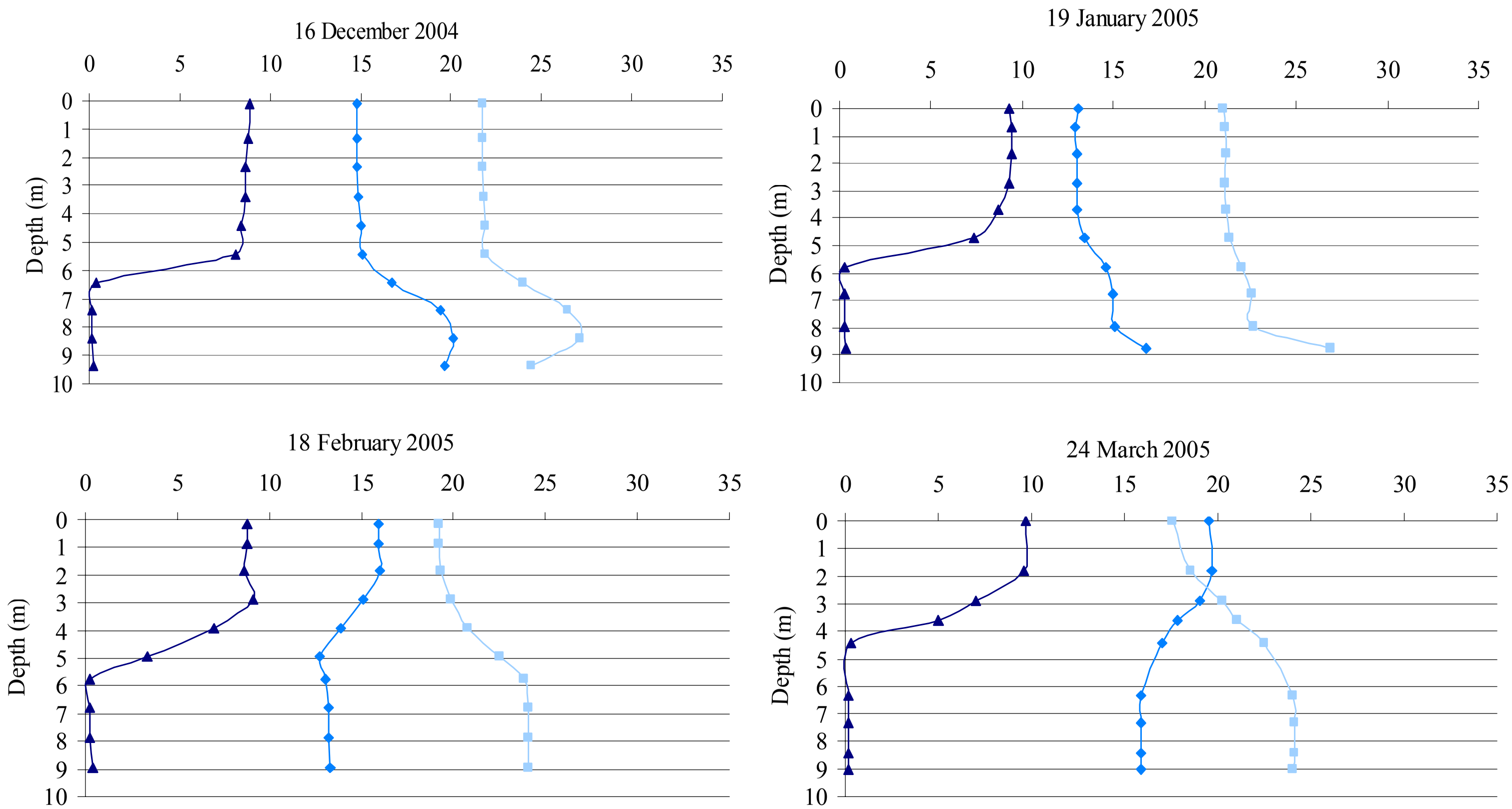
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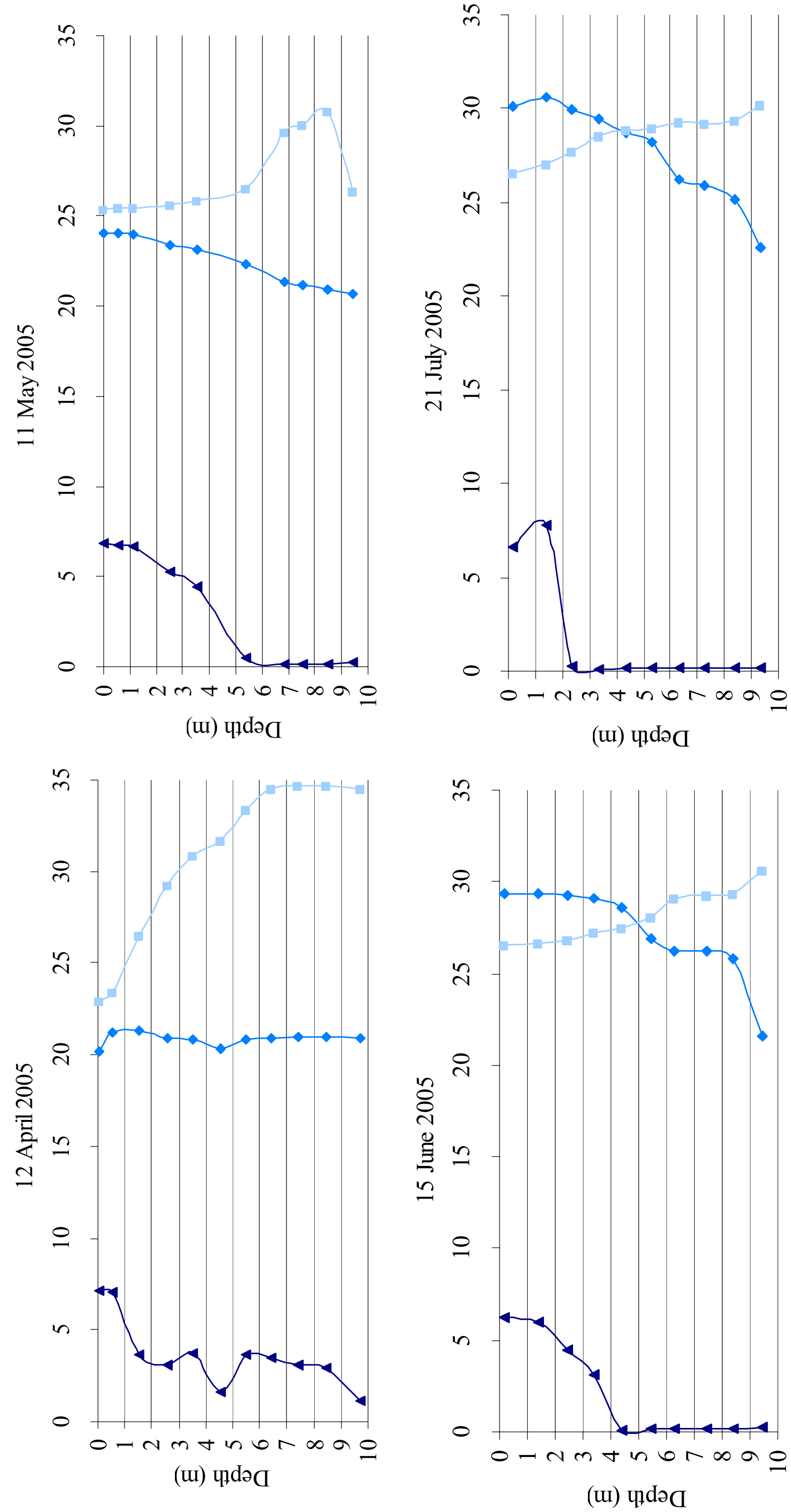
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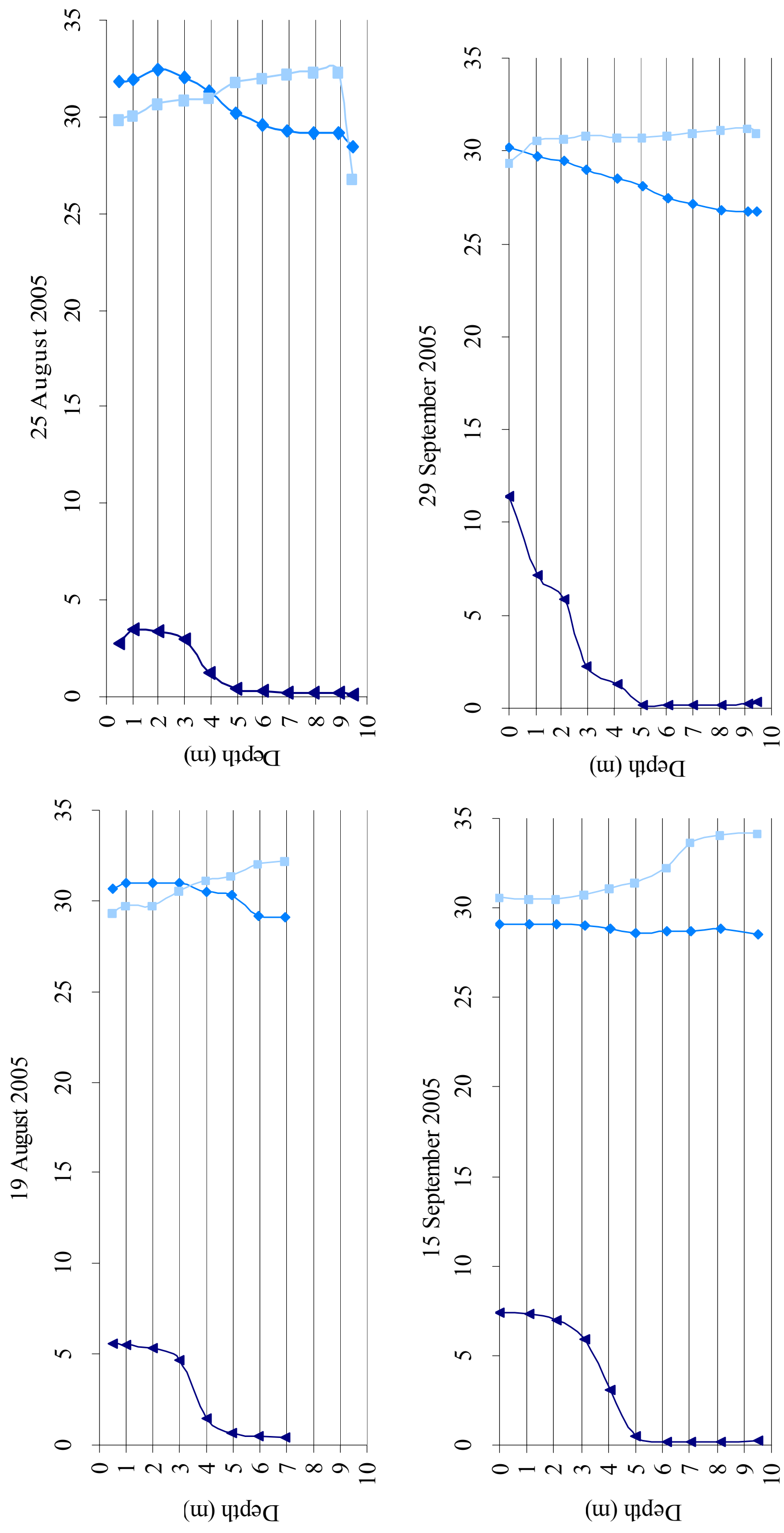
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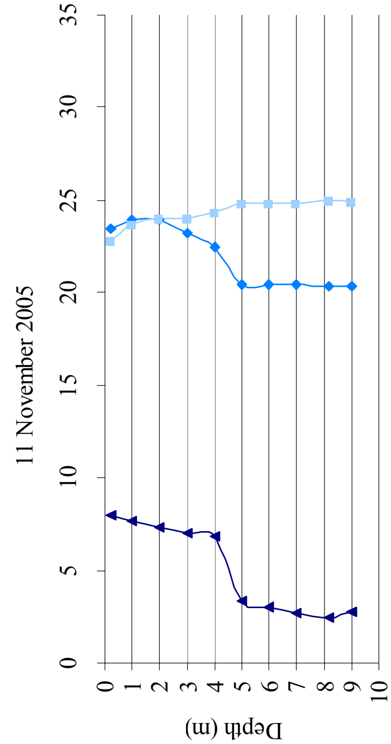
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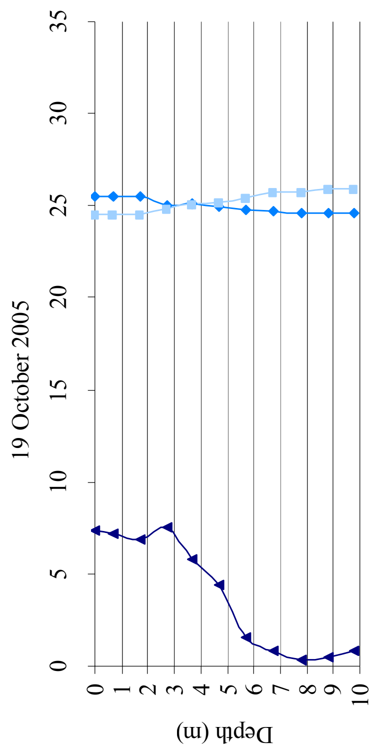
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Station 5:

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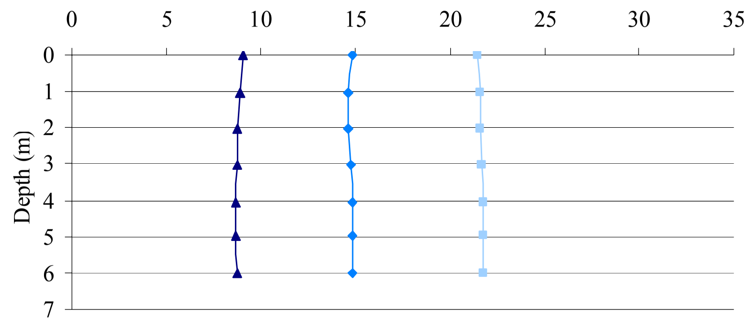

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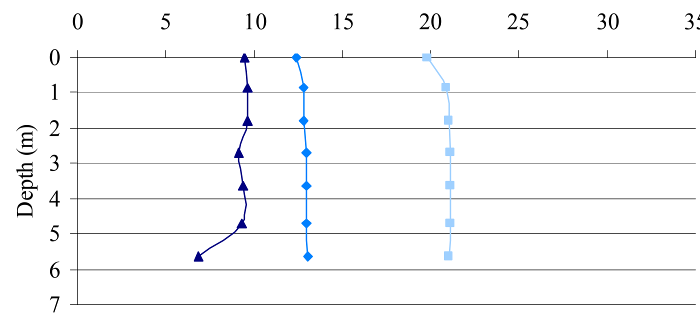

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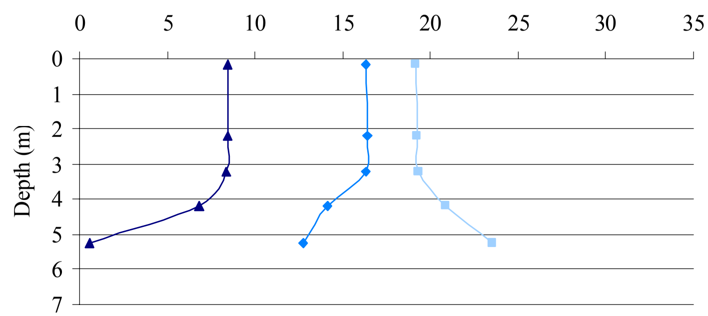

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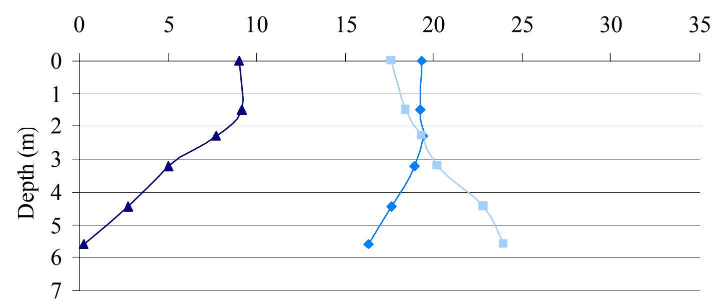

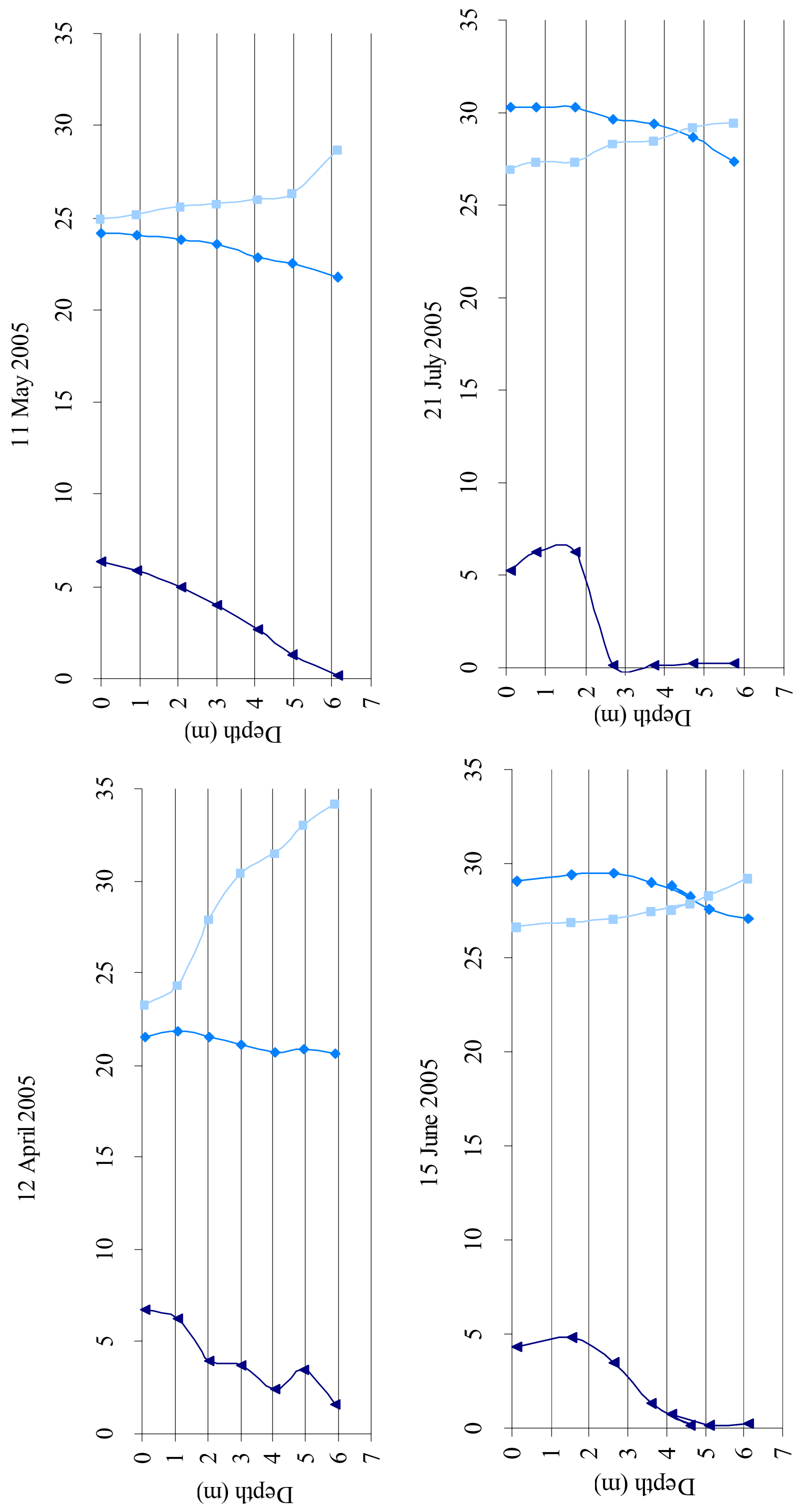
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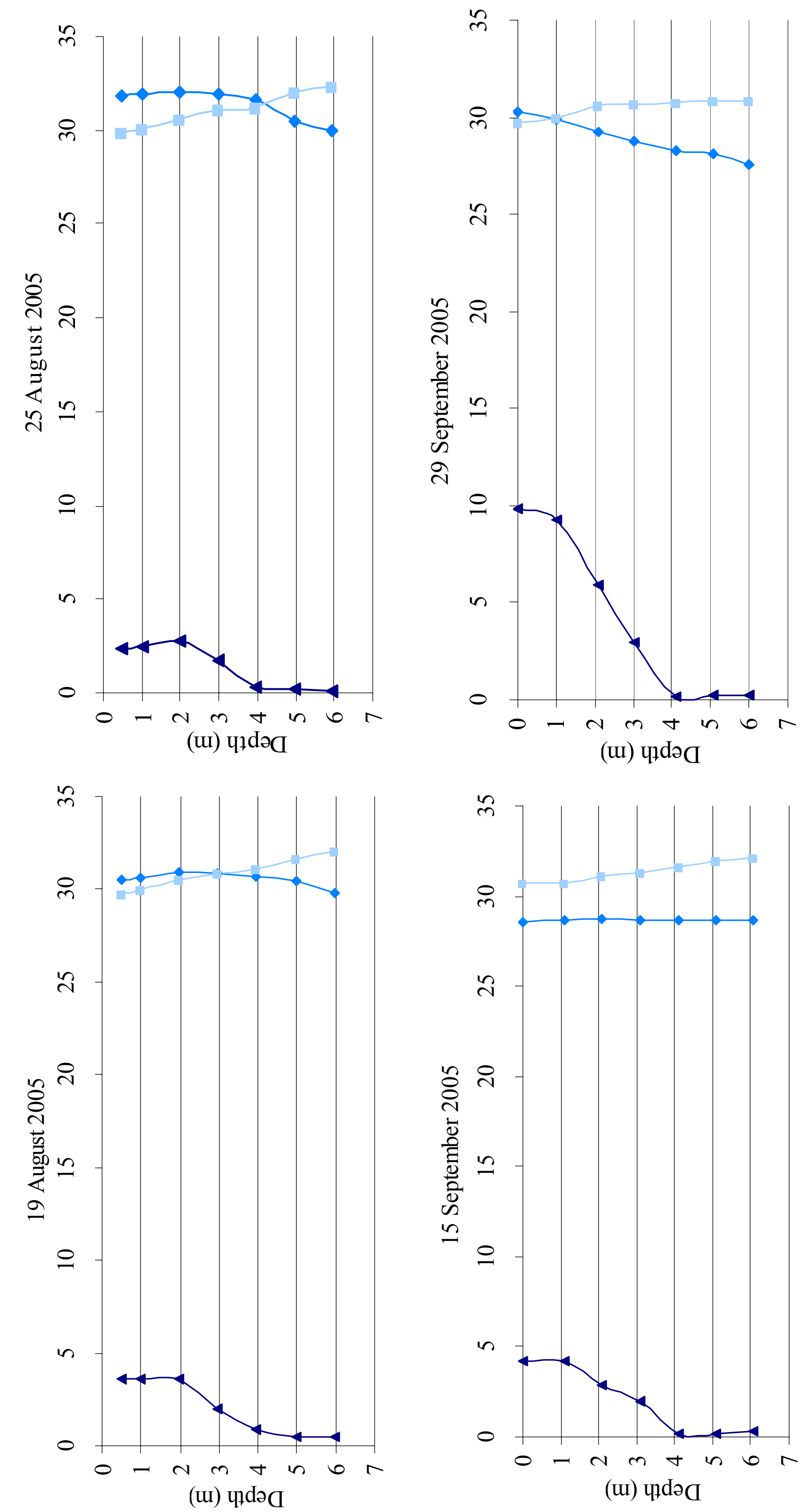
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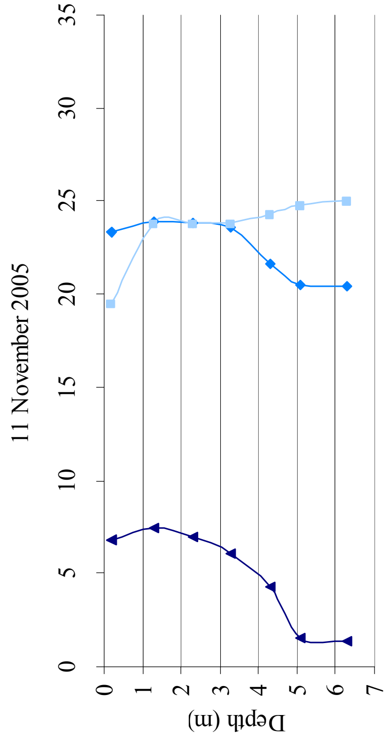
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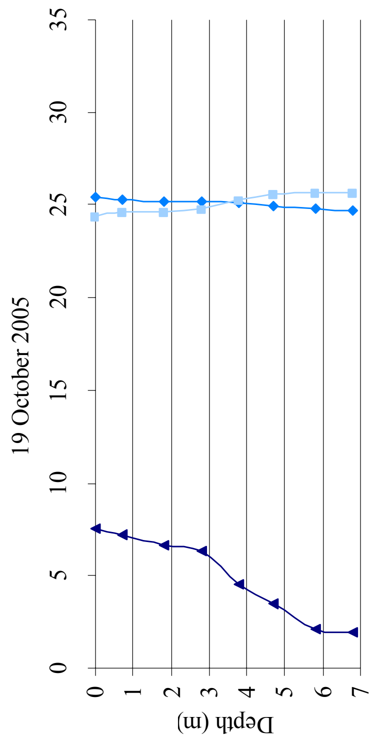
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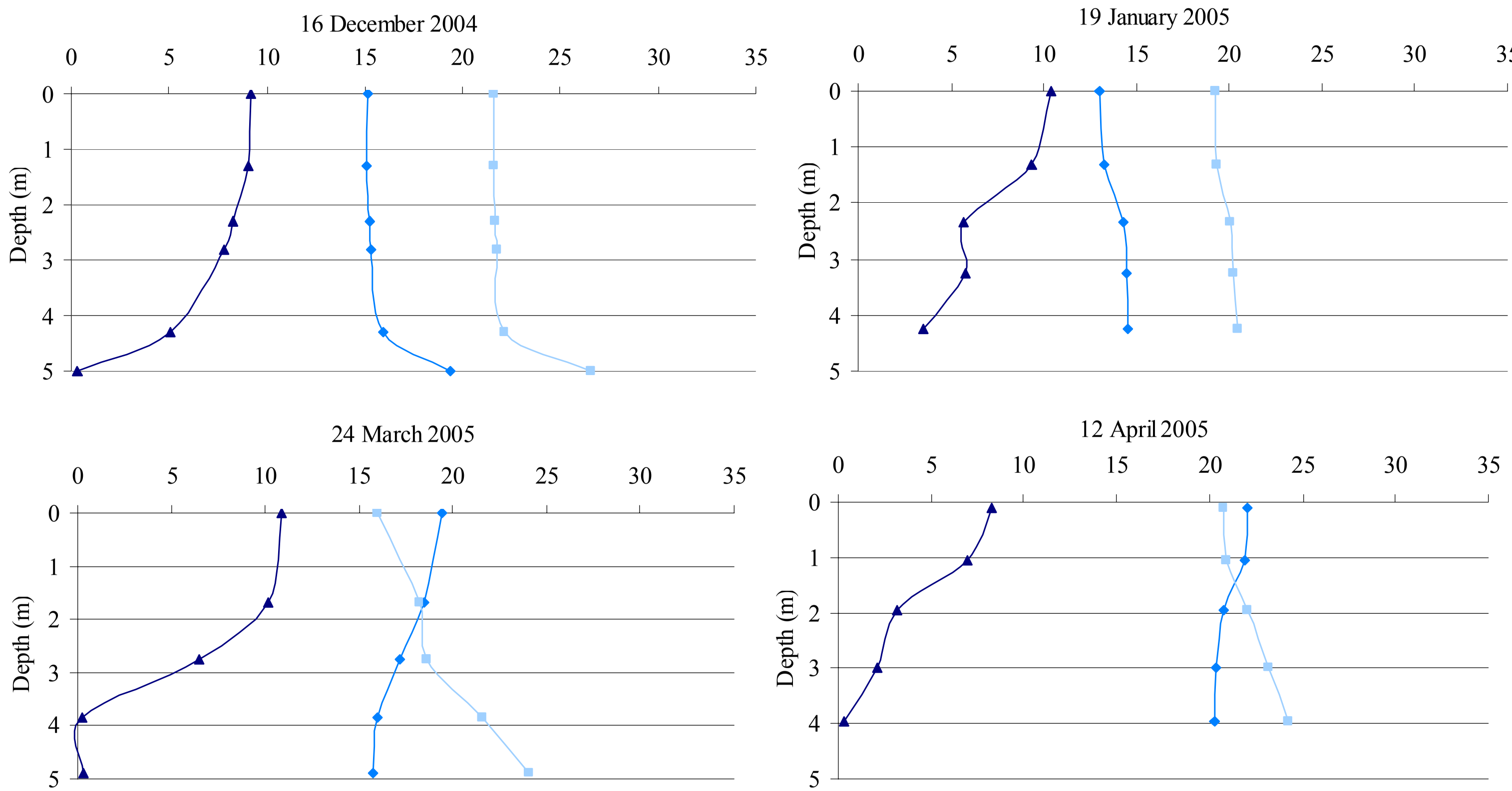
Station 7:



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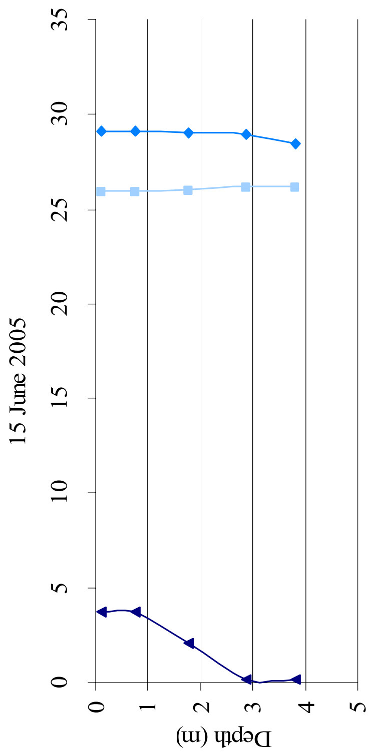
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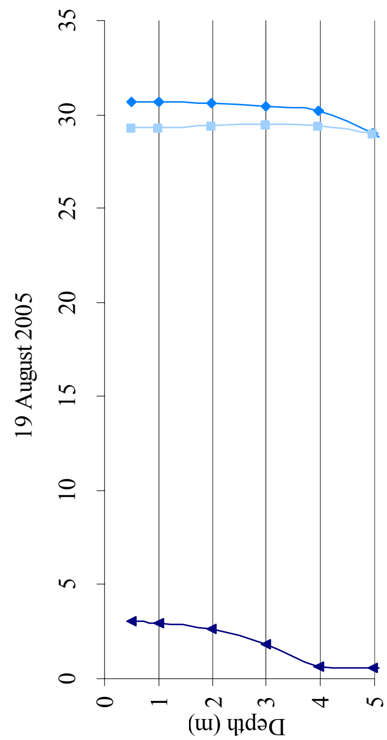
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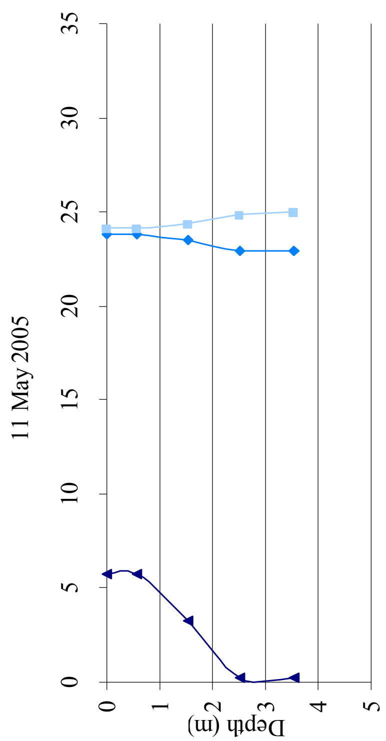
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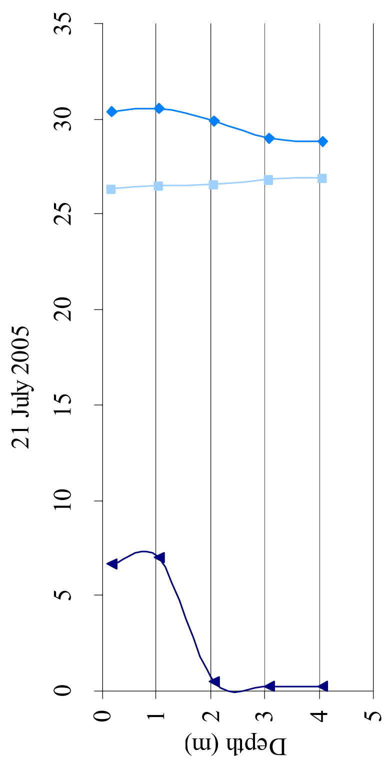
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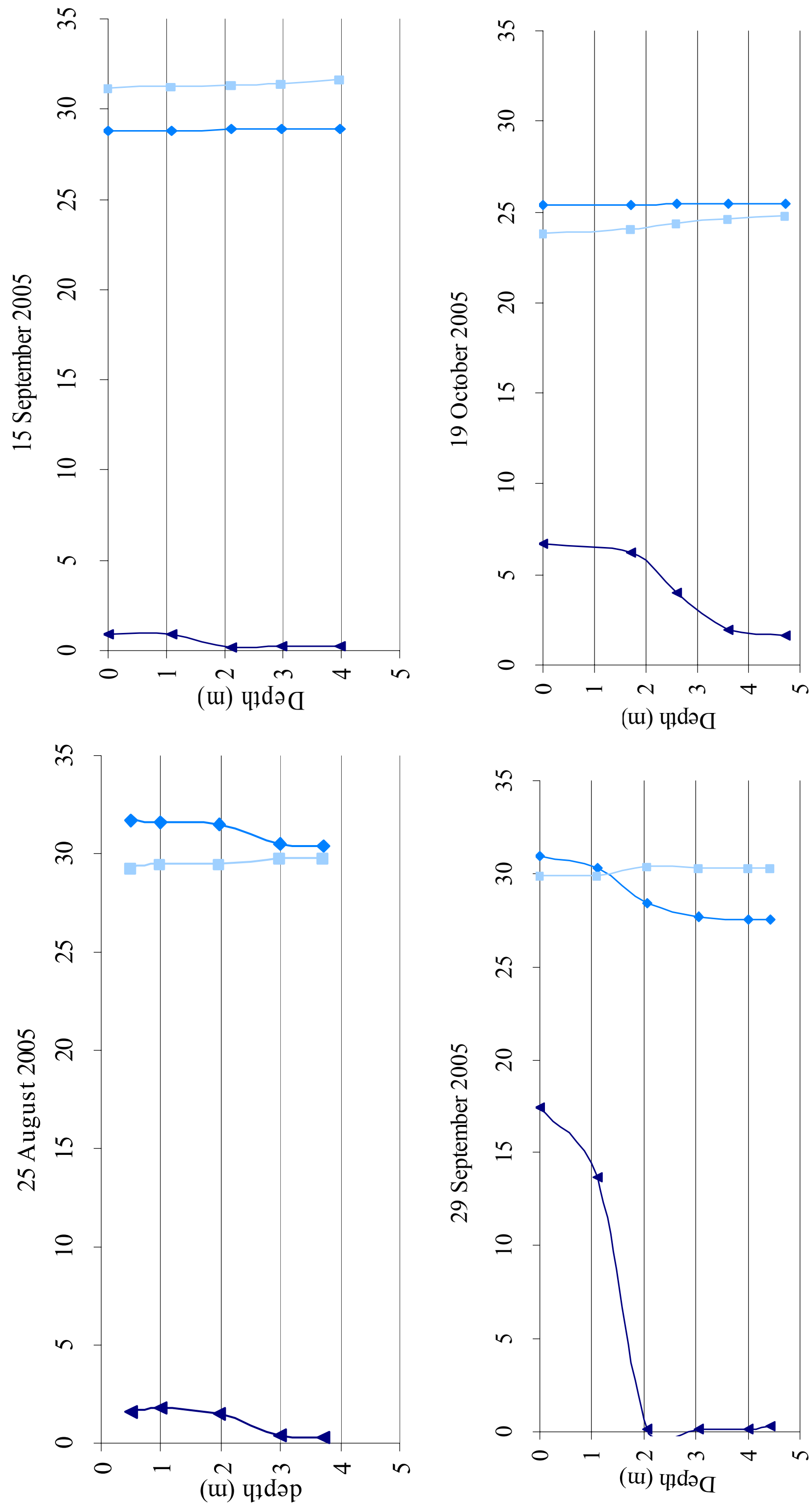
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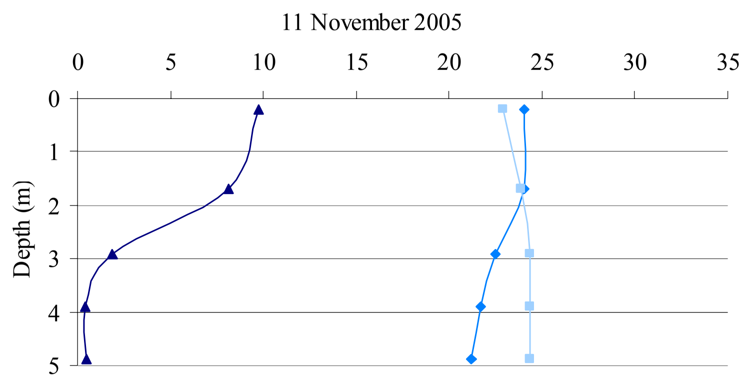
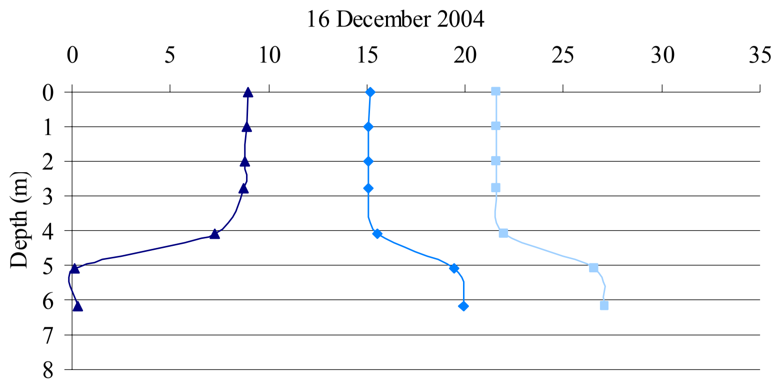
29 September 2005
Depth (m)



Note: data missing for 18 February 2005 due to inclement weather

Station 8: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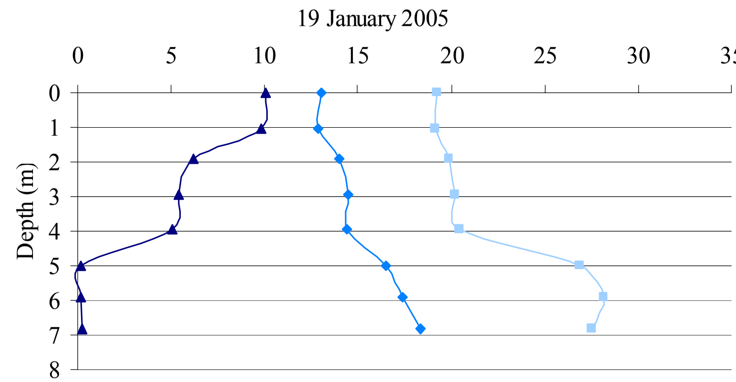
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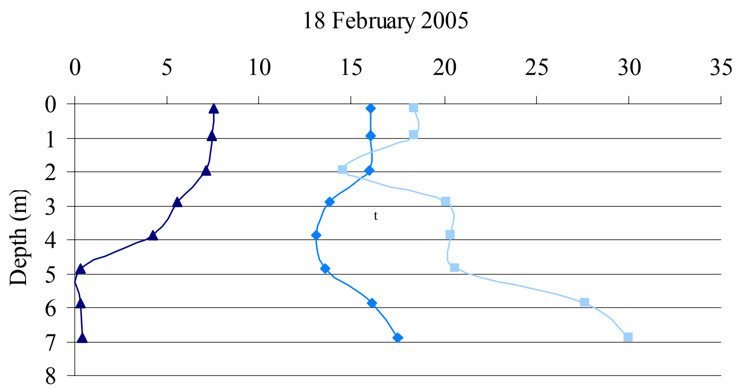
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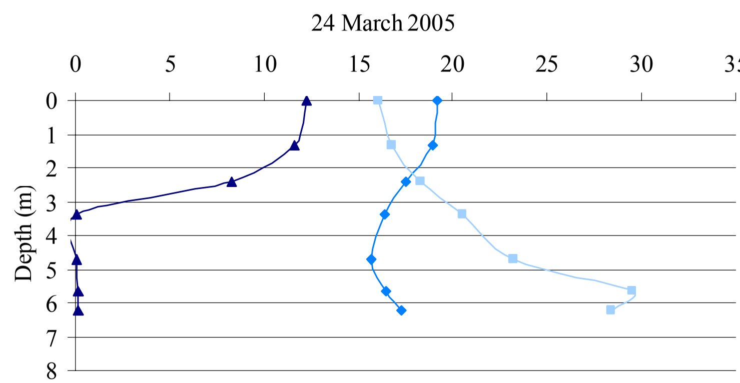
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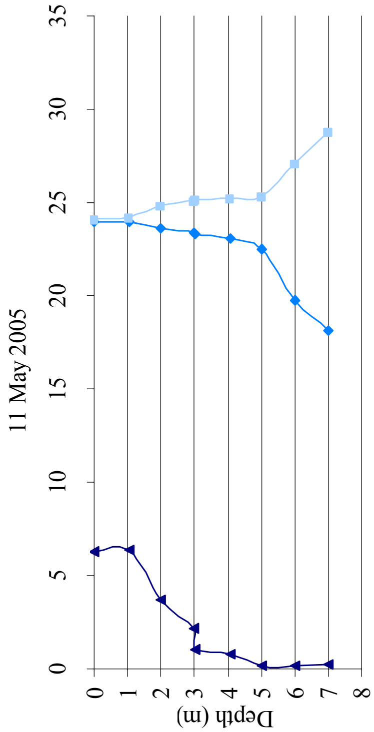
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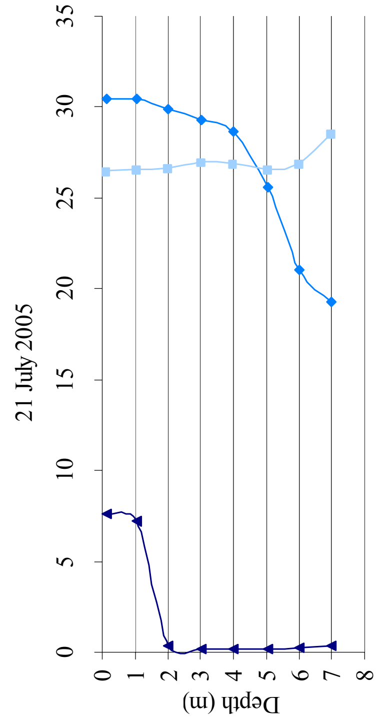
Depth (m)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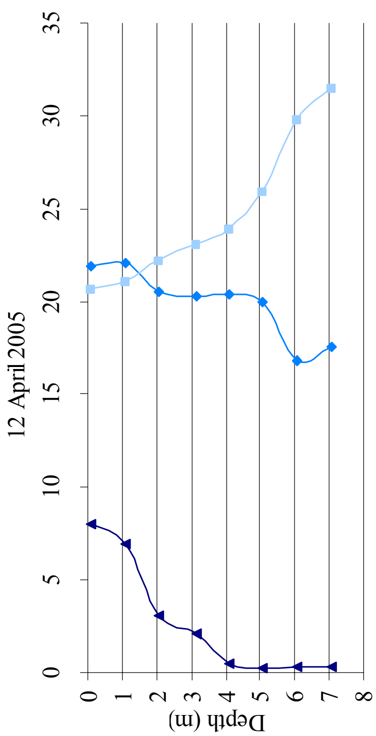
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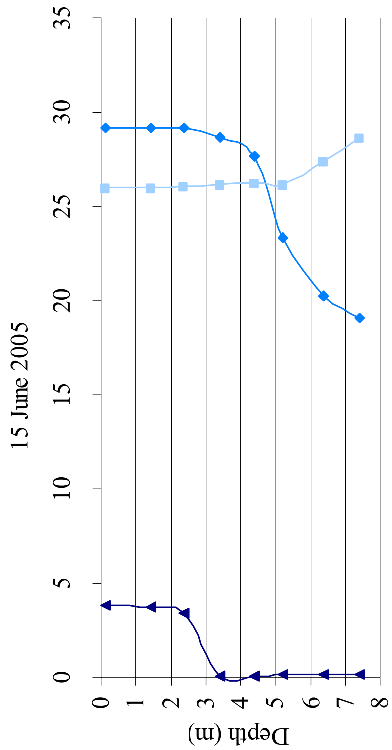
Depth (m)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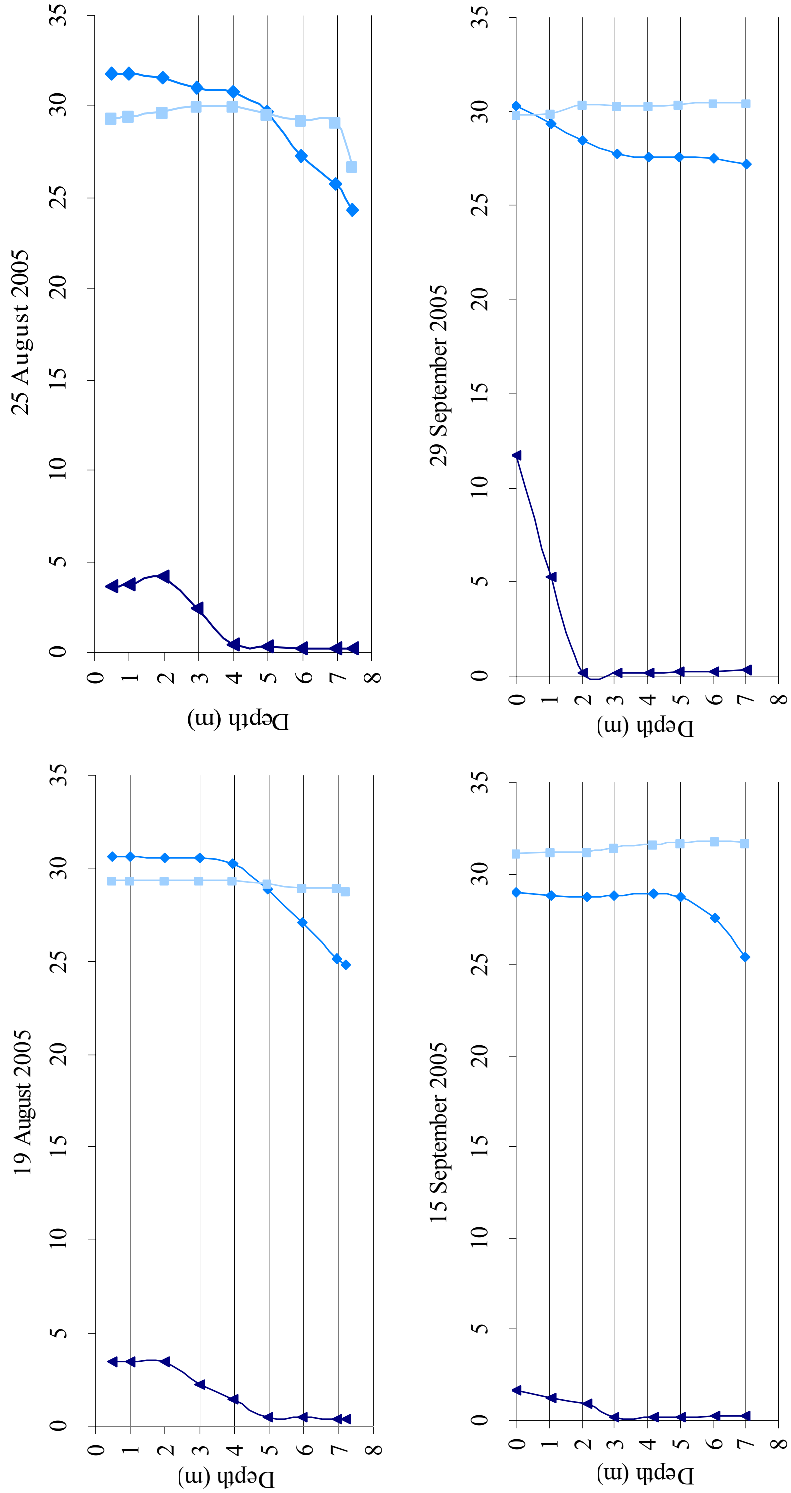
Depth (m)



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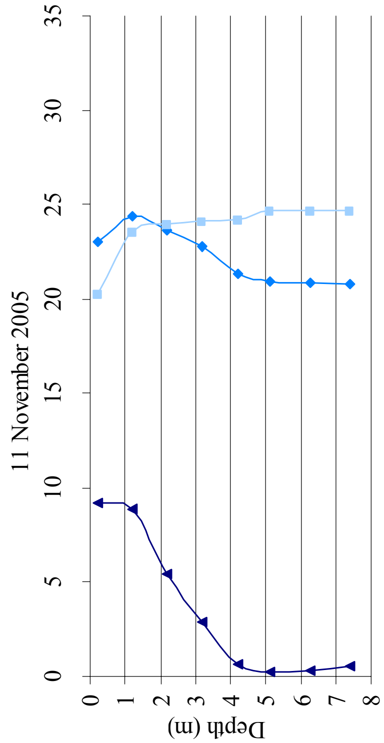
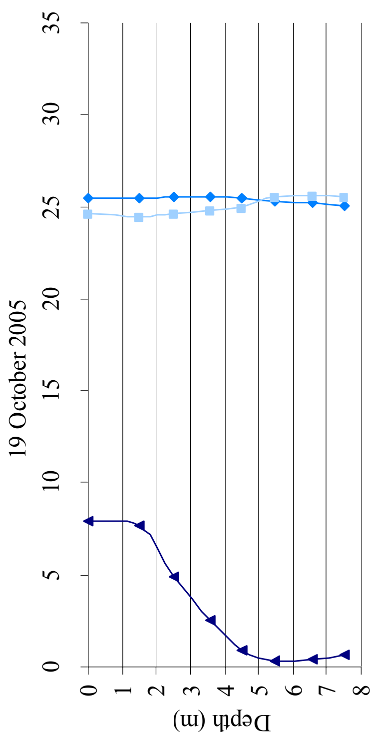
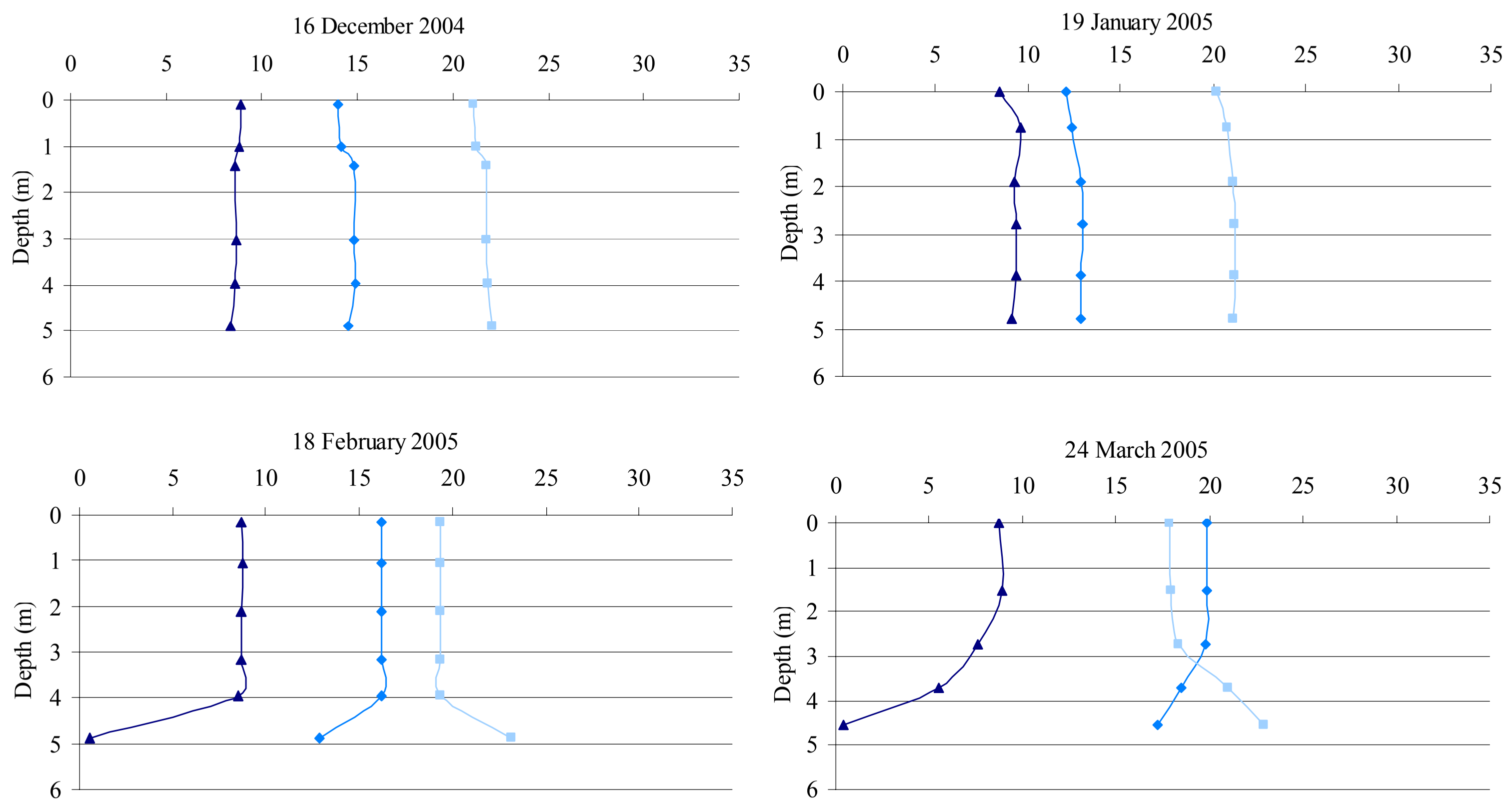
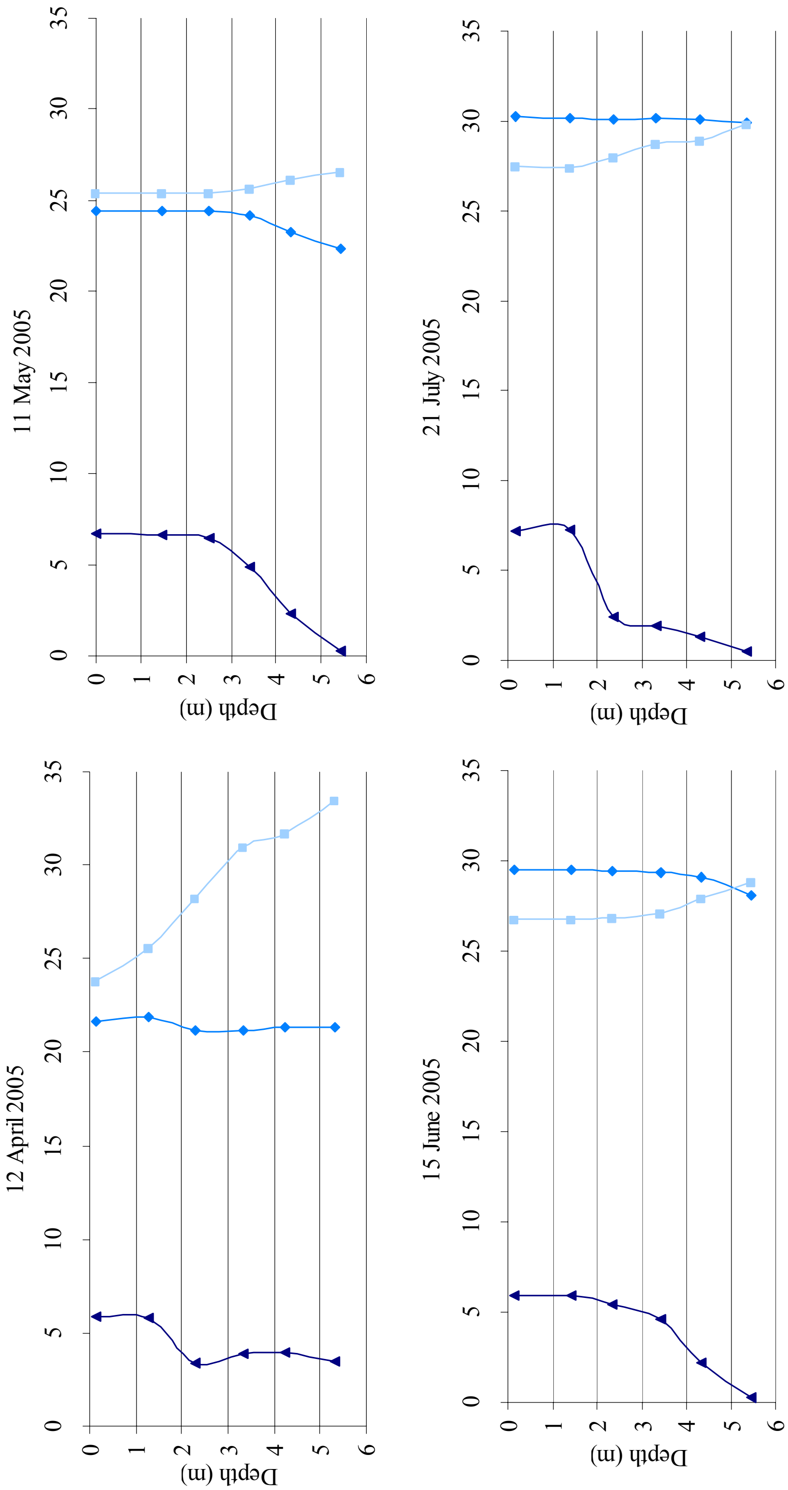
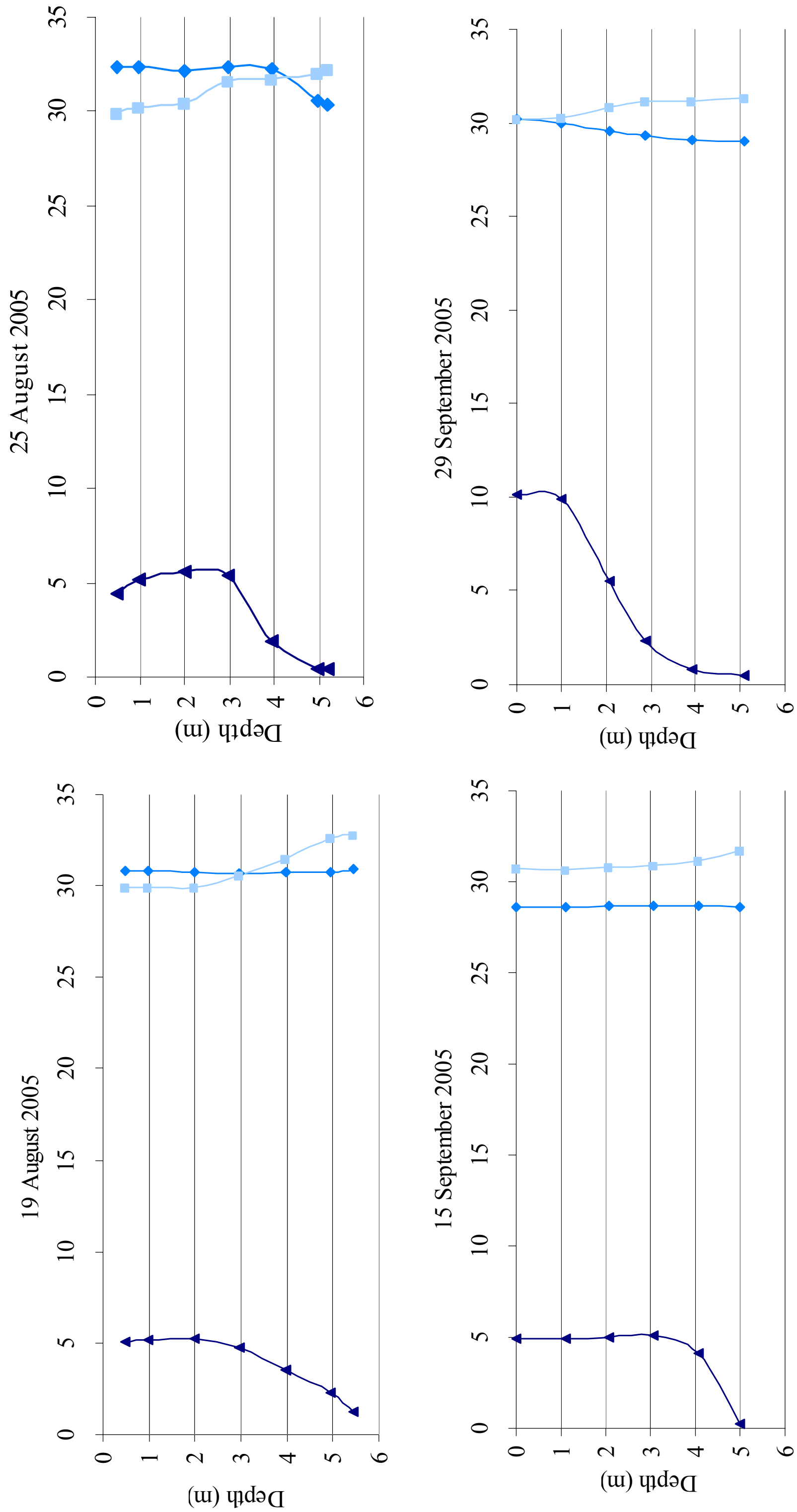

11 November 2005
Depth (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8

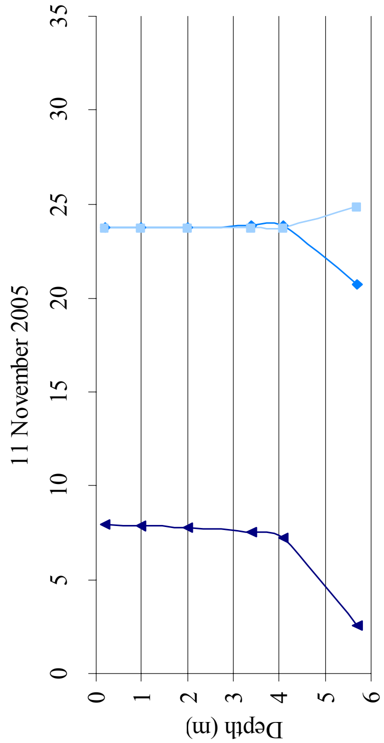

19 October 2005
Depth (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6
7
8

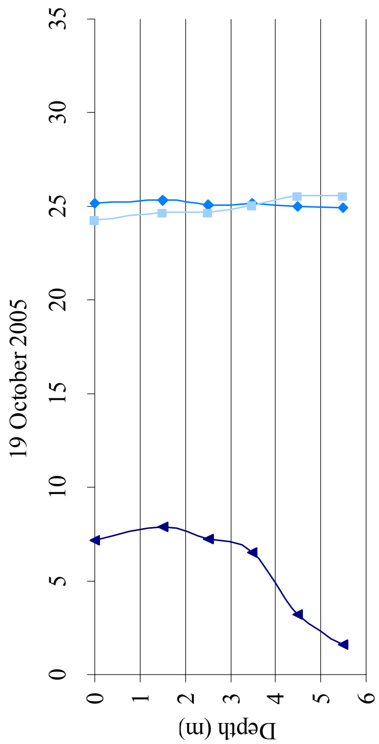
Station 9:


16 December 2004
19 January 2005
18 February 2005
24 March 2005
Depth (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6

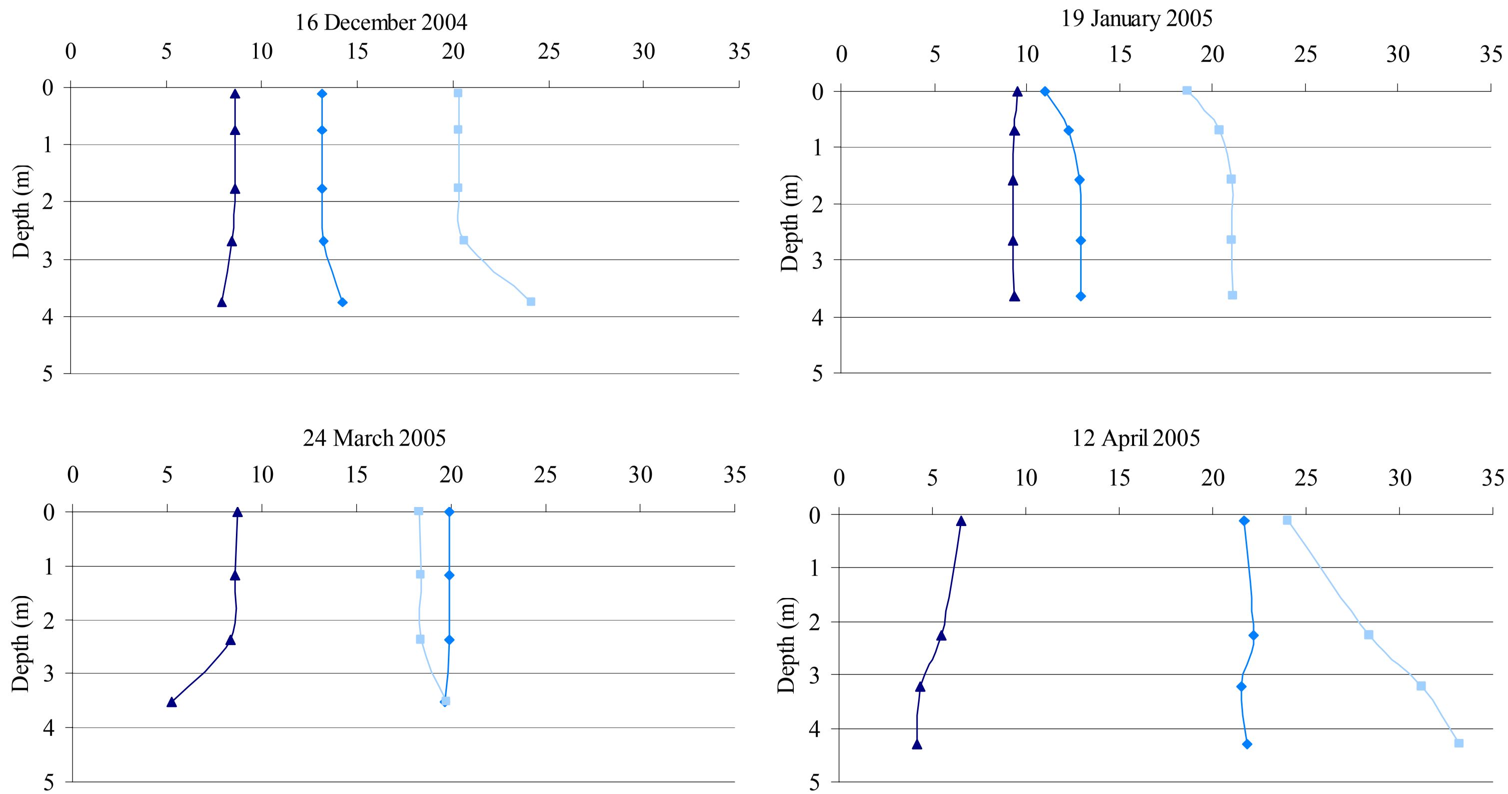

11 May 2005
21 July 2005
12 April 2005
15 June 2005
Depth (m)
Depth (m)
Depth (m)
Depth (m)

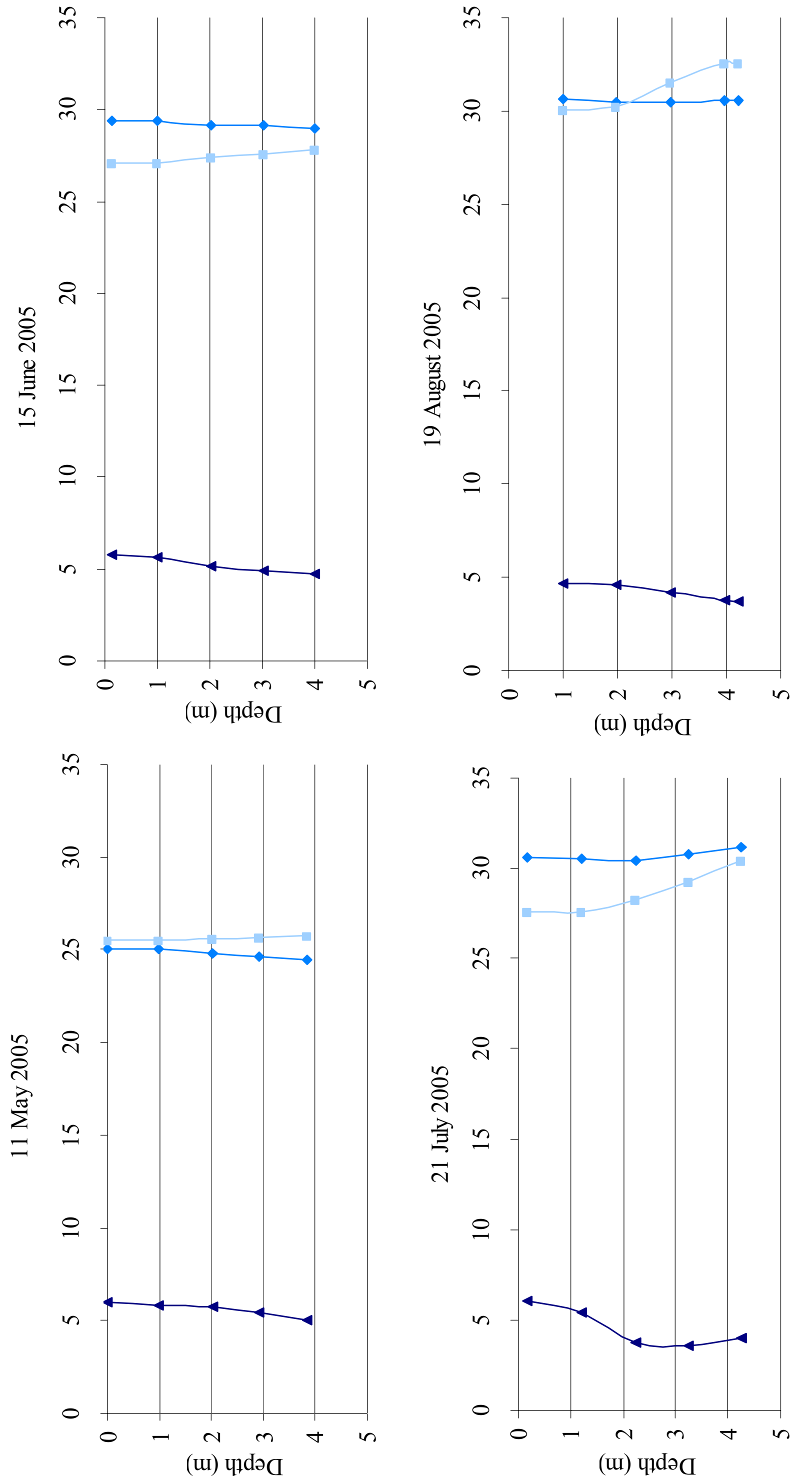

25 August 2005
29 September 2005
19 August 2005
15 September 2005
Depth (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5
6

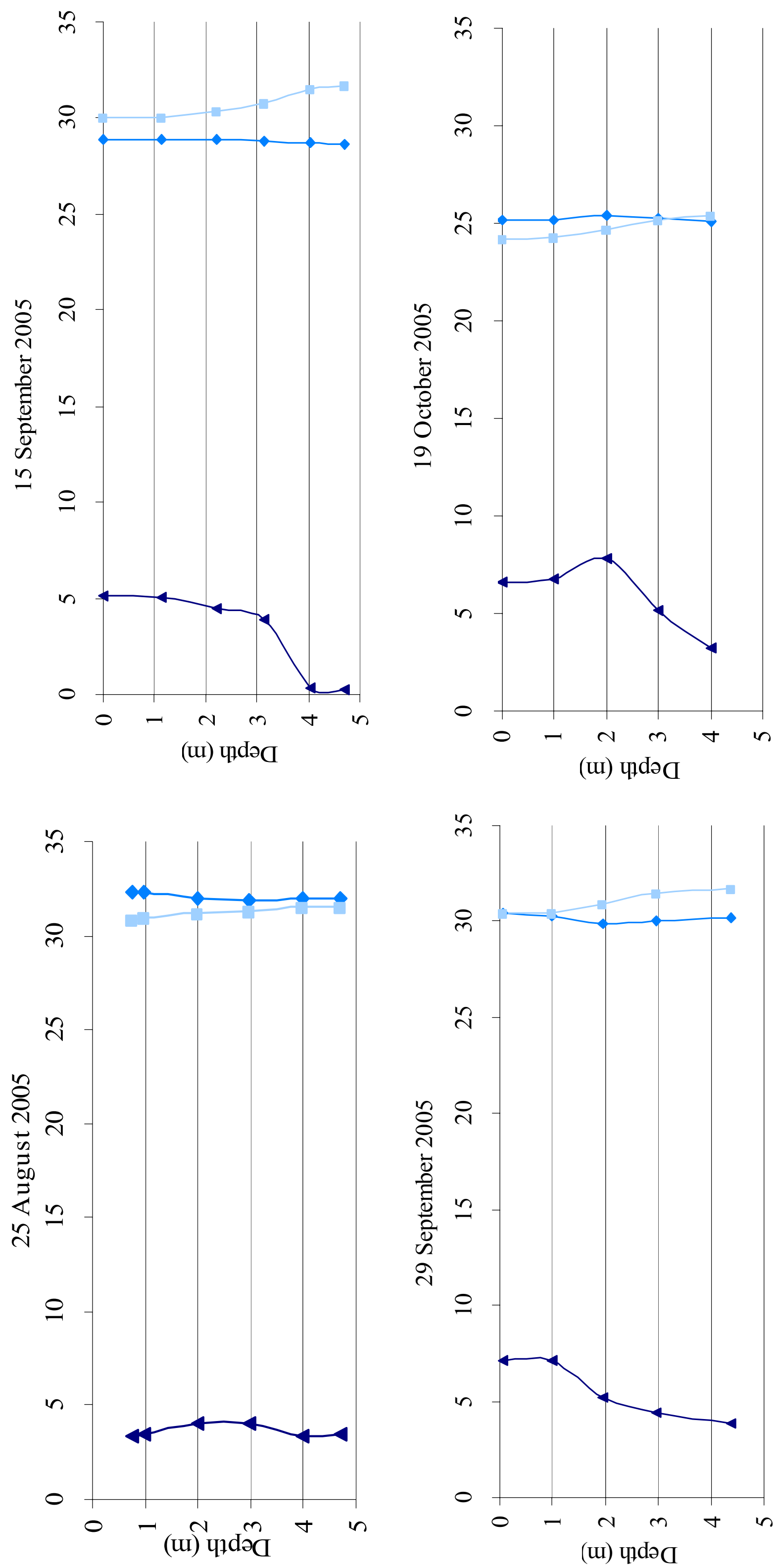

11 November 2005
Depth (m)
0 5 10 15 20 25 30 35
0 1 2 3 4 5 6


19 October 2005
Depth (m)
0 5 10 15 20 25 30 35
0 1 2 3 4 5 6

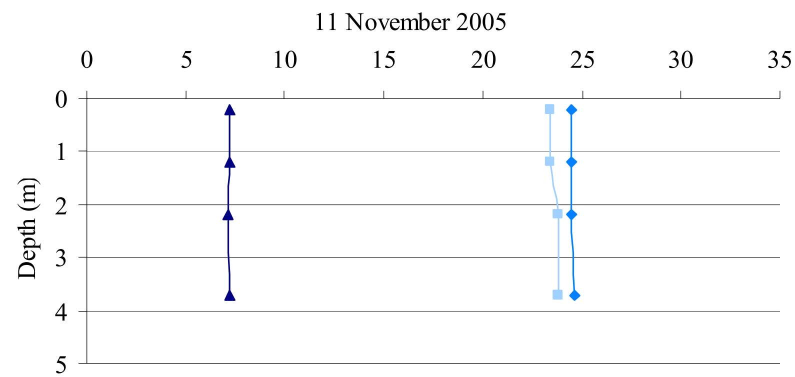
Station 10:


16 December 2004
19 January 2005
24 March 2005
12 April 2005
Depth (m)
0
5
10
15
20
25
30
35
0
1
2
3
4
5


15 June 2005
19 August 2005
11 May 2005
21 July 2005
Depth (m)
0 5 10 15 20 25 30 35
0 1 2 3 4 5

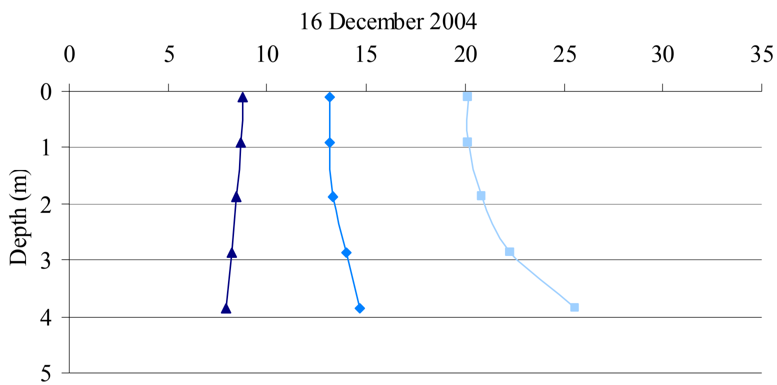


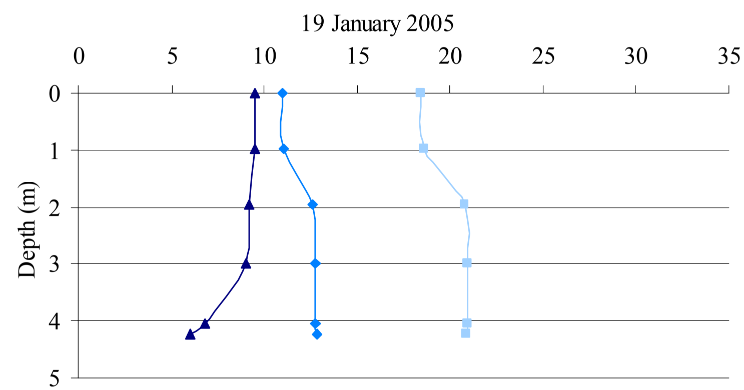
15 September 2005
19 October 2005
25 August 2005
29 September 2005
Depth (m)



Note: data missing for 18 February 2005 due to inclement weather

Station 11:


16 December 2004
0
5
10
15
20
25
30
35
Depth (m)
0
1
2
3
4
5


19 January 2005
0
5
10
15
20
25
30
35
Depth (m)
0
1
2
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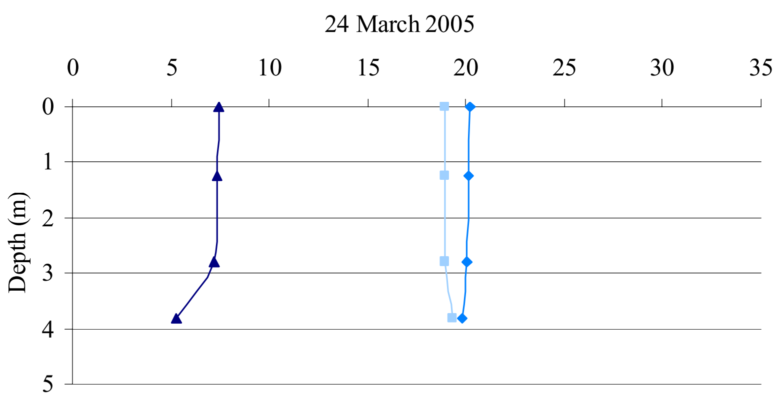
4
5


24 March 2005
0
5
10
15
20
25
30
35
Depth (m)
0
1
2
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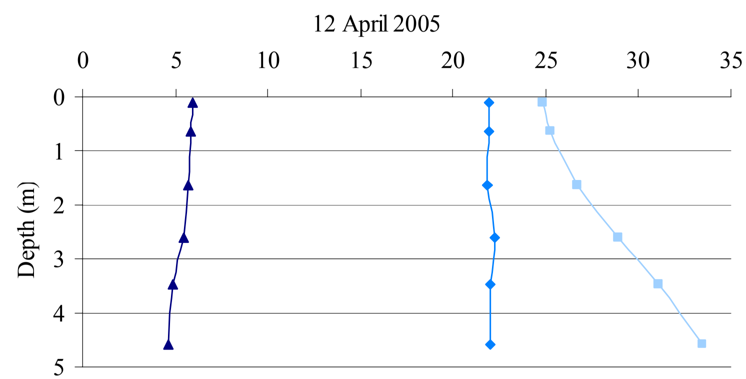
4
5


12 April 2005
0
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35
Depth (m)
0
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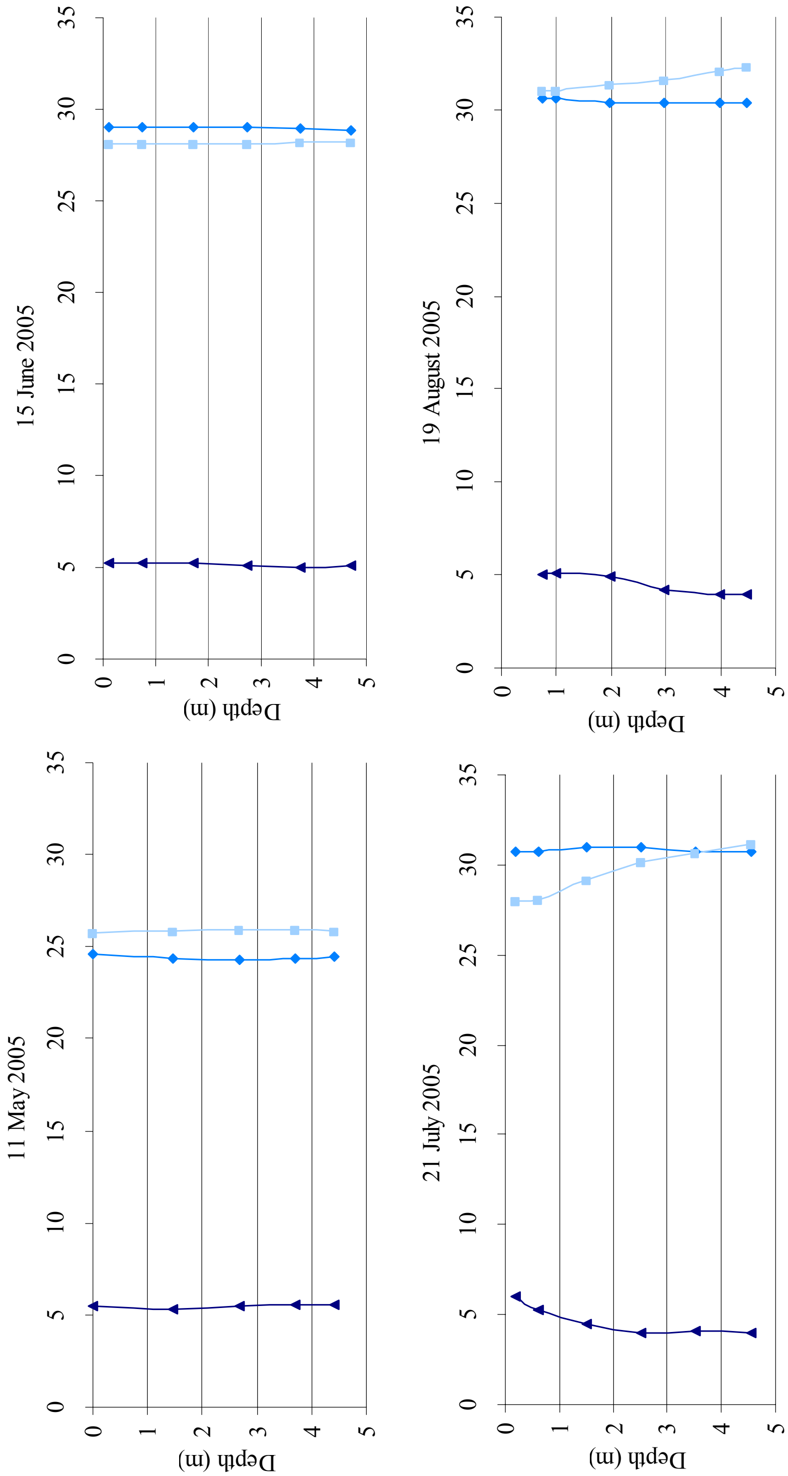
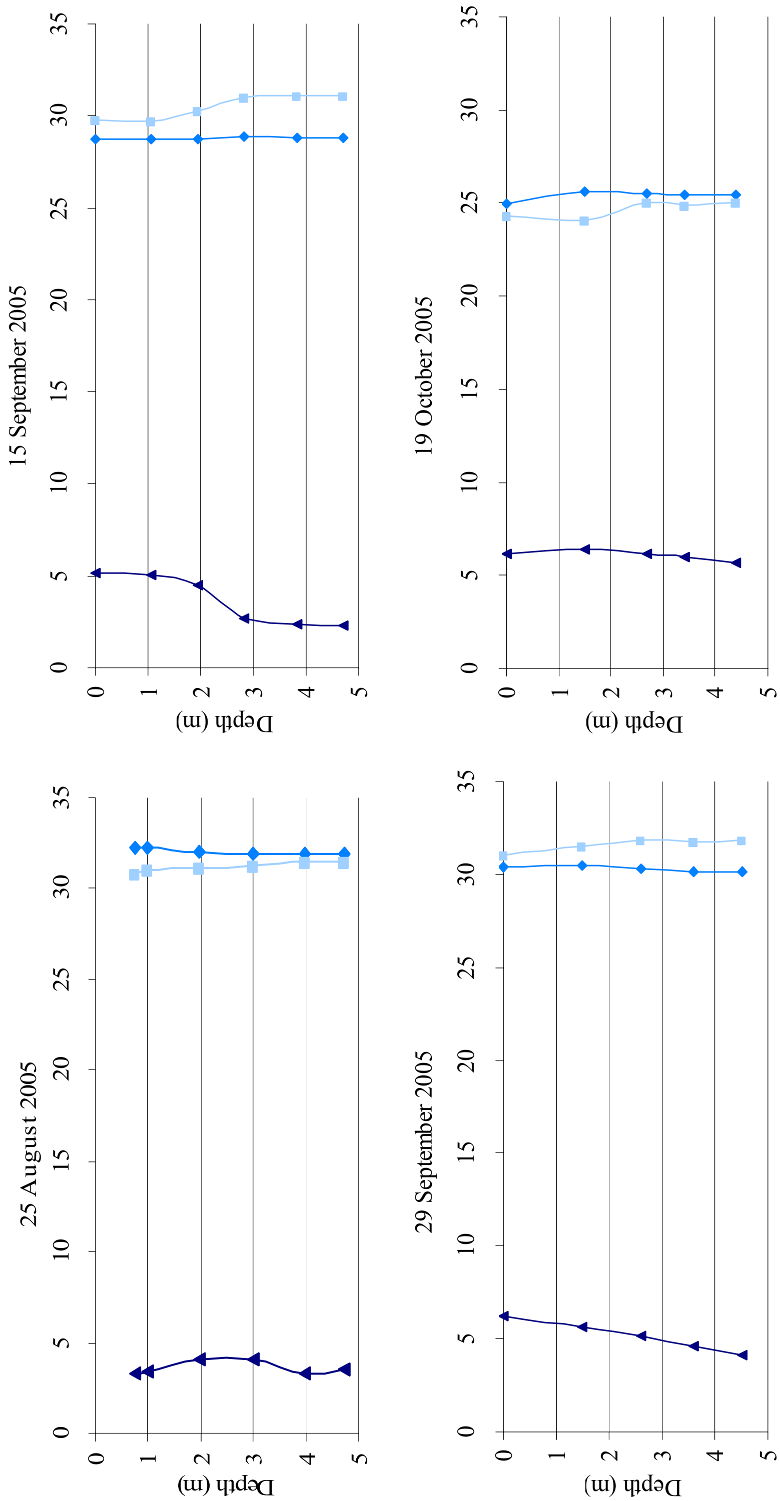

15 June 2005
19 August 2005
11 May 2005
21 July 2005
Depth (m)


15 September 2005
19 October 2005
25 August 2005
29 September 2005
Depth (m)
Depth (m)
Depth (m)
Depth (m)
0
5
10
15
20
25
30
35
0
1
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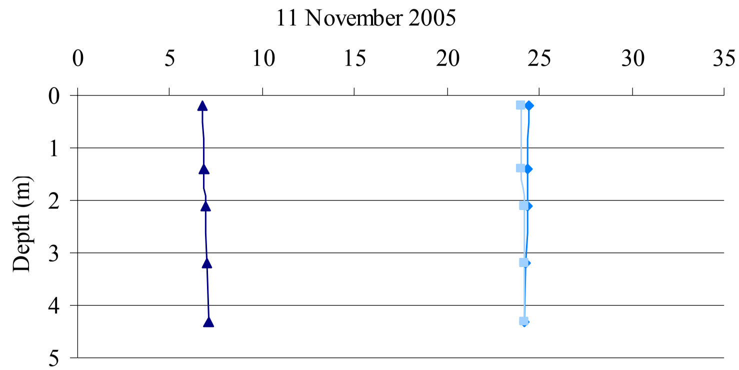
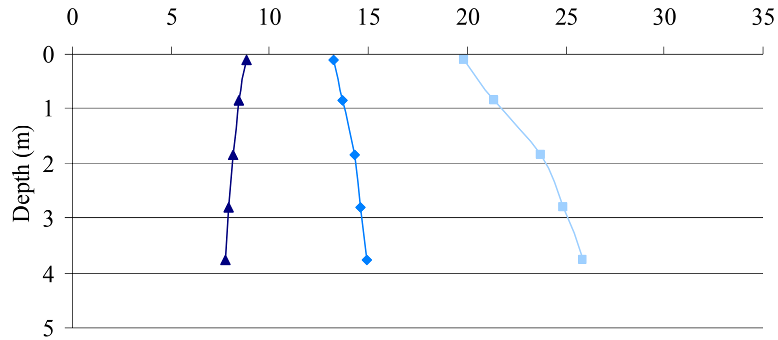
3
4
5



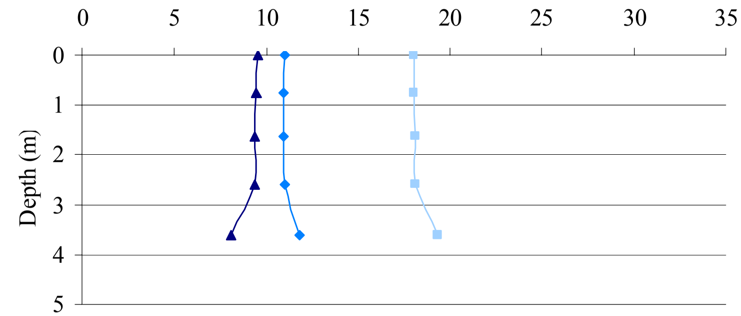
Note: data missing for 18 February 2005 due to inclement weather

Station 12:

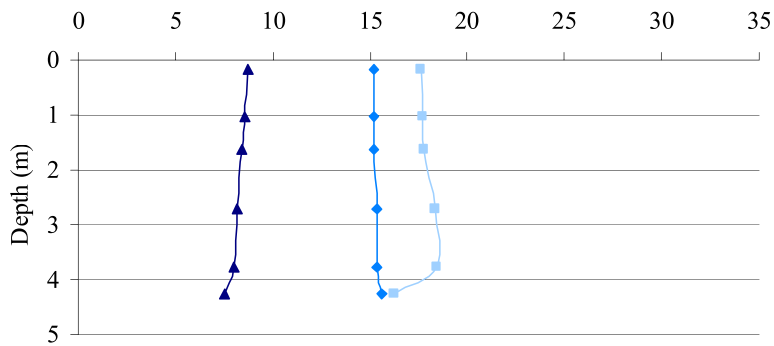
16 December 2004



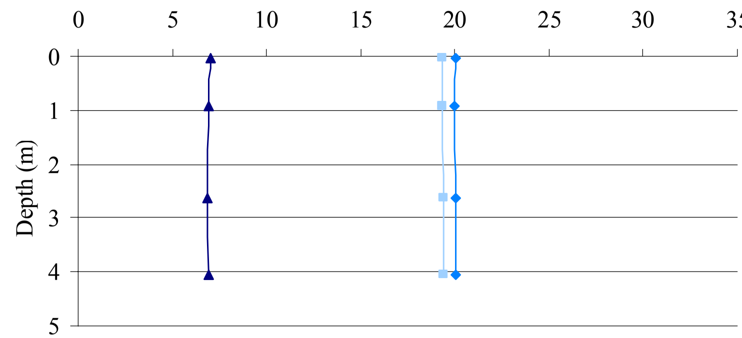
19 January 2005

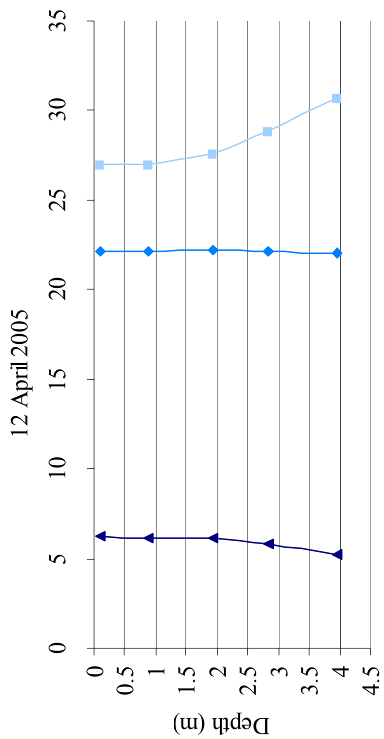


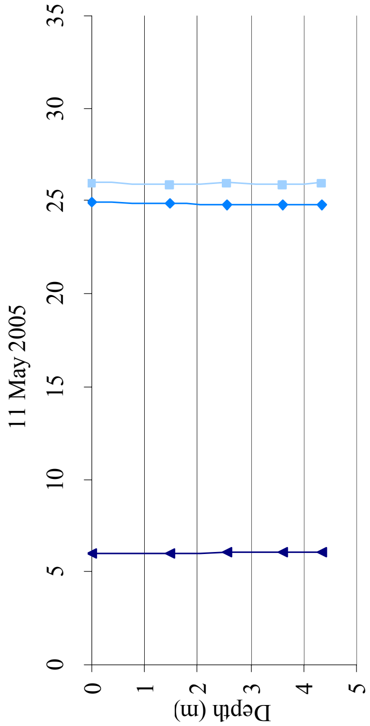
18 February 2005

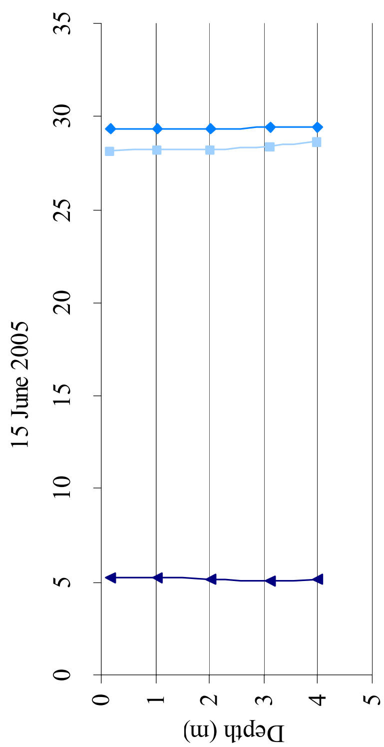


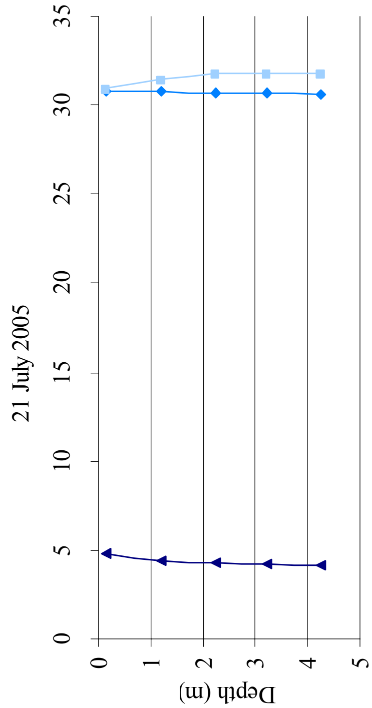
24 March 2005

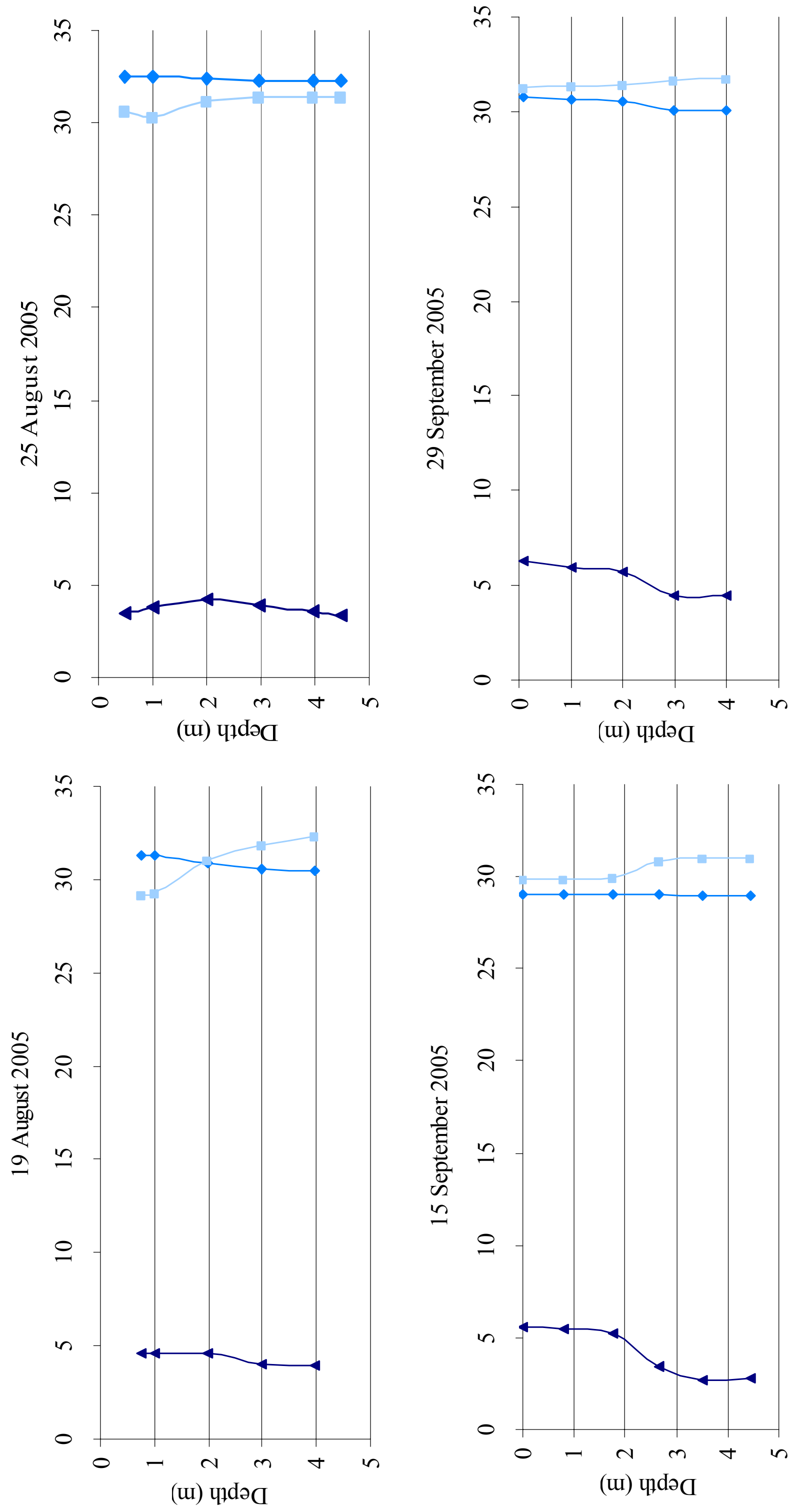


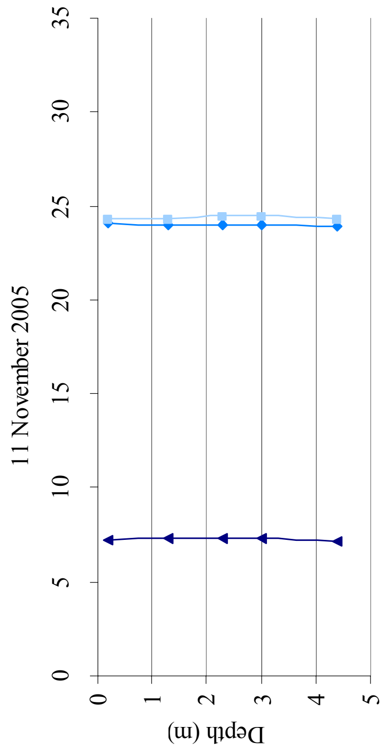

12 April 2005
Depth (m)


11 May 2005
Depth (m)


15 June 2005
Depth (m)


21 July 2005
Depth (m)


25 August 2005
29 September 2005
19 August 2005
15 September 2005
Depth (m)
Depth (m)
Depth (m)
Depth (m)
0 5 10 15 20 25 30 35
0 1 2 3 4 5


11 November 2005
Depth (m)
0
1
2
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4
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0
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10
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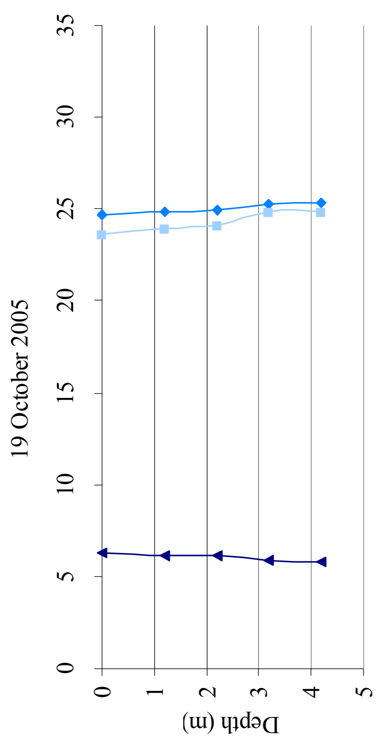
35


19 October 2005
Depth (m)
0
1
2
3
4
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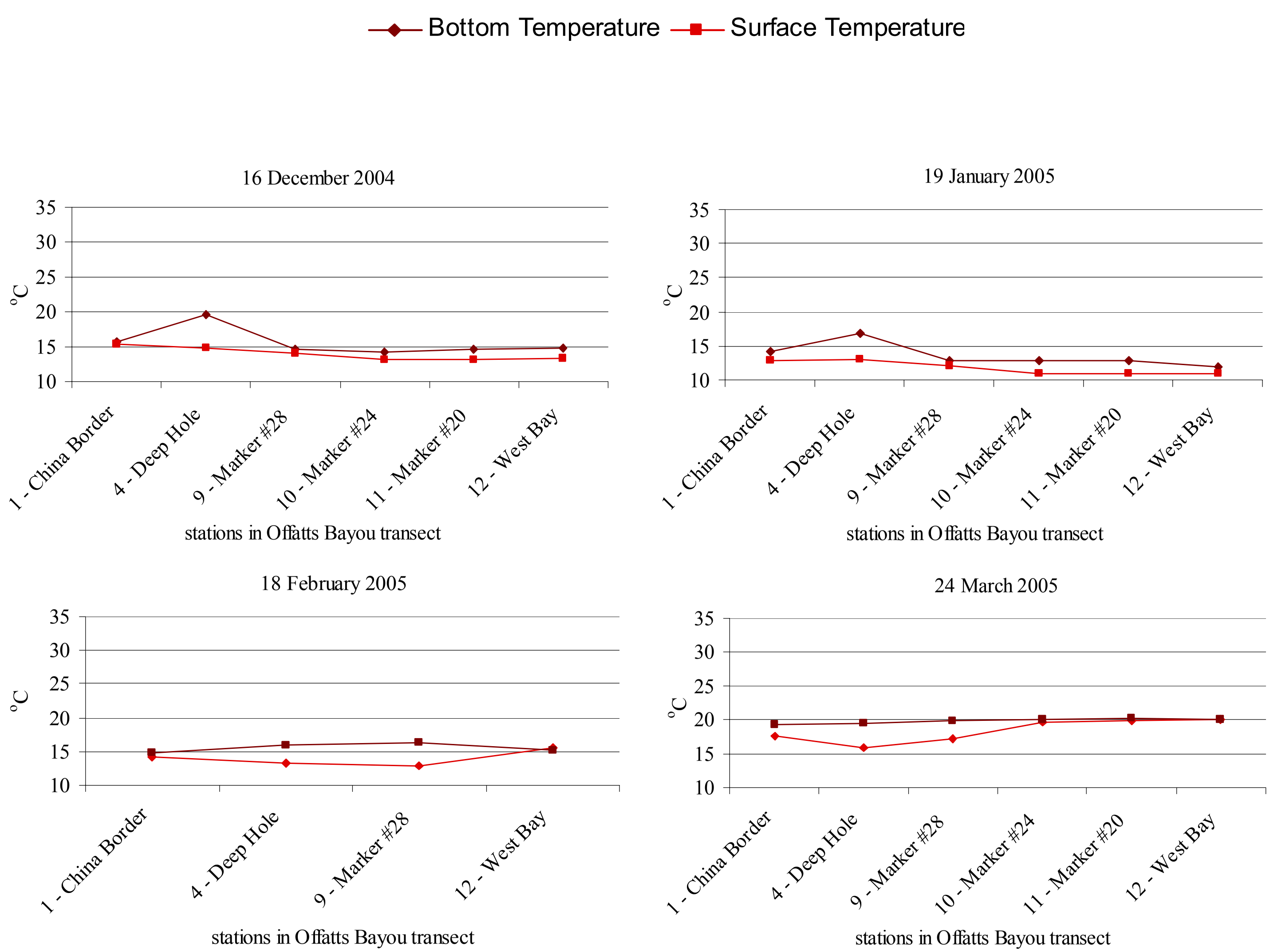
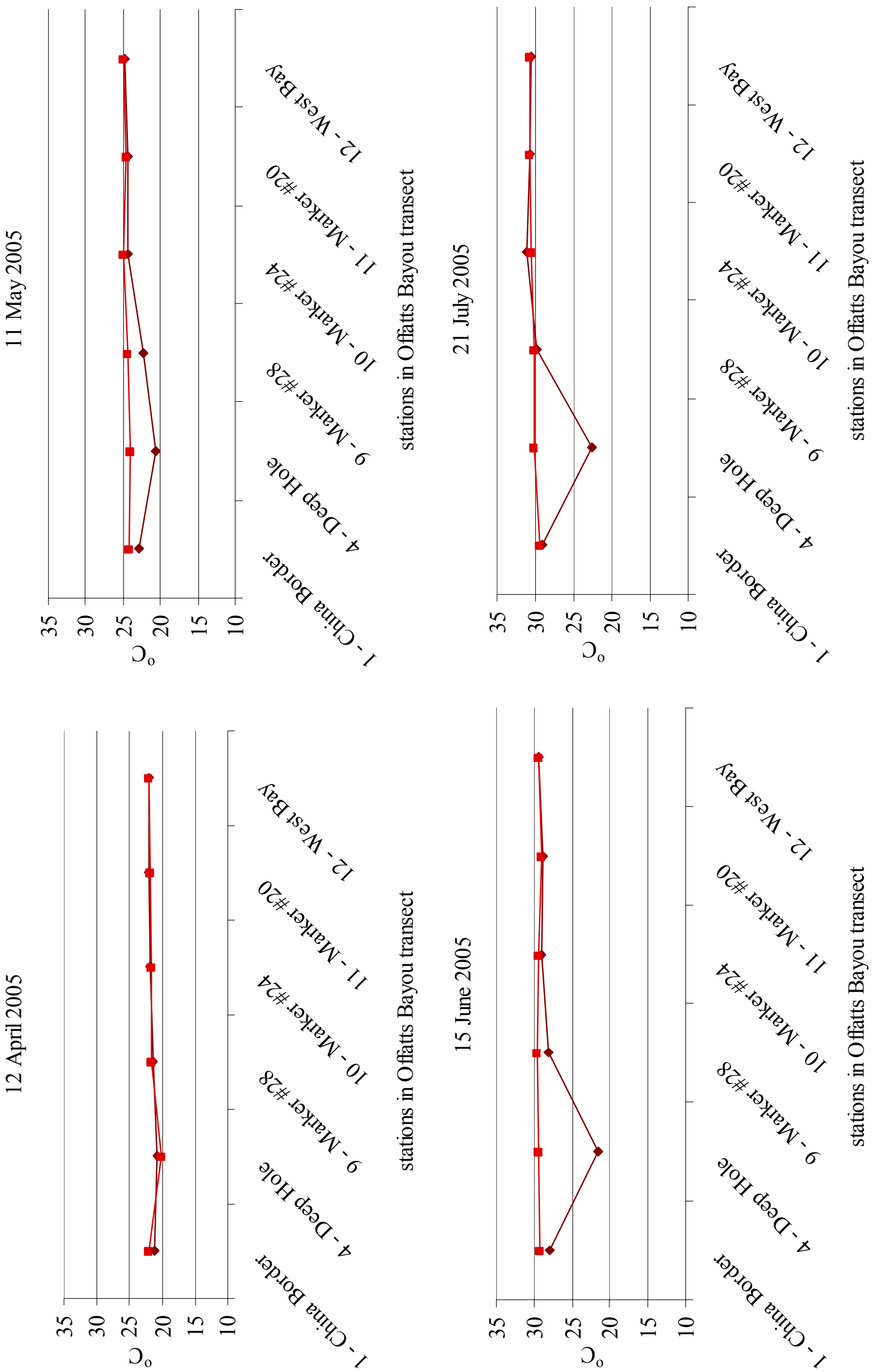
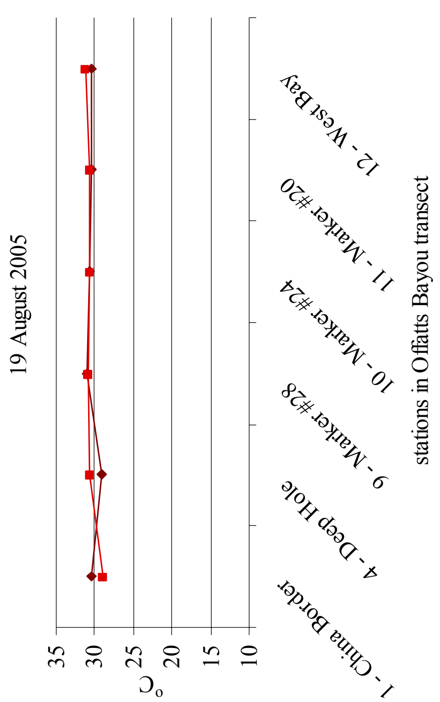
35

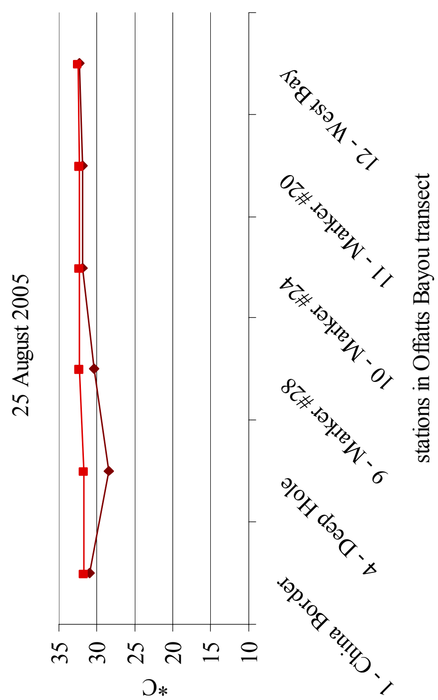
Surface Temperature vs. Bottom Temperature Data

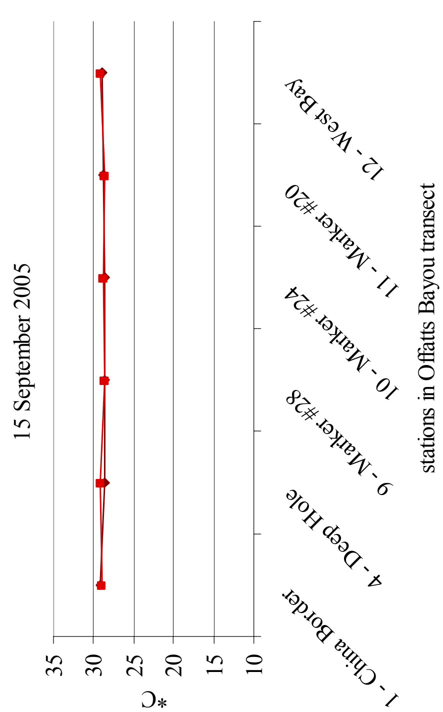




12 April 2005
11 May 2005
15 June 2005
21 July 2005
°C
35
30
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


19 August 2005
°C
35
30
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


25 August 2005
*C
35
30
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


15 September 2005
*C
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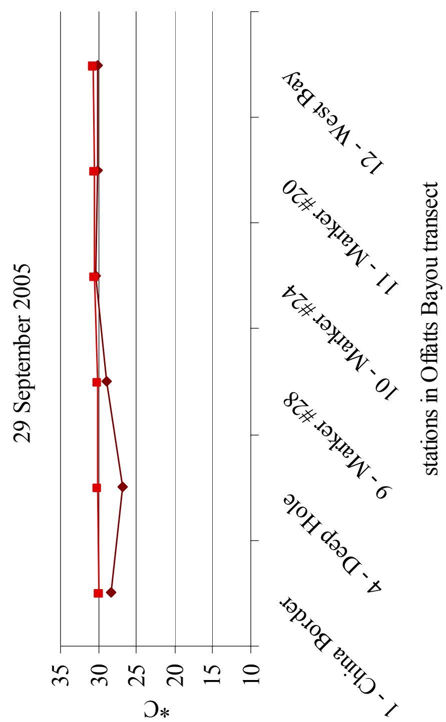
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


29 September 2005
*C
35
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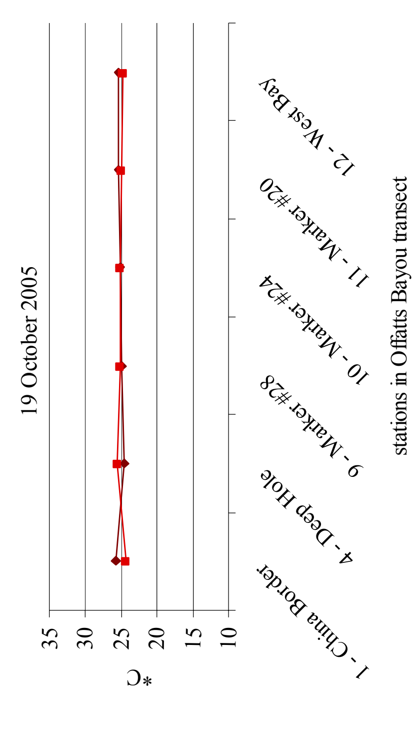
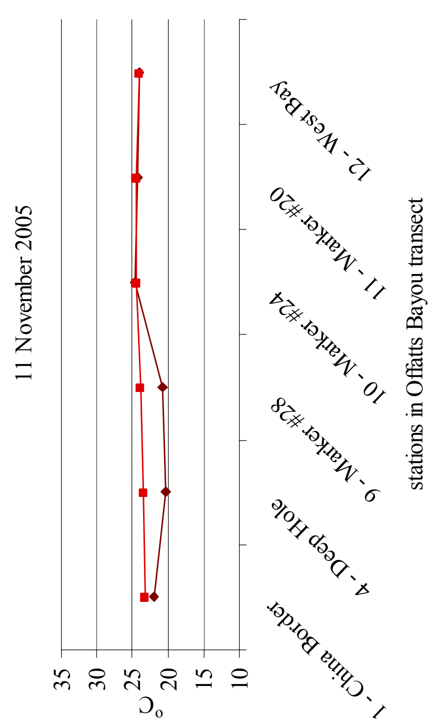
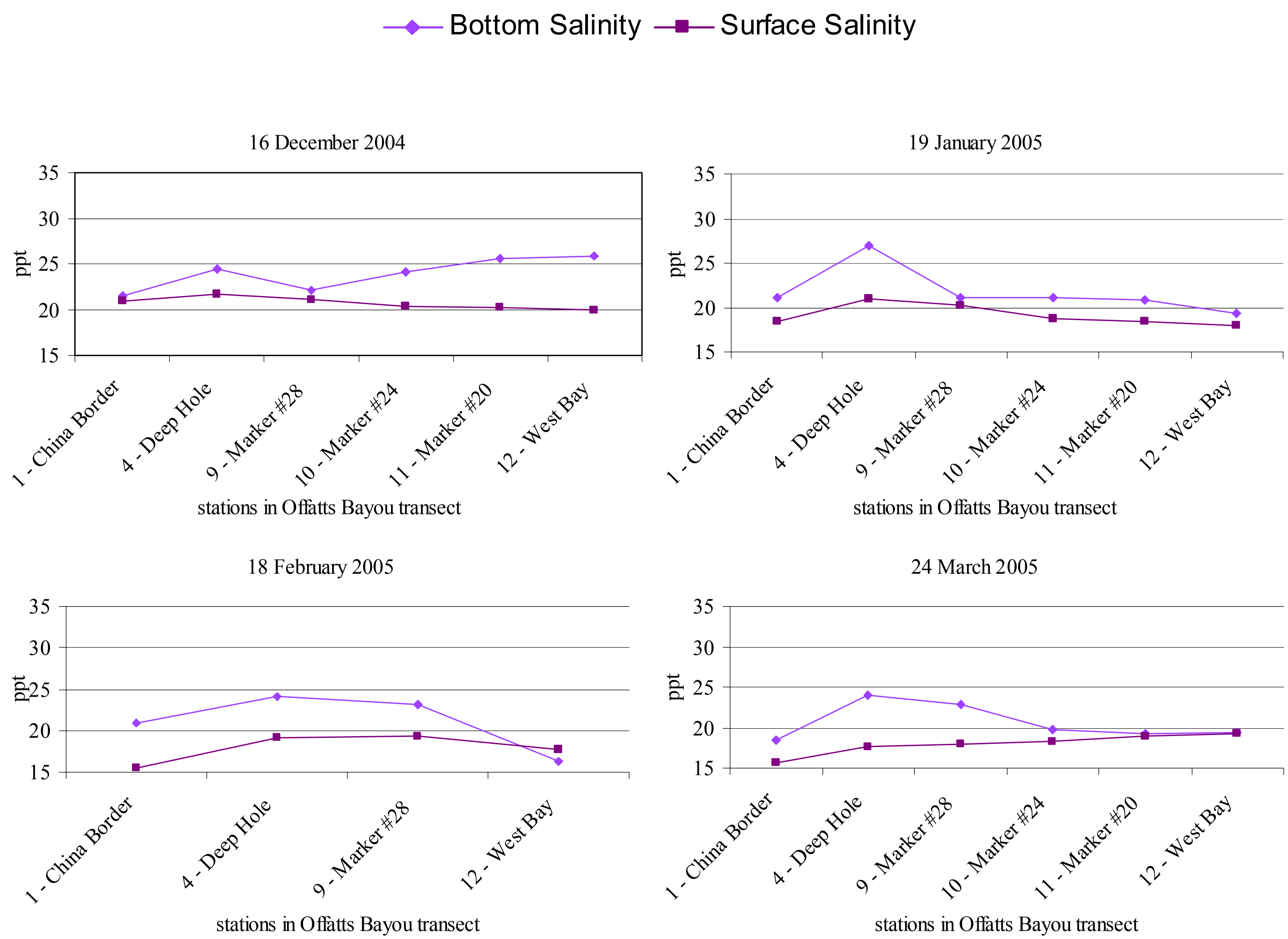
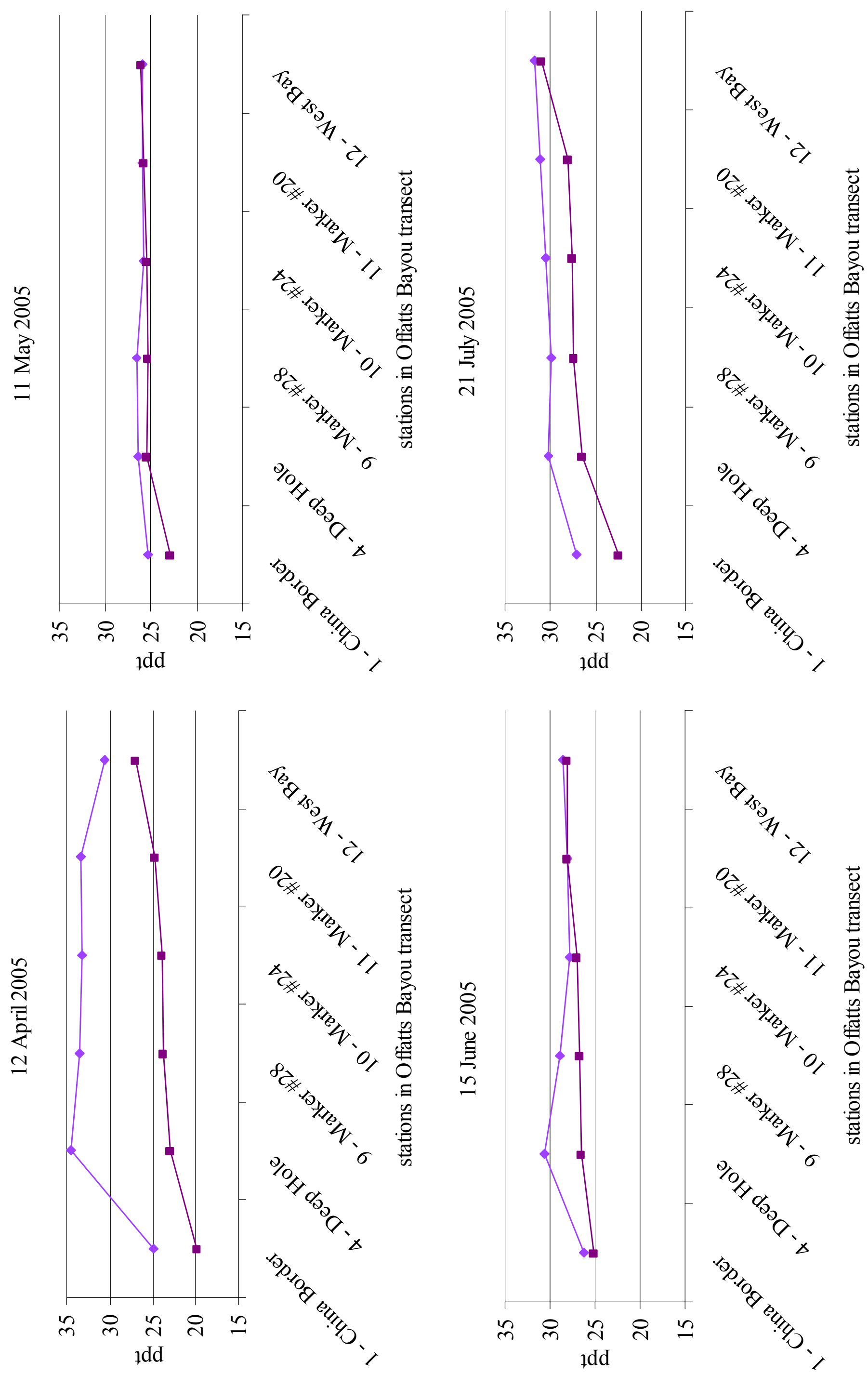
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


19 October 2005
*C
35
30
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

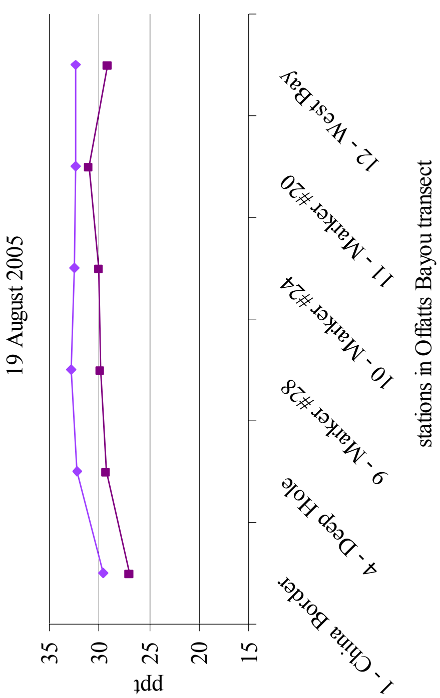

11 November 2005
°C
35
30
25
20
15
10
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

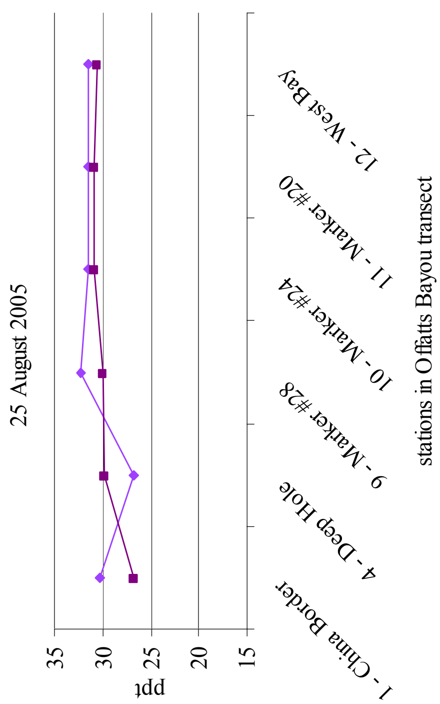
Surface Salinity vs. Bottom Salinity Data

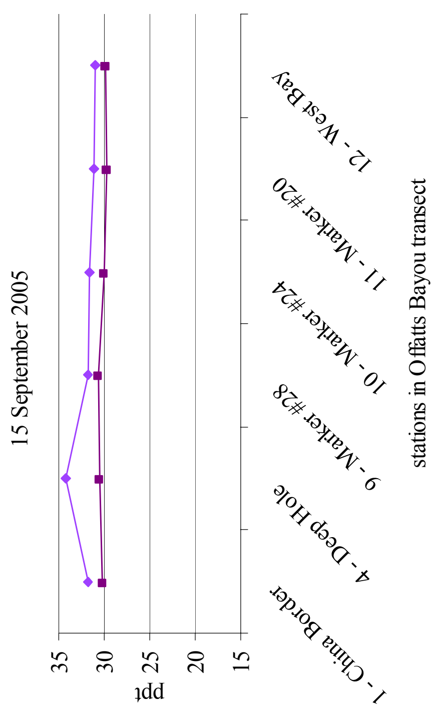


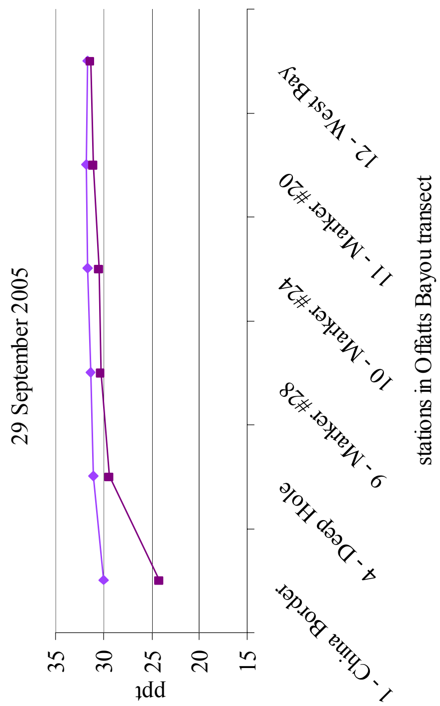


12 April 2005
11 May 2005
15 June 2005
21 July 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


19 August 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


25 August 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


15 September 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


29 September 2005
ppt
35
30
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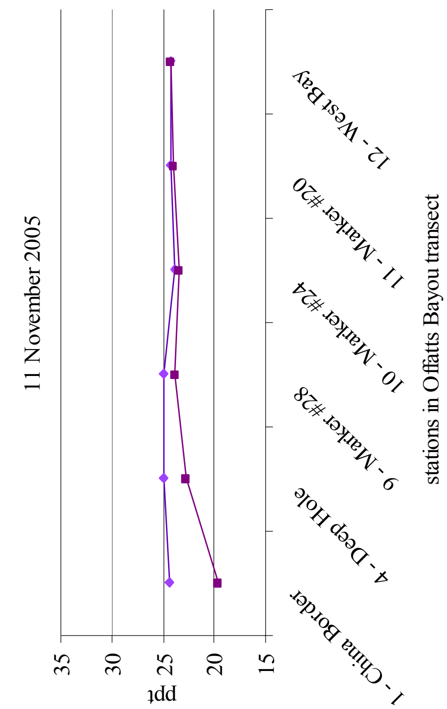
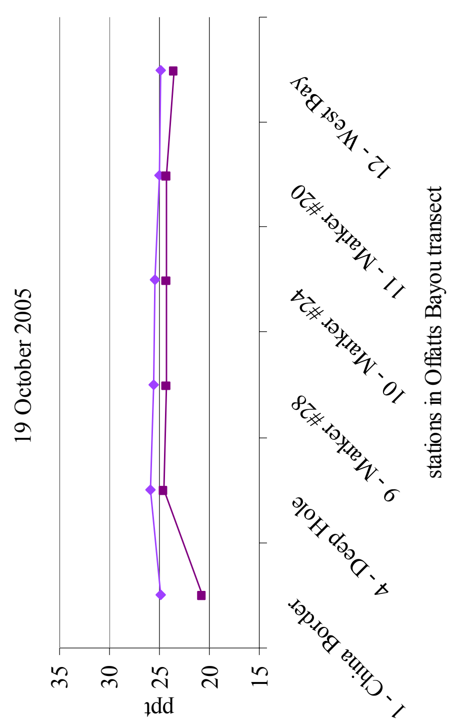
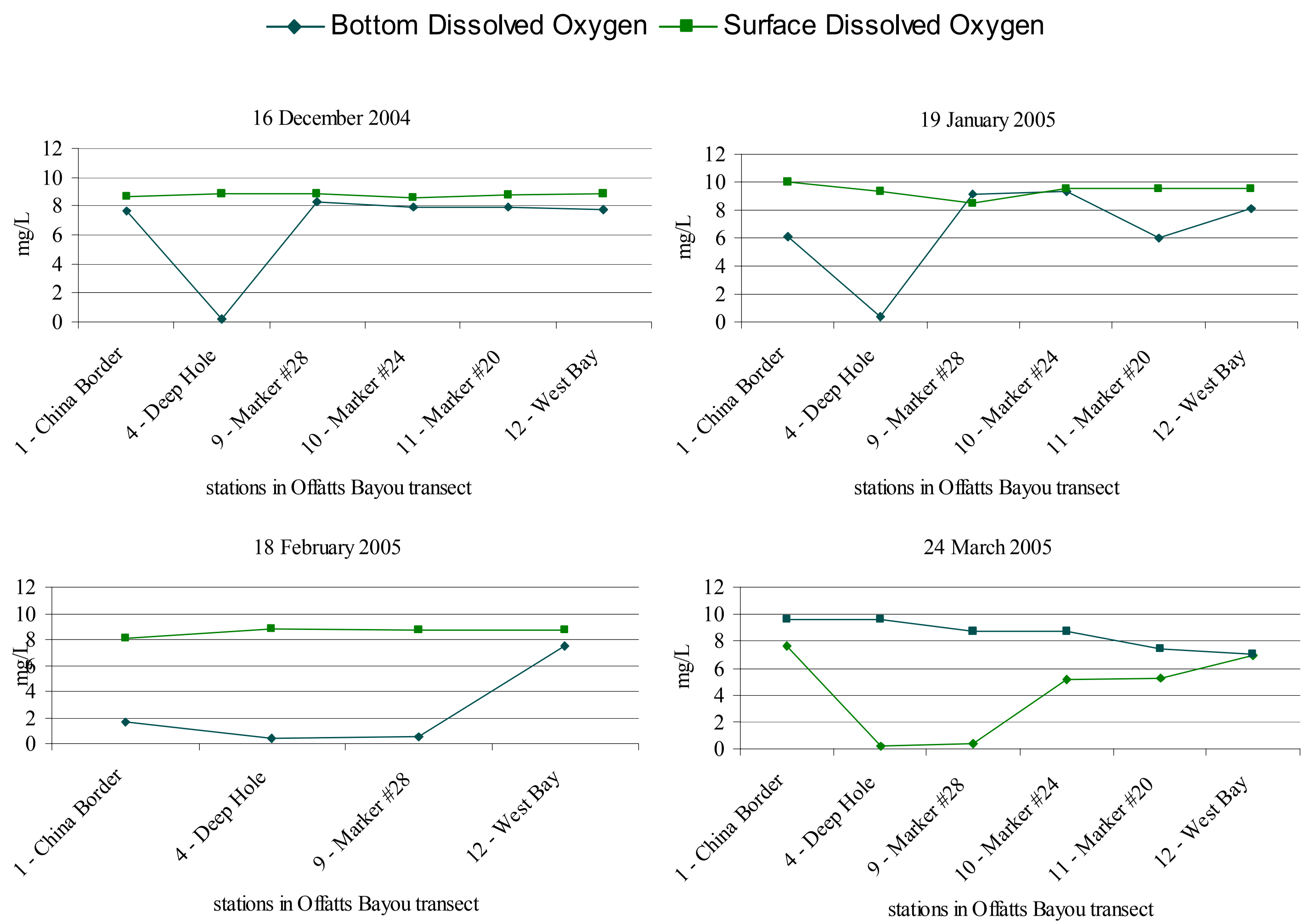
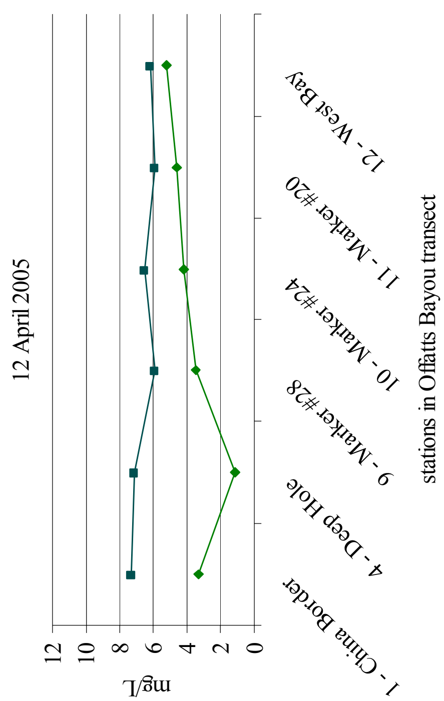
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


11 November 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


19 October 2005
ppt
35
30
25
20
15
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

Surface Dissolved Oxygen vs. Bottom Dissolved Oxygen Data




12 April 2005
mg/L
12
10
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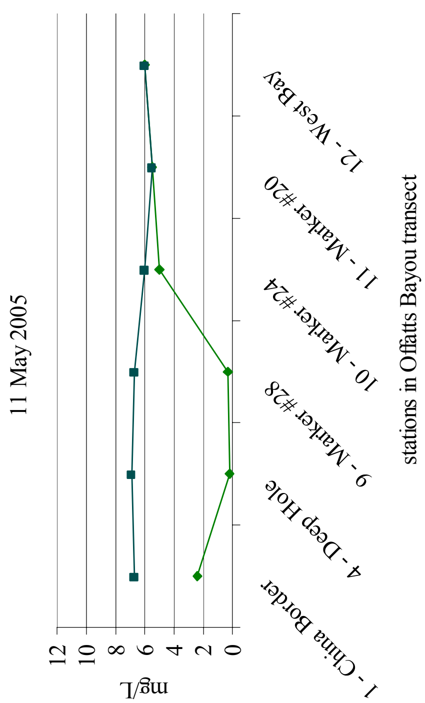
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


11 May 2005
mg/L
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10
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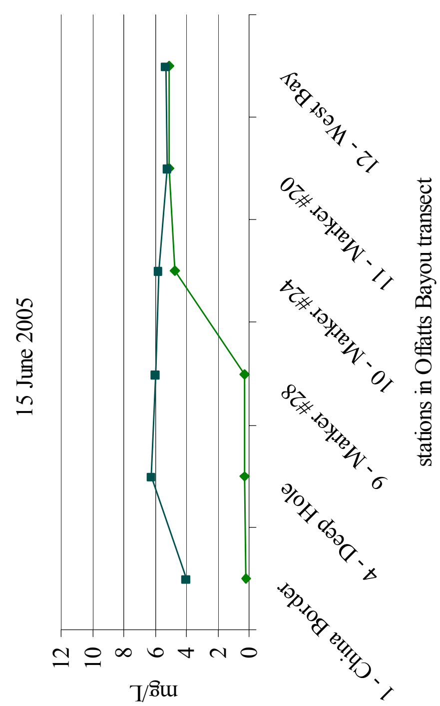
6
4
2
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


15 June 2005
mg/L
12
10
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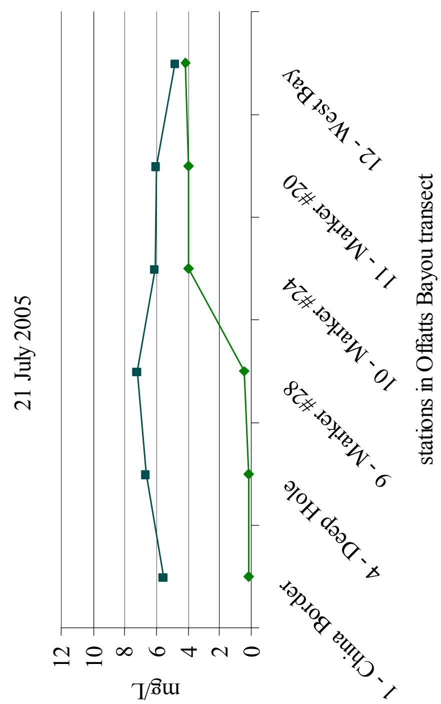
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


21 July 2005
mg/L
12
10
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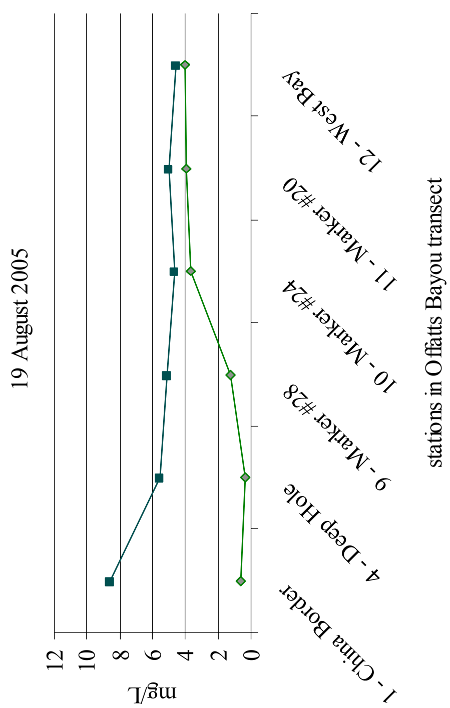
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


19 August 2005
mg/L
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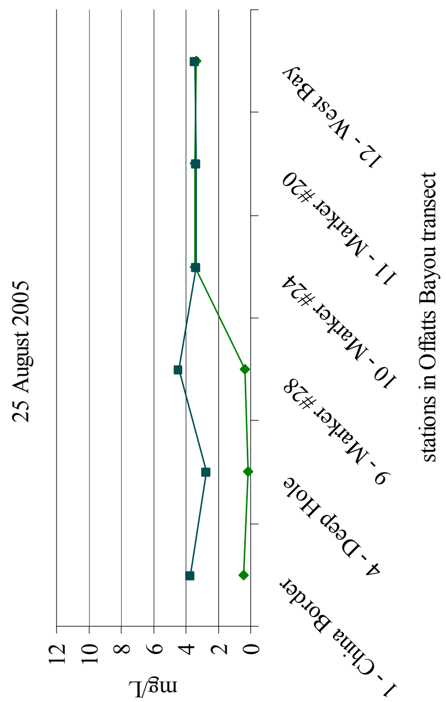
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


25 August 2005
mg/L
12
10
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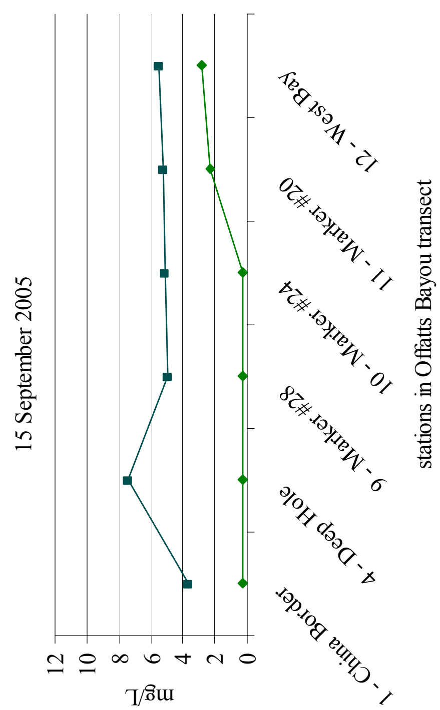
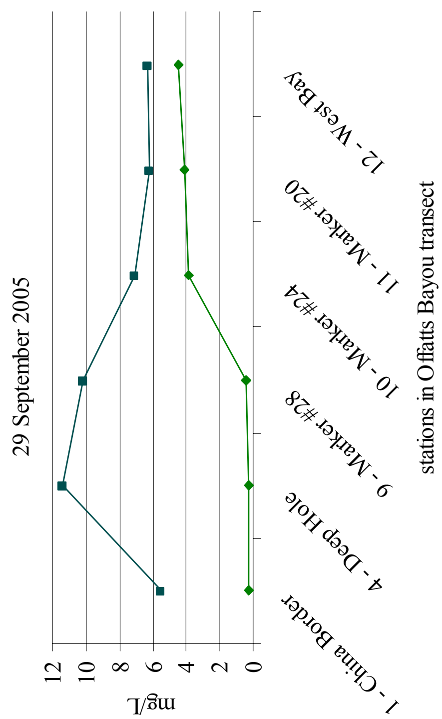
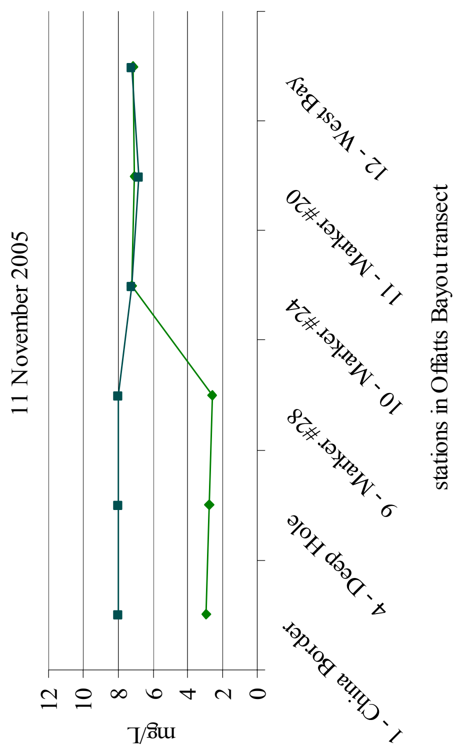
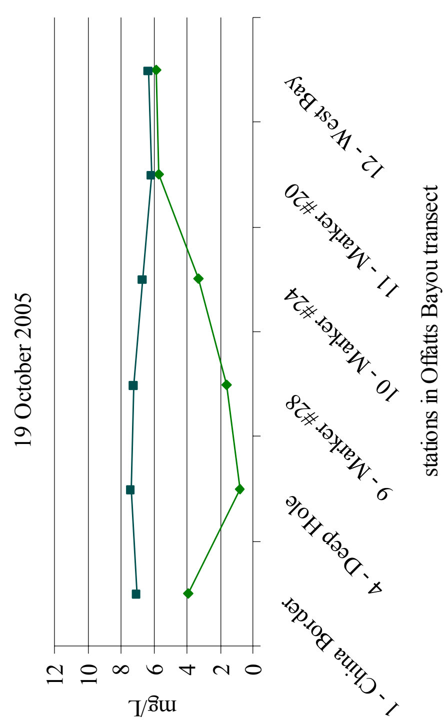
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

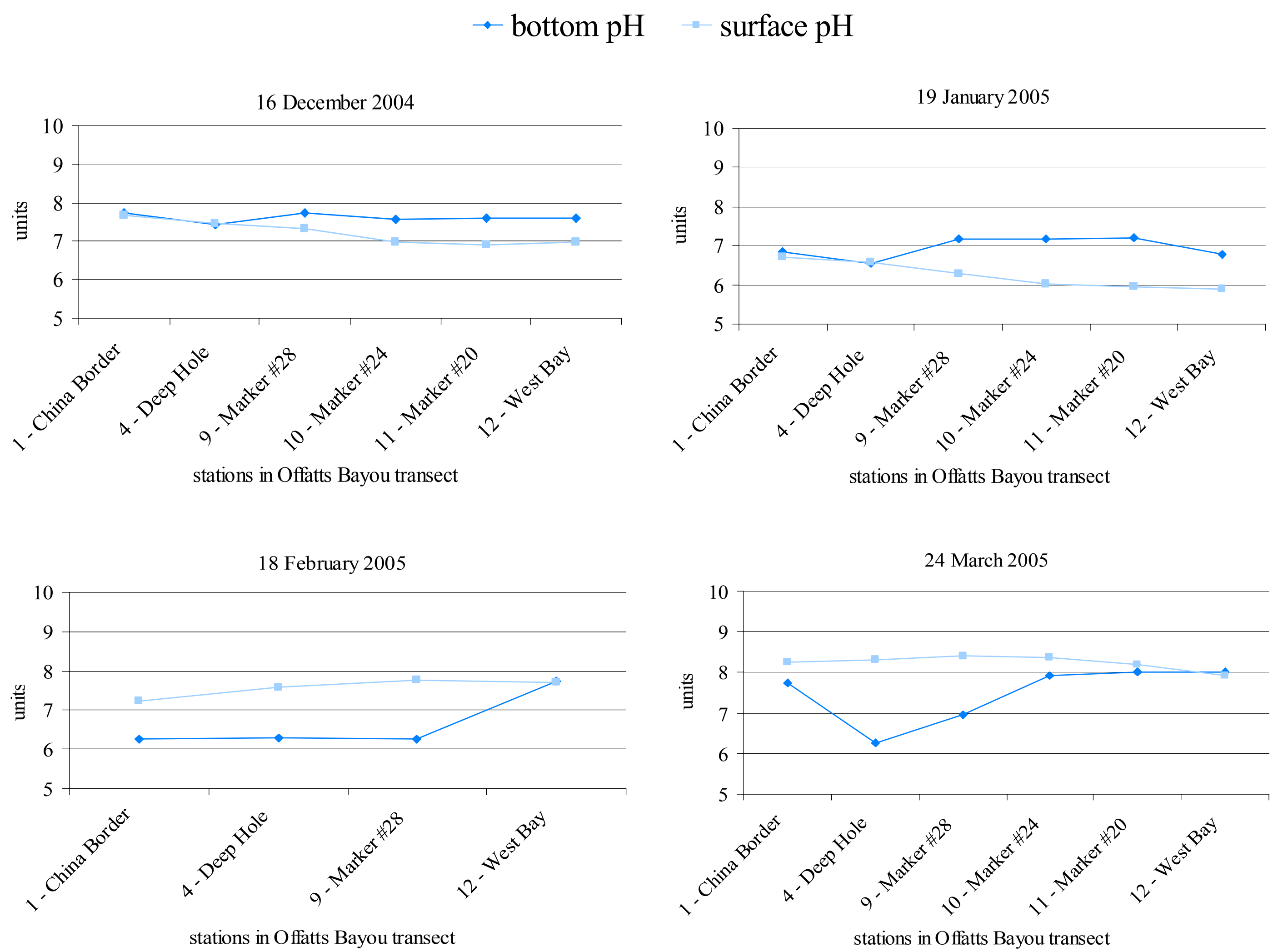

15 September 2005
mg/L
12
10
8
6
4
2
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

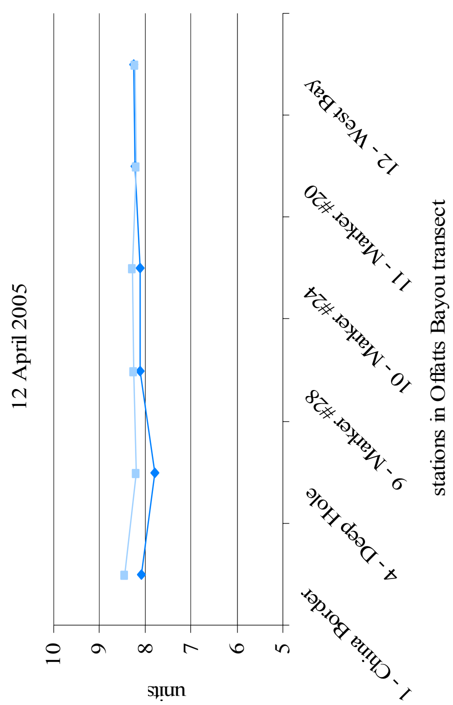

29 September 2005
mg/L
12
10
8
6
4
2
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

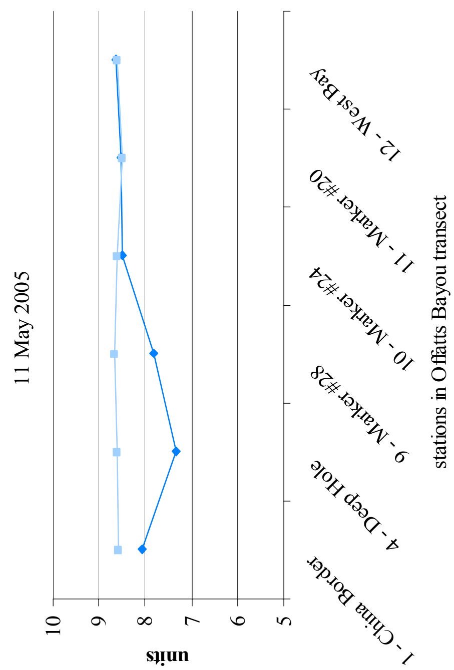

11 November 2005
mg/L
12
10
8
6
4
2
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

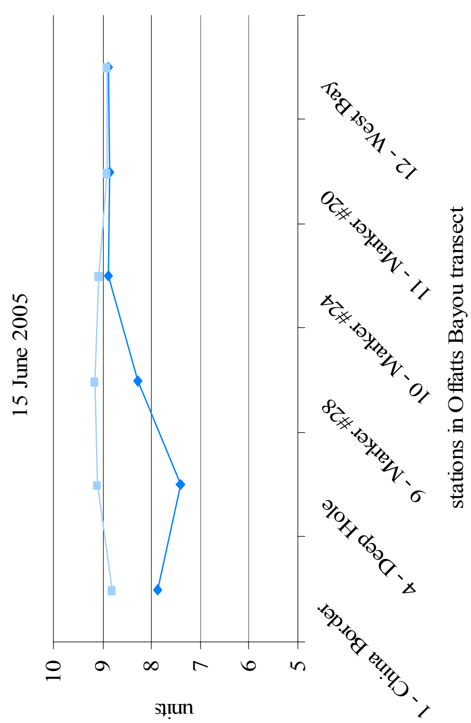

19 October 2005
mg/L
12
10
8
6
4
2
0
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

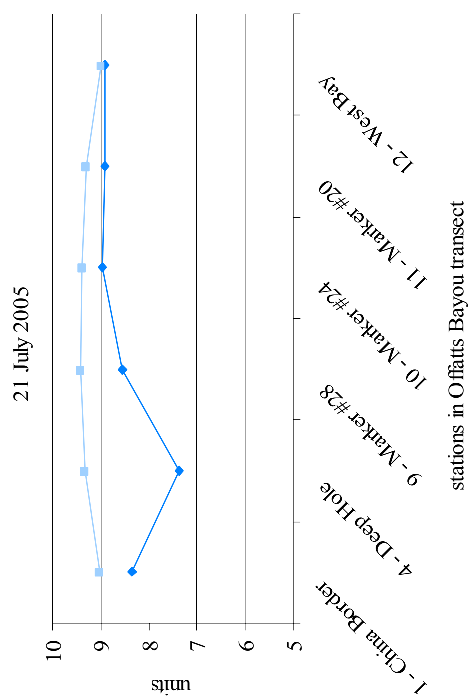
Surface pH vs. Bottom pH data



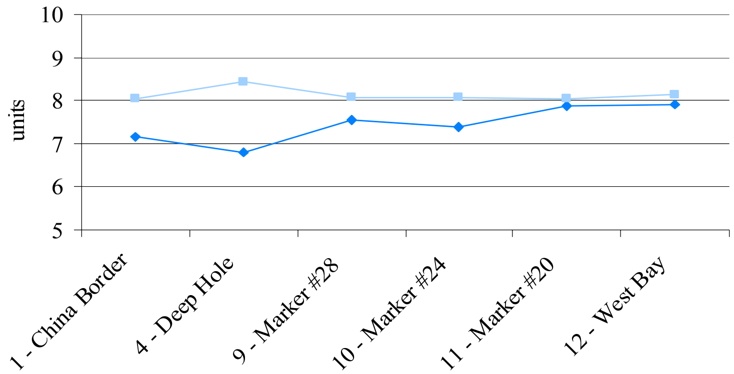

12 April 2005
units
10
9
8
7
6
5
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


11 May 2005
units
10
9
8
7
6
5
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect


15 June 2005
units
10
9
8
7
6
5
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

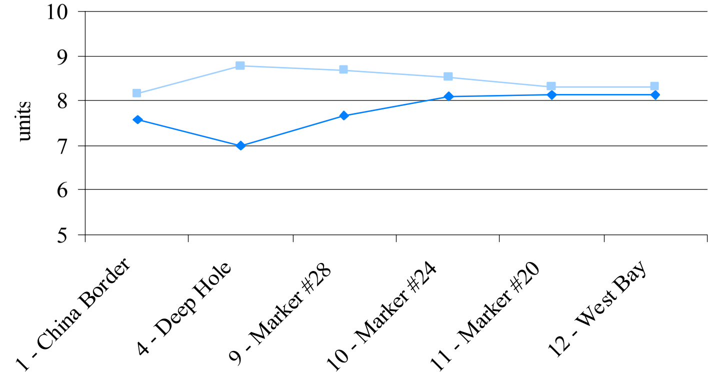

21 July 2005
units
10
9
8
7
6
5
1 - China Border
4 - Deep Hole
9 - Marker #28
10 - Marker #24
11 - Marker #20
12 - West Bay
stations in Offatts Bayou transect

15 September 2005



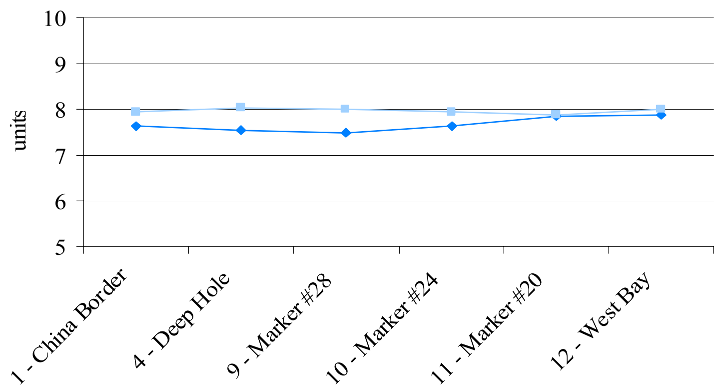
stations in Offatts Bayou transect

29 September 2005



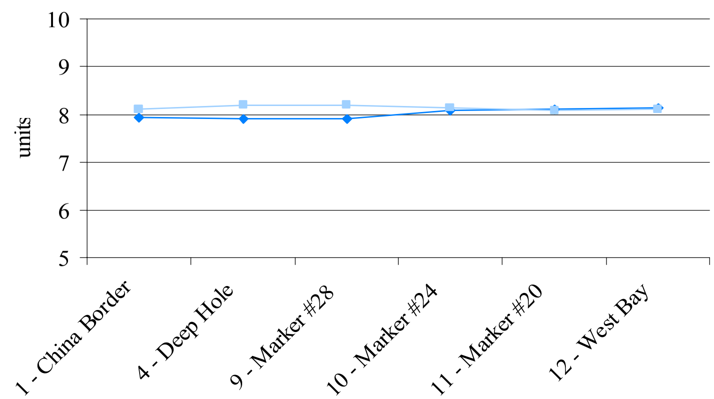
stations in Offatts Bayou transect

19 October 2005



stations in Offatts Bayou transect

11 November 2005



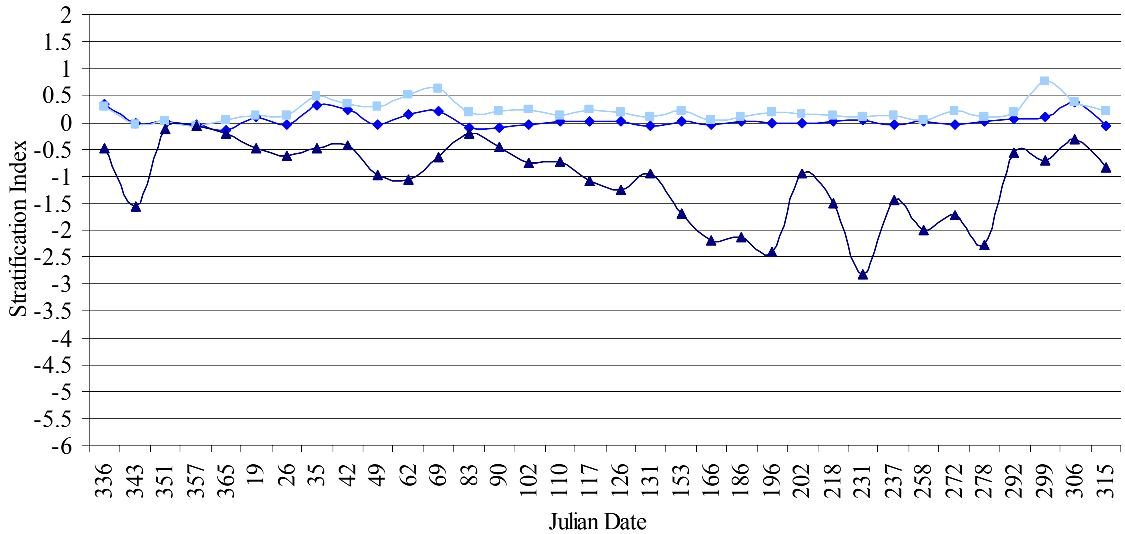
stations in Offatts Bayou transect

Stratification Indices for Temperature, Salinity and Dissolved Oxygen

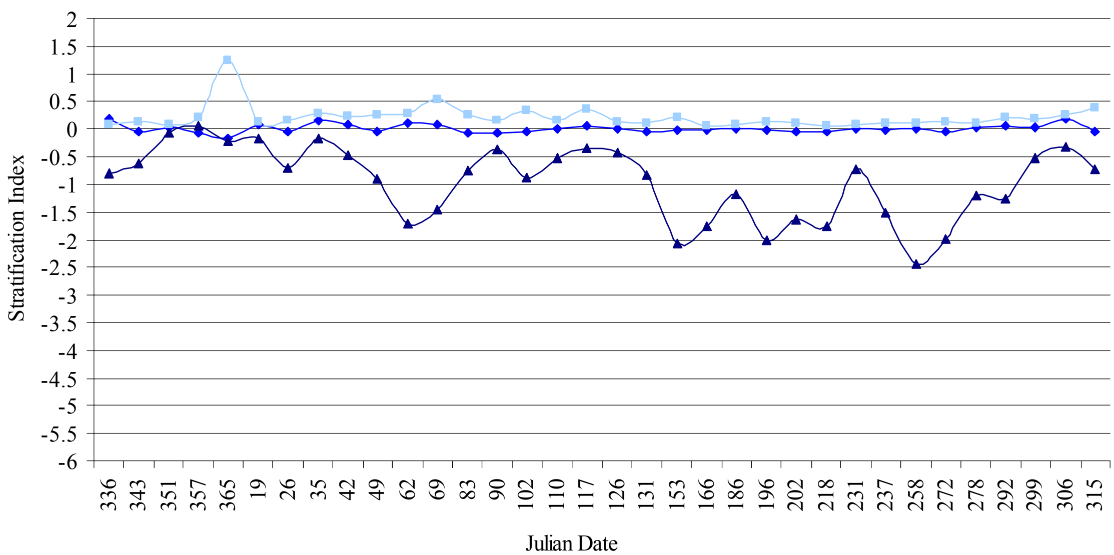
Corresponding Julian dates to sample dates

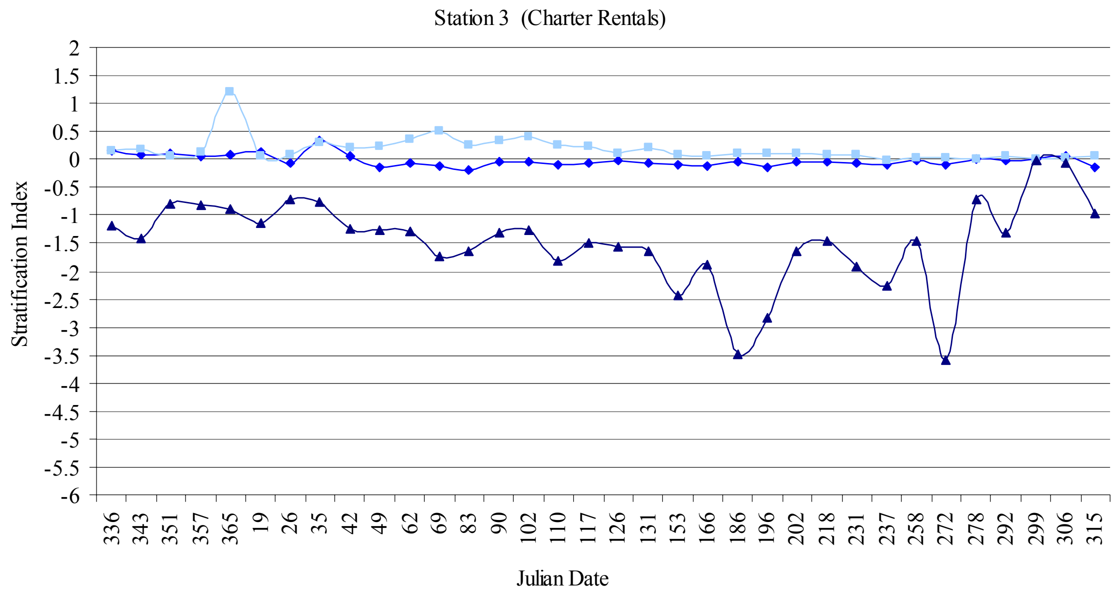
Julian date	date of sample	Julian date	date of sample
336	1-Dec-04	126	6-May-05
343	8-Dec-04	131	11-May-05
351	16-Dec-04	153	2-Jun-05
357	22-Dec-04	166	15-Jun-05
365	30-Dec-04	186	5-Jul-05
19	19-Jan-05	196	15-Jul-05
26	26-Jan-05	202	21-Jul-05
35	4-Feb-05	218	6-Aug-05
42	11-Feb-05	231	19-Aug-05
49	18-Feb-05	237	25-Aug-05
62	3-Mar-05	258	15-Sep-05
69	10-Mar-05	272	29-Sep-05
83	24-Mar-05	278	5-Oct-05
90	31-Mar-05	292	19-Oct-05
102	12-Apr-05	299	26-Oct-05
110	20-Apr-05	306	2-Nov-05
117	27-Apr-05	315	11-Nov-05

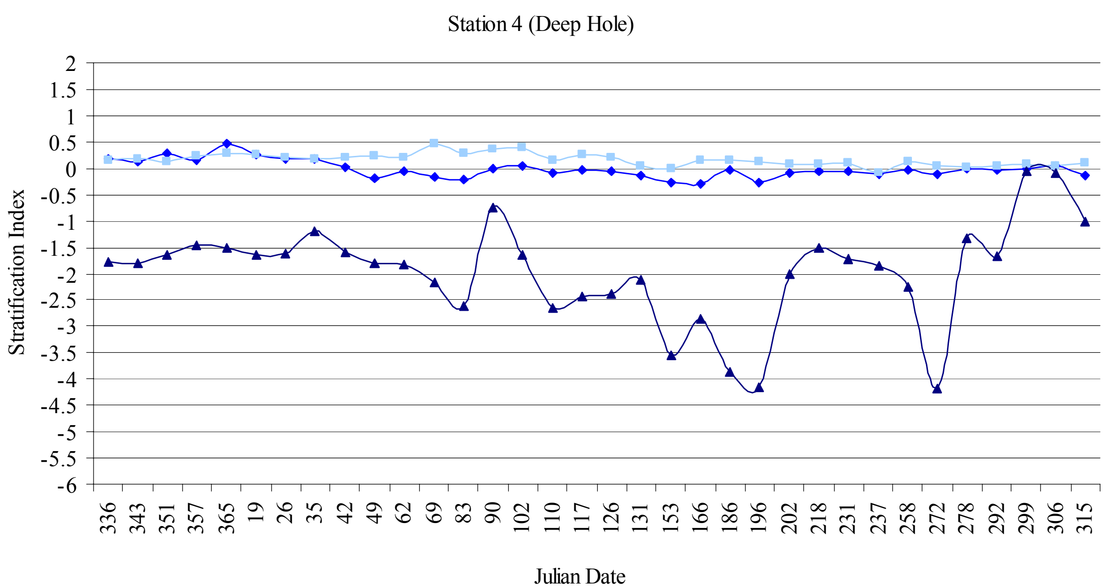
Station 1 (China Border)

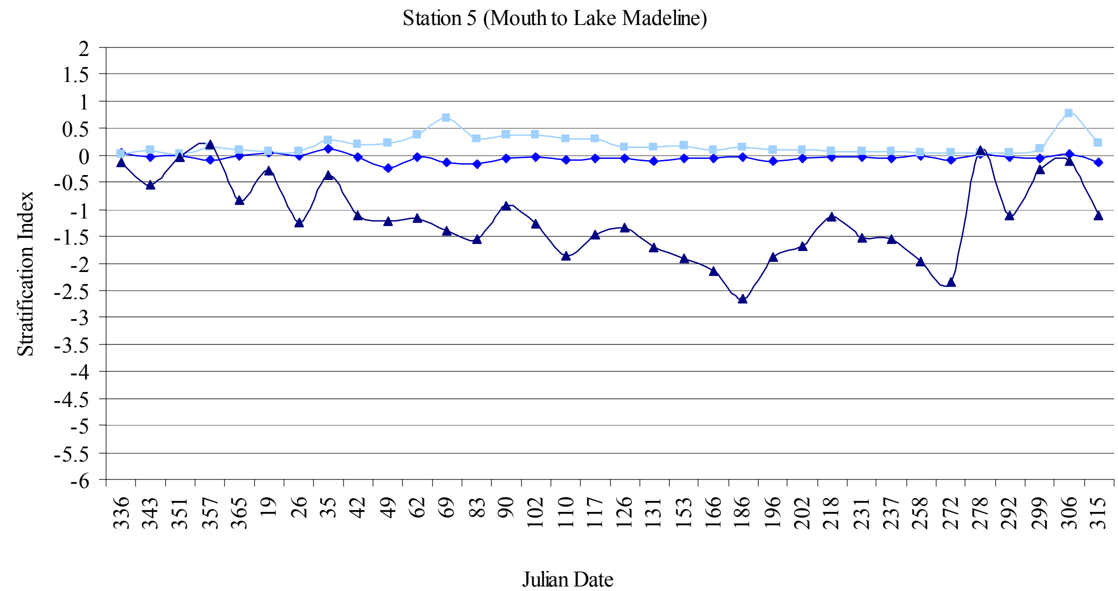


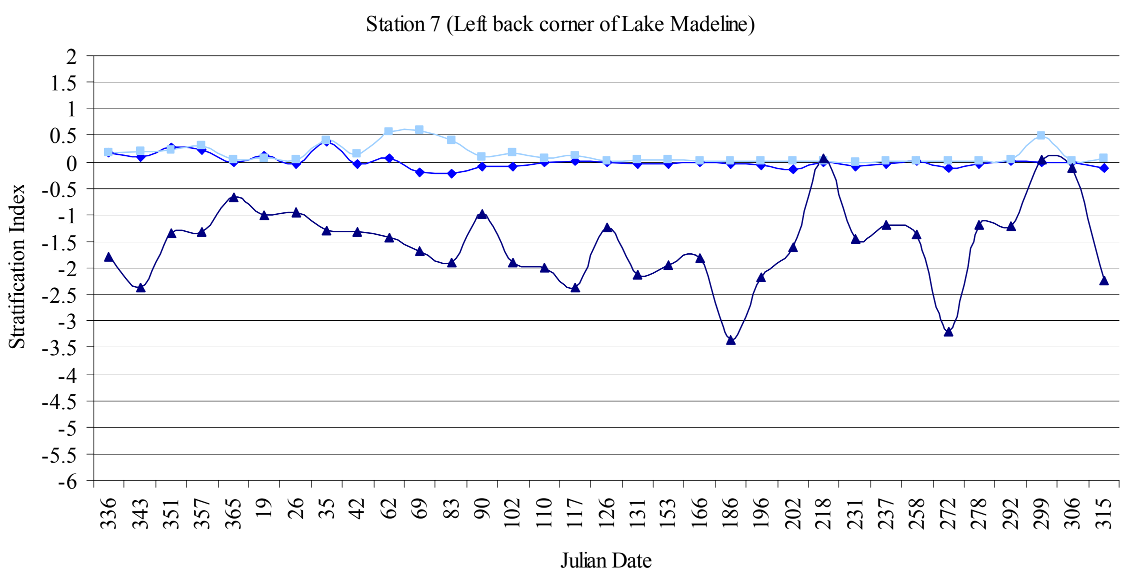
Station 2 (Back Bay)

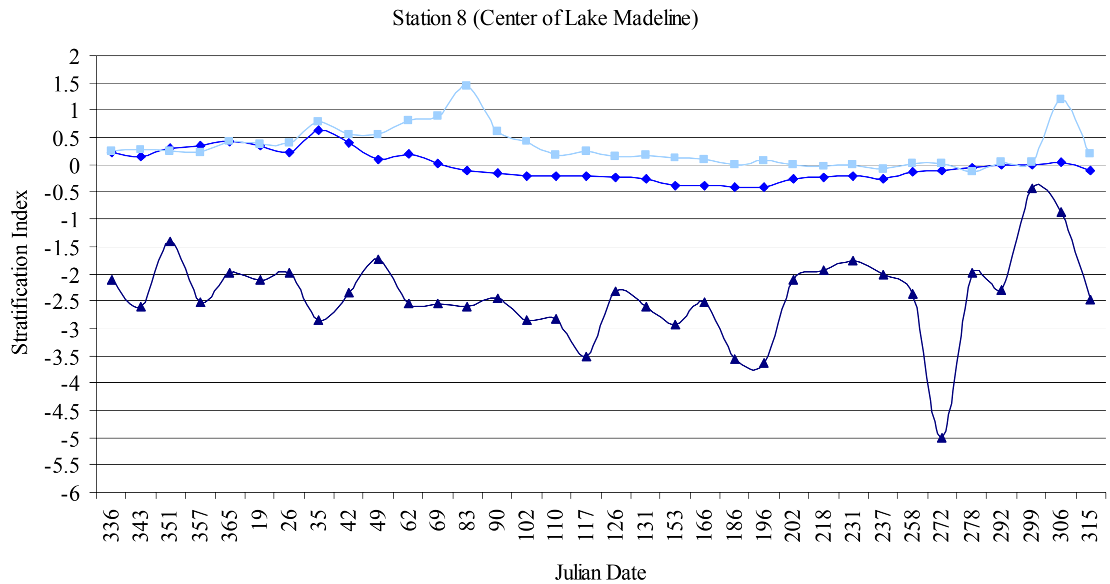


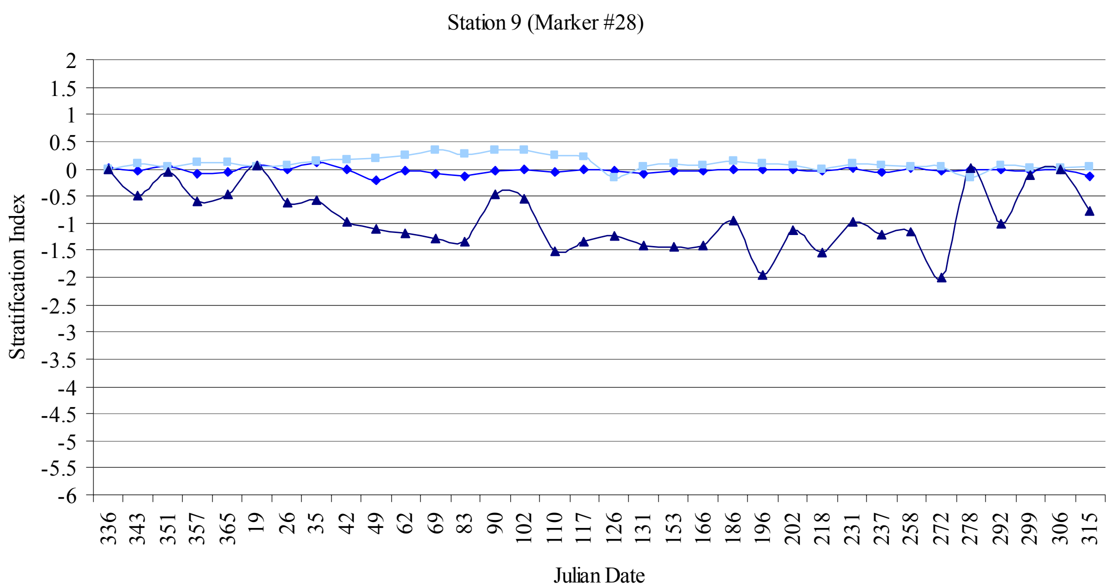

Station 3 (Charter Rentals)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336 343 351 357 365 19 26 35 42 49 62 69 83 90 102 110 117 126 131 153 166 186 196 202 218 231 237 258 272 278 292 299 306 315
Julian Date

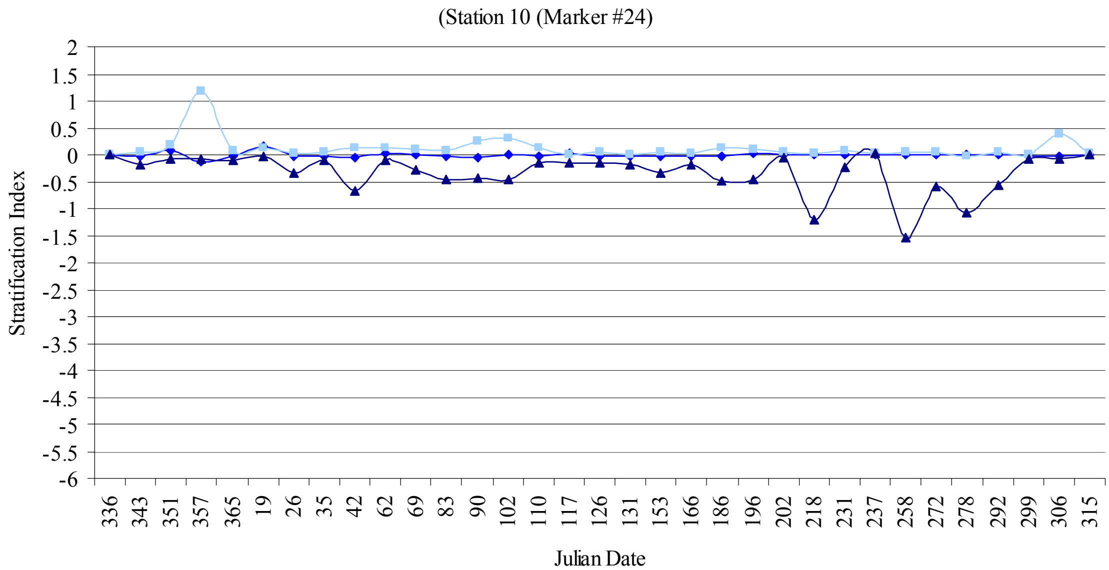

Station 4 (Deep Hole)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336 343 351 357 365 19 26 35 42 49 62 69 83 90 102 110 117 126 131 153 166 186 196 202 218 231 237 258 272 278 292 299 306 315
Julian Date

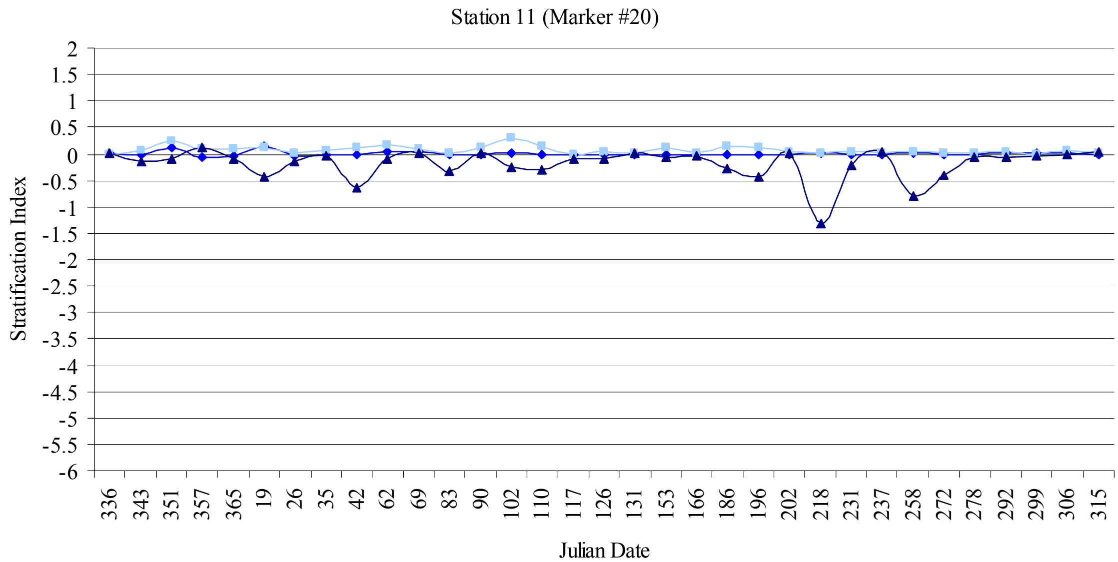

Station 5 (Mouth to Lake Madeline)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336 343 351 357 365 19 26 35 42 49 62 69 83 90 102 110 117 126 131 153 166 186 196 202 218 231 237 258 272 278 292 299 306 315
Julian Date

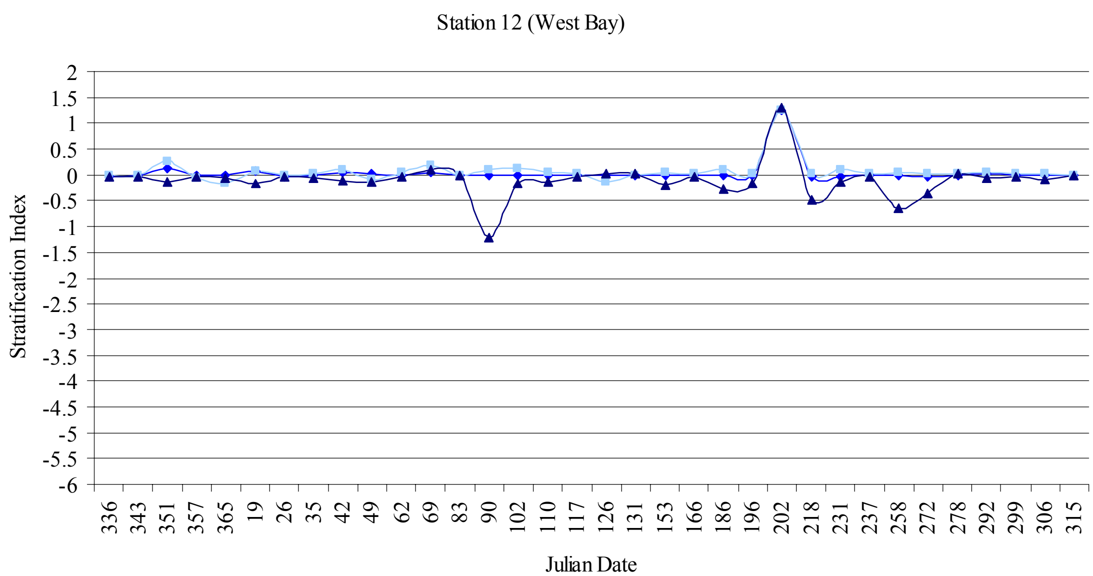

Station 7 (Left back corner of Lake Madeline)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336 343 351 357 365 19 26 35 42 62 69 83 90 102 110 117 126 131 153 166 186 196 202 218 231 237 258 272 278 292 299 306 315
Julian Date


Station 8 (Center of Lake Madeline)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336
343
351
357
365
19
26
35
42
49
62
69
83
90
102
110
117
126
131
153
166
186
196
202
218
231
237
258
272
278
292
299
306
315
Julian Date


Station 9 (Marker #28)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336
343
351
357
365
19
26
35
42
49
62
69
83
90
102
110
117
126
131
153
166
186
196
202
218
231
237
258
272
278
292
299
306
315
Julian Date


(Station 10 (Marker #24)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336
343
351
357
365
19
26
35
42
62
69
83
90
102
110
117
126
131
153
166
186
196
202
218
231
237
258
272
278
292
299
306
315
Julian Date

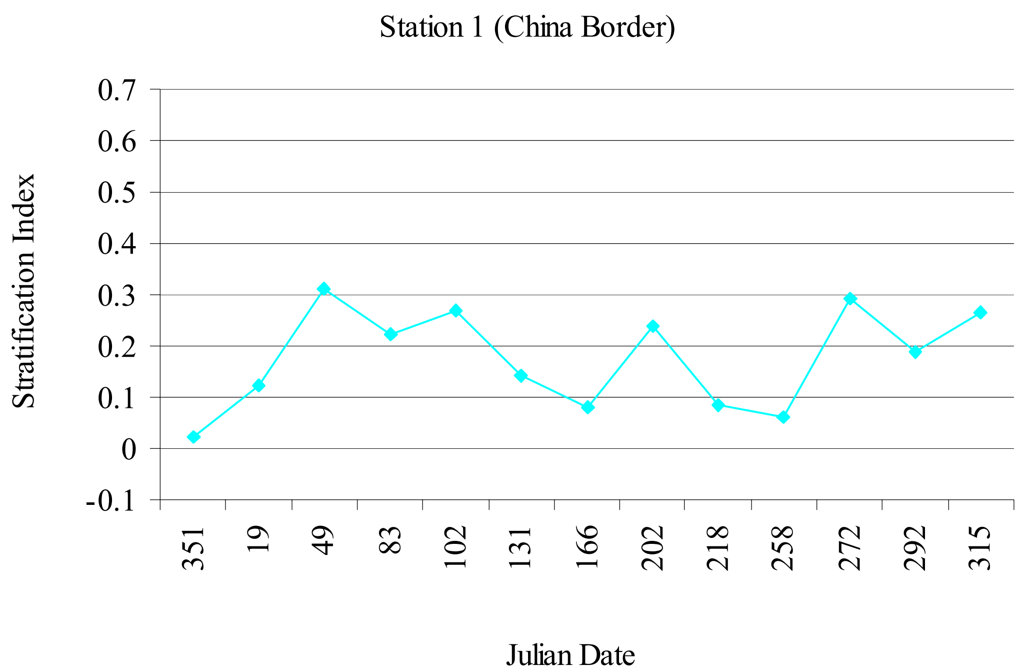

Station 11 (Marker #20)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336
343
351
357
365
19
26
35
42
62
69
83
90
102
110
117
126
131
153
166
186
196
202
218
231
237
258
272
278
292
299
306
315
Julian Date


Station 12 (West Bay)
Stratification Index
2
1.5
1
0.5
0
-0.5
-1
-1.5
-2
-2.5
-3
-3.5
-4
-4.5
-5
-5.5
-6
336
343
351
357
365
19
26
35
42
49
62
69
83
90
102
110
117
126
131
153
166
186
196
202
218
231
237
258
272
278
292
299
306
315
Julian Date

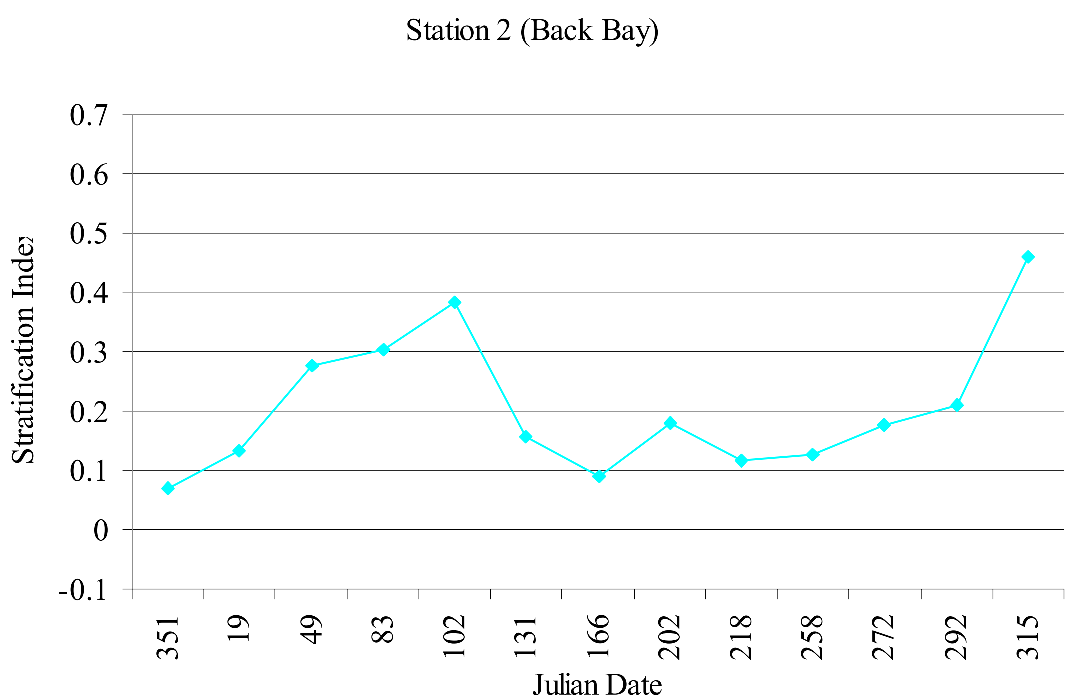
Monthly Stratification Indices for Density

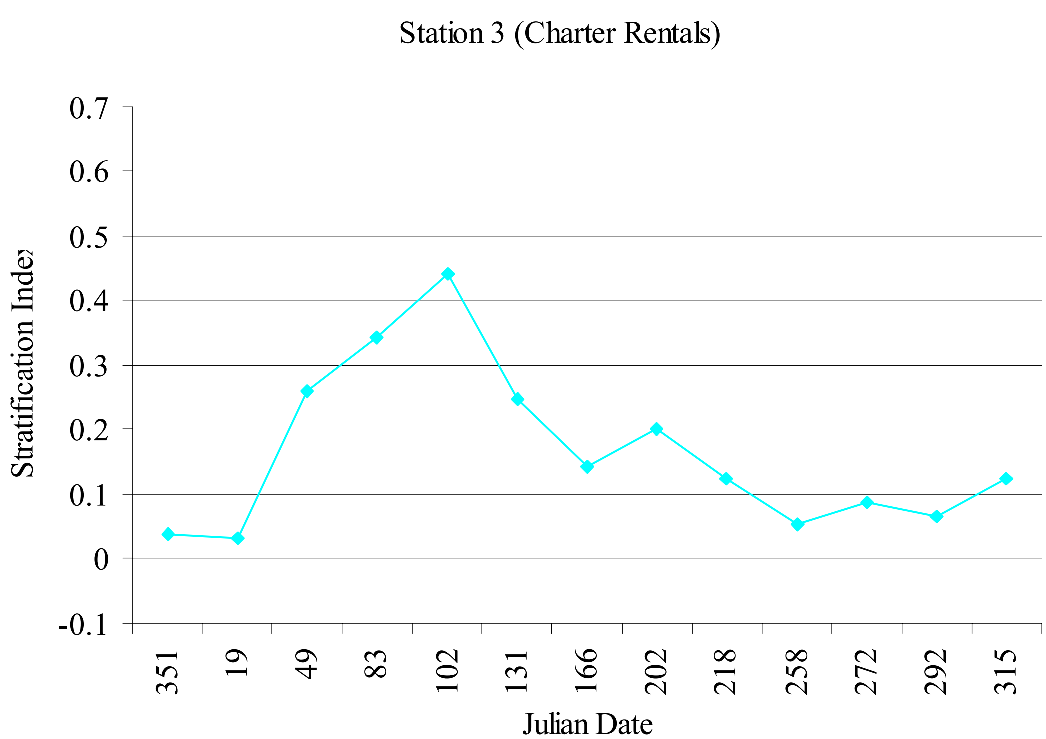
Julian date	date of sample
351	16-Dec-04
19	19-Jan-05
49	18-Feb-05
83	24-Mar-05
102	12-Apr-05
131	11-May-05
166	15-Jun-05
202	21-Jul-05
218	19-Aug-05
258	15-Sep-05
272	29-Sep-05
292	19-Oct-05
315	11-Nov-05

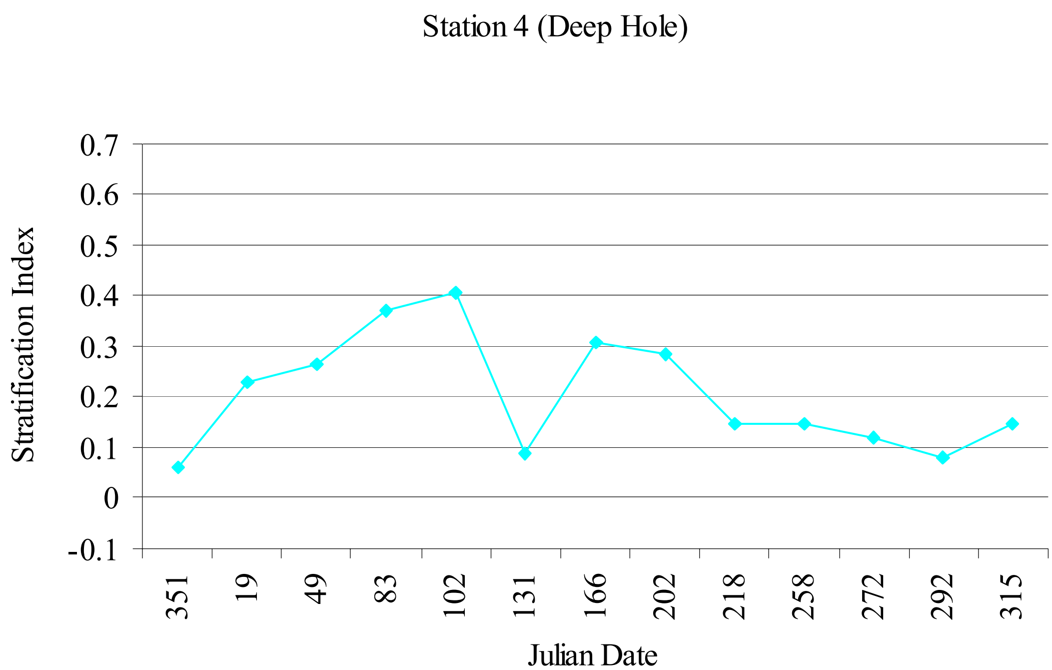
low stratification = <1
mid stratification = 1 to 2
hi stratification = >2

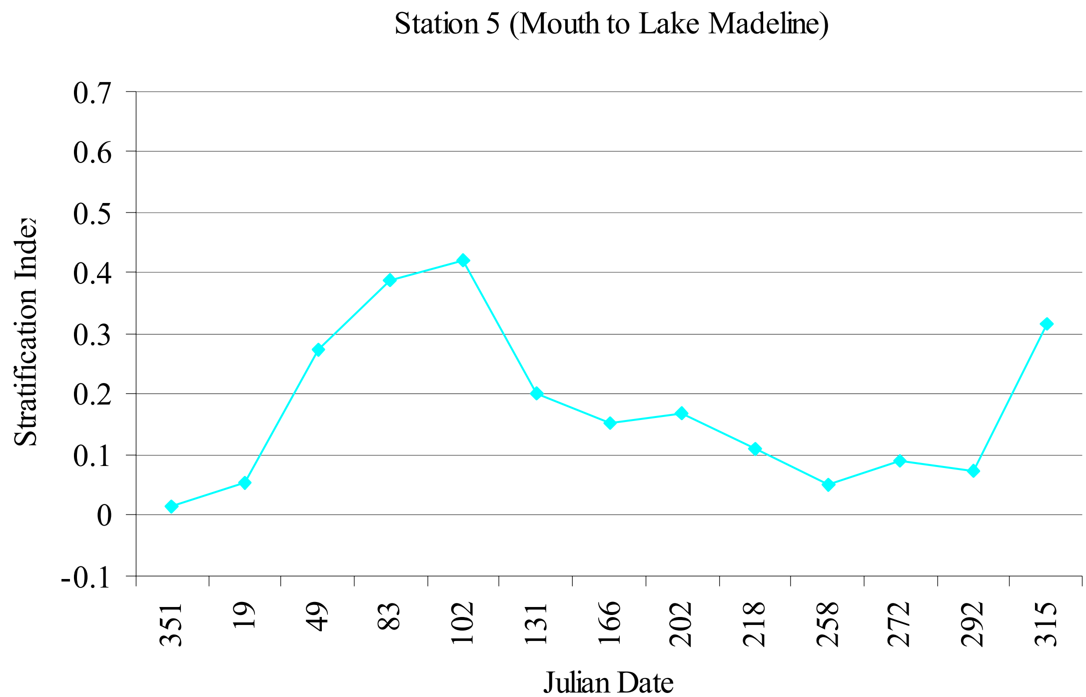


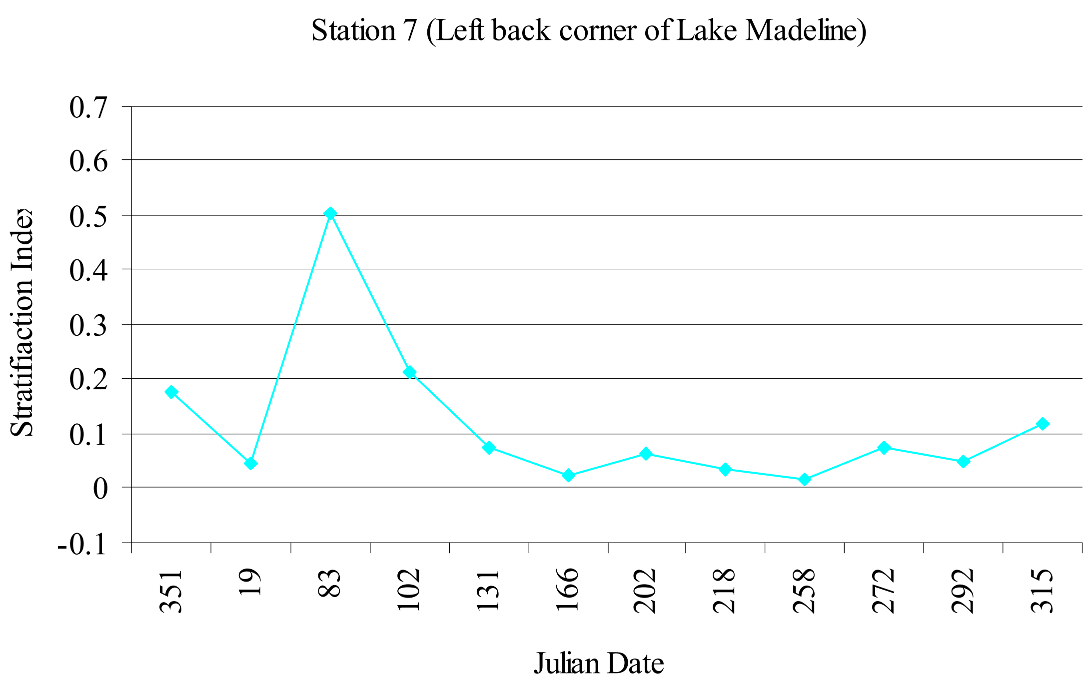
Station 1 (China Border)
Stratification Index
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date


Station 2 (Back Bay)
Stratification Index
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date

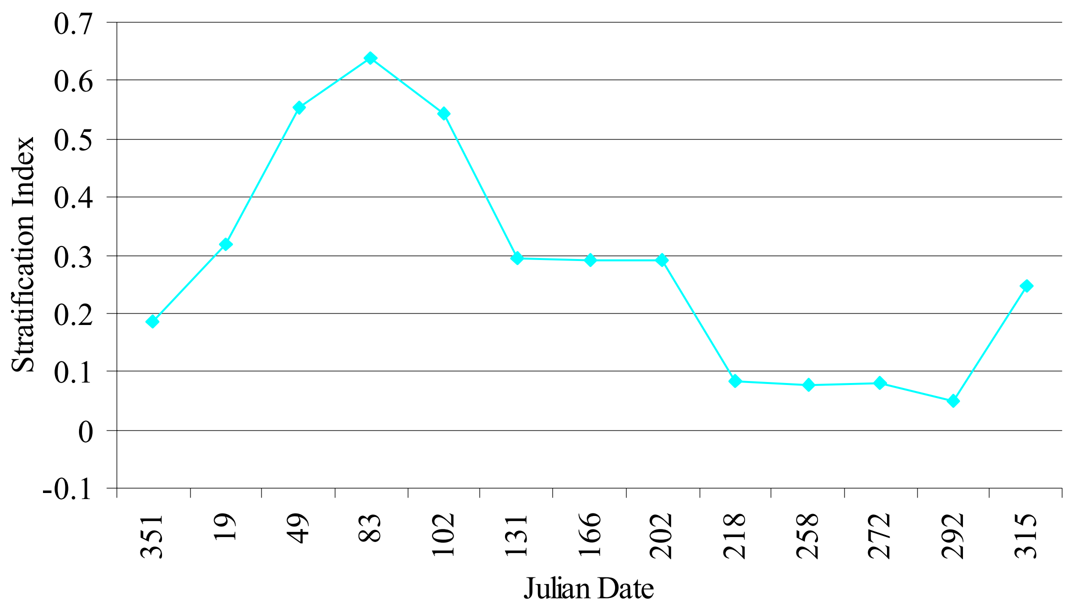

Station 3 (Charter Rentals)
Stratification Index
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date


Station 4 (Deep Hole)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
Stratification Index
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date

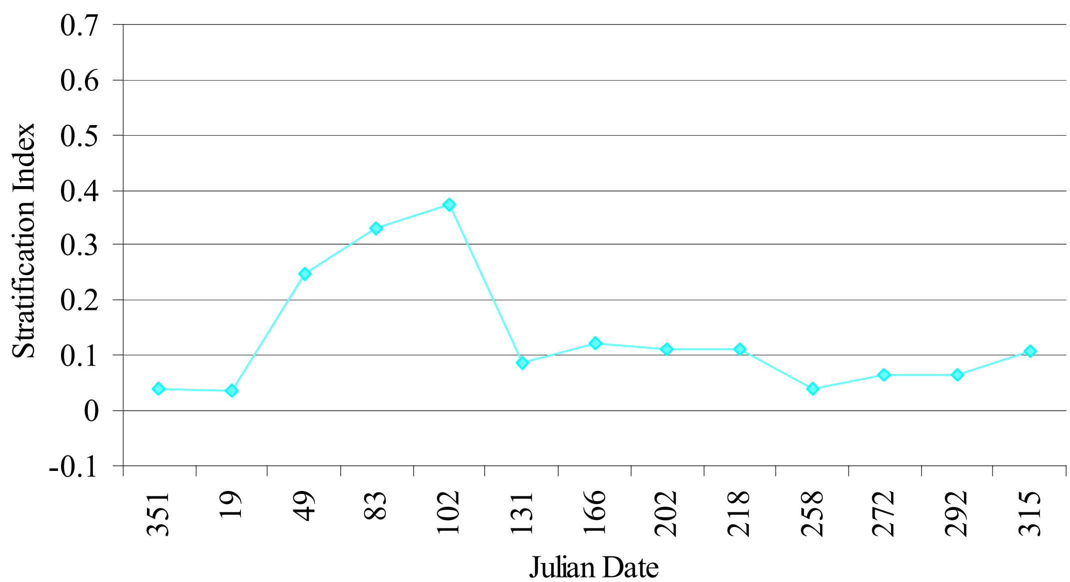

Station 5 (Mouth to Lake Madeline)
Stratification Index
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date

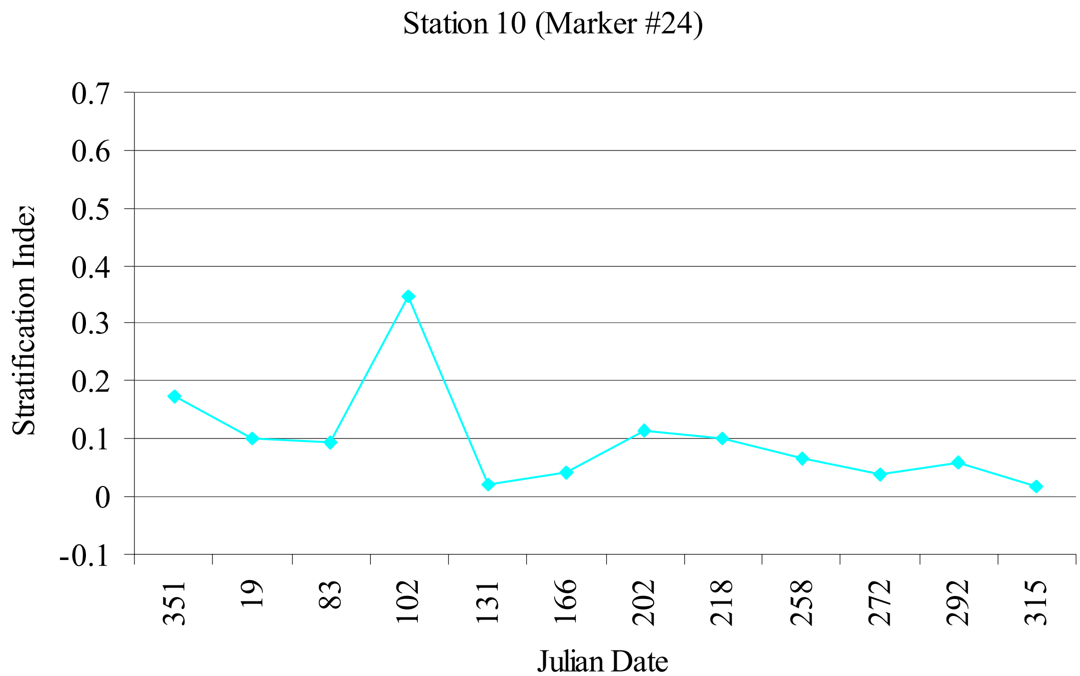

Station 7 (Left back corner of Lake Madeline)
Stratifiaction Index
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
351
19
83
102
131
166
202
218
258
272
292
315
Julian Date

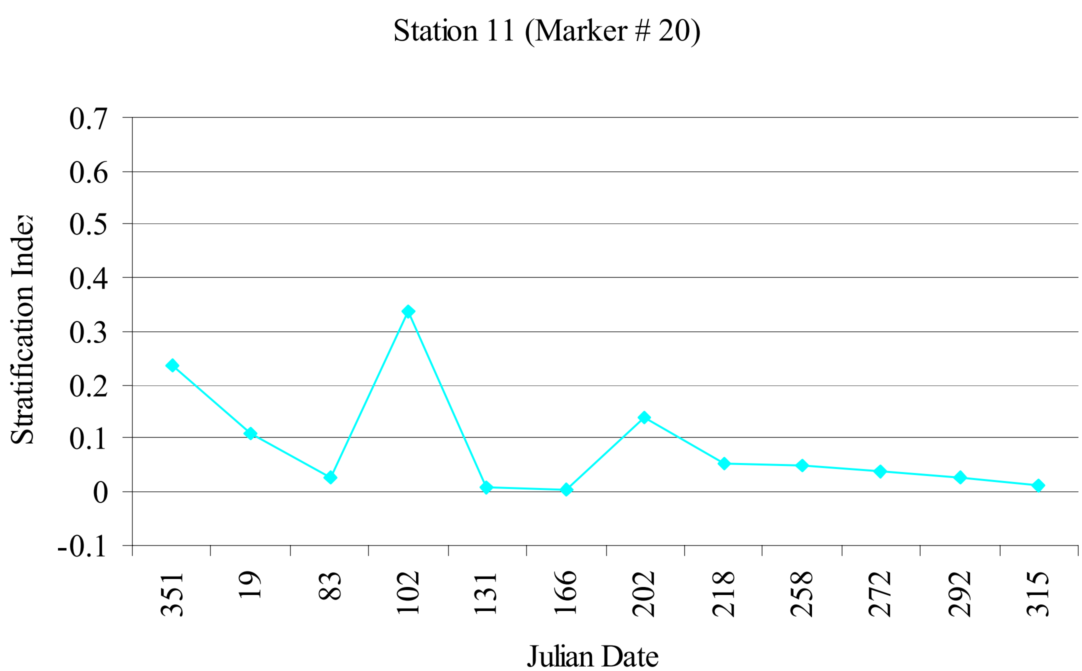
Station 8 (Center of Lake Madeline)

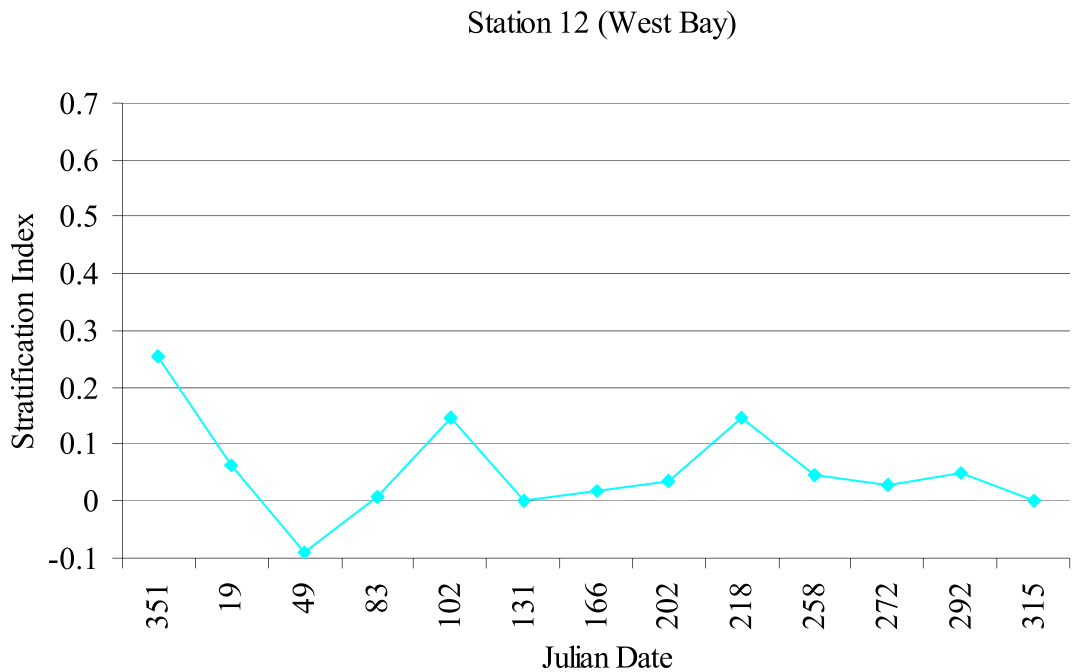


Station 9 (Marker #28)




Station 10 (Marker #24)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
Stratification Index
351
19
83
102
131
166
202
218
258
272
292
315
Julian Date


Station 11 (Marker # 20)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
Stratification Index
351
19
83
102
131
166
202
218
258
272
292
315
Julian Date


Station 12 (West Bay)
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
Stratification Index
351
19
49
83
102
131
166
202
218
258
272
292
315
Julian Date

APPENDIX B

STATISTICAL ANALYSIS DATA

1. Monthly Surface, Middle and Bottom Temperature, Salinity, Dissolved Oxygen and pH Data.

Sample Month	Mean Surface Temperature (°C)	hi to low order	standard deviation
Dec-04	15.4	10	2.1
Jan-05	13.4	11	1.3
Feb-05	12.7	12	2.4
Mar-05	17.9	9	2.2
Apr-05	21.9	7	0.4
May-05	23.3	6	0.4
Jun-05	28.7	4	0.5
Jul-05	30.7	2	0.5
Aug-05	31.1	1	0.8
Sep-05	29.6	3	0.8
Oct-05	24.6	5	3.2
Nov-05	21.1	8	3.0
Sample Month	Mean Surface Salinity (ppt)	hi to low order	standard deviation
Dec-04	21.0	8	1.7
Jan-05	19.3	10	1.0
Feb-05	18.1	11	2.2
Mar-05	16.1	12	2.2
Apr-05	23.7	7	3.0
May-05	24.6	4	1.4
Jun-05	25.5	5	1.8
Jul-05	28.3	3	2.2
Aug-05	29.3	2	1.3
Sep-05	29.8	1	1.6
Oct-05	25.0	6	4.9
Nov-05	20.5	9	5.0

Sample Month	Mean Surface Dissolved Oxygen (mg/L)	hi to low order	standard deviation
Dec-04	9.1	3	1.8
Jan-05	9.5	2	1.4
Feb-05	9.7	1	0.8
Mar-05	8.6	4	1.3
Apr-05	6.7	7	0.6
May-05	6.7	12	0.6
Jun-05	5.5	10	1.0
Jul-05	5.6	9	1.4
Aug-05	4.2	11	1.6
Sep-05	7.2	6	3.8
Oct-05	6.1	8	2.2
Nov-05	8.2	5	0.9
Sample Month	Mean Surface pH	hi to low order	standard deviation
Dec-04	7.4	11	0.3
Jan-05	6.7	10	0.3
Feb-05	6.5	6	0.3
Mar-05	7.9	5	0.3
Apr-05	8.3	3	0.1
May-05	8.5	2	0.1
Jun-05	9.3	1	0.1
Jul-05	not recorded		not recorded
Aug-05	not recorded	7	not recorded
Sep-05	8.6	4	0.3
Oct-05	8.0	9	0.1
Nov-05	8.2	8	0.1
Sample Month	Mean Middle Temperature (°C)	hi to low order	standard deviation
Dec-04	15.3	10	0.8
Jan-05	13.8	11	0.8
Feb-05	13.1	12	1.0
Mar-05	17.8	9	1.0
Apr-05	21.8	7	0.6
May-05	23.0	6	0.6

Sample Month	Mean Middle Temperature (°C)	hi to low order	standard deviation
Jun-05	28.5	4	0.4
Jul-05	30.4	2	0.6
Aug-05	30.9	1	0.5
Sep-05	28.9	3	0.5
Oct-05	24.8	5	0.7
Nov-05	21.4	8	0.9
Sample Month	Mean Middle Salinity (ppt)	hi to low order	standard deviation
Dec-04	17.9	11	1.2
Jan-05	20.2	9	0.6
Feb-05	20.2	9	1.0
Mar-05	18.9	10	1.8
Apr-05	26.8	4	3.4
May-05	25.6	7	0.6
Jun-05	26.7	5	0.9
Jul-05	29.8	3	1.4
Aug-05	30.1	2	0.7
Sep-05	30.7	1	0.7
Oct-05	26.6	6	0.7
Nov-05	23.7	8	1.8
Sample Month	Mean Middle Dissolved Oxygen (mg/L)	hi to low order	standard deviation
Dec-04	7.7	3	1.7
Jan-05	8.3	2	1.6
Feb-05	8.5	1	1.8
Mar-05	6.1	5	2.7
Apr-05	3.9	8	2.0
May-05	4.8	7	1.6
Jun-05	2.9	10	1.9
Jul-05	2.4	12	1.6
Aug-05	3.1	9	1.5
Sep-05	2.7	11	2.1
Oct-05	5.3	6	1.9

Sample Month	Mean Middle Dissolved Oxygen (mg/L)	hi to low order	standard deviation
Nov-05	6.8	4	1.4
Sample Month	Mean middle pH	hi to low order	standard deviation
Dec-04	7.3	5	0.3
Jan-05	6.9	6	0.3
Feb-05	6.6	7	0.4
Mar-05	7.6	3	0.4
Apr-05	8.1	3	0.3
May-05	8.3	2	0.2
Jun-05	8.6	1	0.2
Jul-05	not recorded		
Aug-05	not recorded		
Sep-05	7.9	4	0.3
Oct-05	7.9	4	0.2
Nov-05	8.1	3	0.1
Sample Month	Mean Bottom Temperature (°C)	hi to low order	standard deviation
Dec-04	16.5	10	2.2
Jan-05	14.4	11	1.7
Feb-05	13.3	12	2.0
Mar-05	17.2	9	1.2
Apr-05	21.1	7	1.3
May-05	22.0	6	1.6
Jun-05	26.4	4	3.2
Jul-05	28.7	2	3.1
Aug-05	29.7	1	2.0
Sep-05	28.4	3	1.1
Oct-05	24.7	5	0.8
Nov-05	20.8	8	1.3
Sample Month	Mean Bottom Salinity (ppt)	hi to low order	standard deviation
Dec-04	23.6	9	2.7
Jan-05	21.8	12	2.6

Sample Month	Mean Bottom Salinity (ppt)	hi to low order	standard deviation
Feb-05	23.0	10	3.2
Mar-05	22.3	11	3.6
Apr-05	29.7	4	4.2
May-05	26.4	7	2.0
Jun-05	27.6	5	1.4
Jul-05	30.8	2	1.9
Aug-05	30.7	3	1.7
Sep-05	31.4	1	0.7
Oct-05	26.7	6	1.0
Nov-05	24.6	8	0.4
Sample Month	Mean Bottom Dissolved Oxygen (mg/L)	hi to low order	standard deviation
Dec-04	4.8	2	3.5
Jan-05	4.5	3	3.1
Feb-05	3.5	5	2.8
Mar-05	3.0	6	2.9
Apr-05	2.5	7	2.8
May-05	2.3	8	2.6
Jun-05	1.5	10	2.1
Jul-05	1.4	11	1.7
Aug-05	1.9	9	1.4
Sep-05	1.0	12	1.4
Oct-05	3.6	4	2.0
Nov-05	5.3	1	2.2
Sample Month	Mean Bottom pH	hi to low order	standard deviation
Dec-04	7.3	6	0.3
Jan-05	6.8	8	0.3
Feb-05	6.3	9	0.4
Mar-05	7.2	7	0.6
Apr-05	7.8	3	0.5
May-05	7.8	3	0.5
Jun-05	8.9	1	0.6
Jul-05	not recorded		

Sample Month Aug-05	Mean Bottom pH not recorded	hi to low order	standard deviation
Sep-05	7.5	5	0.4
Oct-05	7.7	4	0.3
Nov-05	8.0	2	0.2

2. Seasonal Surface, Middle and Bottom
Temperature, Salinity, Dissolved Oxygen and pH Data

Season-Surface	Temperature mean (°C)	Standard deviation
winter 2004-2005	15.3	2.9
spring 2005	22.5	1.1
summer 2005	30.2	0.9
autumn 2005	23.2	3.6
Season-Surface	Salinity mean (ppt)	Standard deviation
winter 2004-2005	18.7	3.1
spring 2005	24.0	2.5
summer 2005	28.3	1.6
autumn 2005	23.2	5.3
Season-Surface	DO mean (mg/L)	Standard deviation
winter 2004-2005	9.2	1.5
spring 2005	6.7	0.6
summer 2005	5.5	1.1
autumn 2005	6.9	2.1
Season-Surface	pH mean	Standard deviation
winter 2004-2005	7.3	0.8
spring 2005	8.4	0.1
summer 2005	not recorded	not recorded
autumn 2005	8.0	0.2
Season-Middle	Temperature mean (°C)	Standard deviation
winter 2004-2005	15.3	0.9
spring 2005	22.3	1.0
summer 2005	29.9	1.2
autumn 2005	23.5	3.3
Season-Middle	Salinity mean (ppt)	Standard deviation
winter 2004-2005	19.0	1.2
spring 2005	26.3	2.8
summer 2005	29.5	1.9
autumn 2005	25.4	3.1

Season-Middle winter 2004-2005	DO mean in mg/L 7.5	Standard deviation 2.0
spring 2005	4.3	1.9
summer 2005	2.8	1.8
autumn 2005	5.7	2.3
Season-Middle	pH mean	Standard deviation
winter 2004-2005	7.2	0.3
spring 2005	8.2	0.3
summer 2005	not recorded	not recorded
autumn 2005	8.0	0.2
Season-Bottom	Temperature mean (°C)	Standard deviation
winter 2004-2005	15.7	2.8
spring 2005	21.4	1.5
summer 2005	28.5	2.8
autumn 2005	23.1	3.3
Season-Bottom	Salinity mean (ppt)	Standard deviation
winter 2004-2005	22.9	3.3
spring 2005	28.4	4.1
summer 2005	30.2	2.2
autumn 2005	25.8	2.3
Season-Bottom	DO mean (mg/L)	Standard deviation
winter 2004-2005	4.1	3.3
spring 2005	2.4	2.3
summer 2005	1.3	1.6
autumn 2005	4.3	2.9
Season-Bottom	pH mean	Standard deviation
winter 2004-2005	7.0	0.6
spring 2005	7.8	0.5
summer 2005	not recorded	not recorded
autumn 2005	7.8	0.3

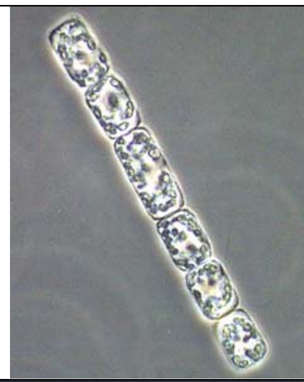
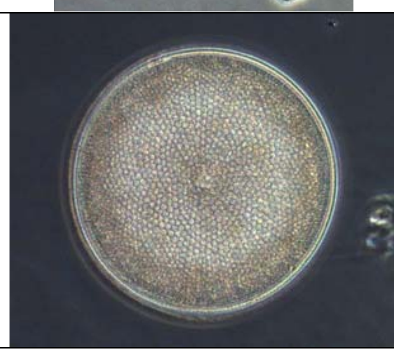
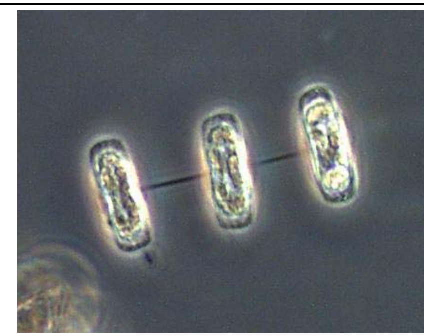
3. Annual Surface, Middle and Bottom
Temperature, Salinity, Dissolved Oxygen and pH Data

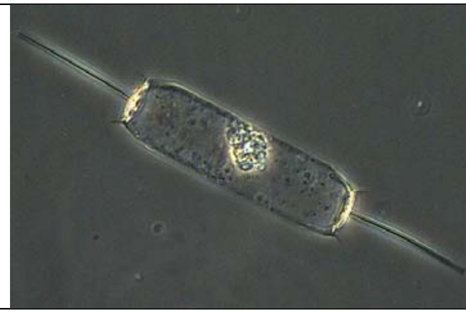
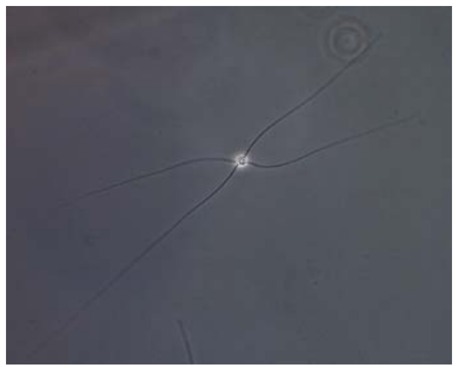
Depth	Temperature mean (ºC)	Standard deviation
surface	20.7	6.2
middle	20.6	6.0
bottom	20.3	5.5
	Salinity mean (ppt)	Standard deviation
surface	22.2	4.9
middle	24.0	4.3
bottom	25.7	4.3
	DO2 mean (mg/L)	Standard deviation
surface	7.8	2.2
middle	5.7	3.0
bottom	3.3	3.1
	pH mean	Standard deviation
surface	7.9	0.9
middle	7.7	0.7
bottom	7.5	0.7

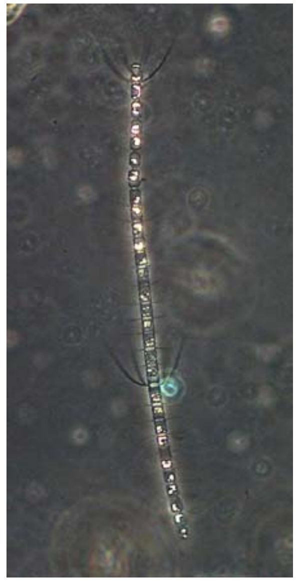
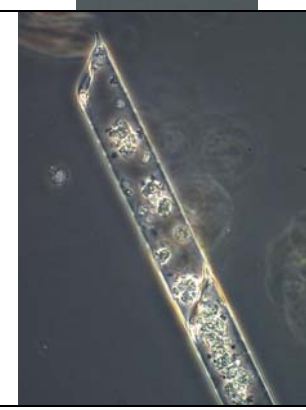
APPENDIX C

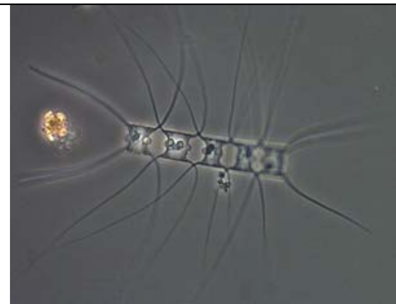
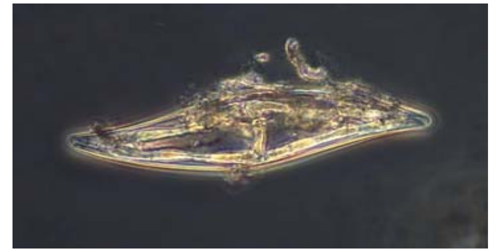
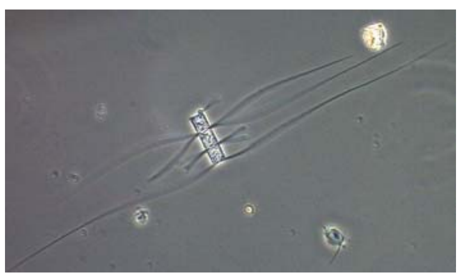
PHYTOPLANKTON, CHL a and PHAEO a DATA

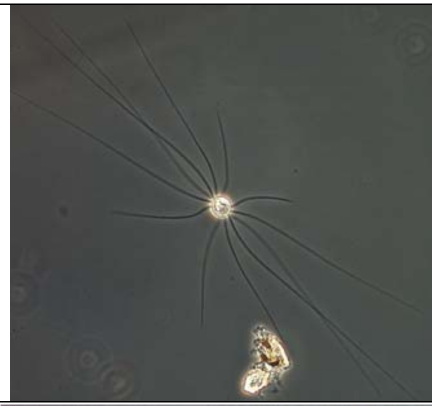
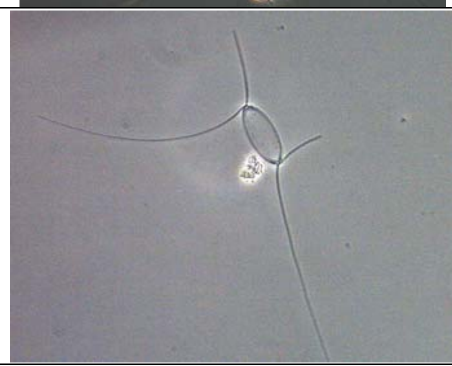
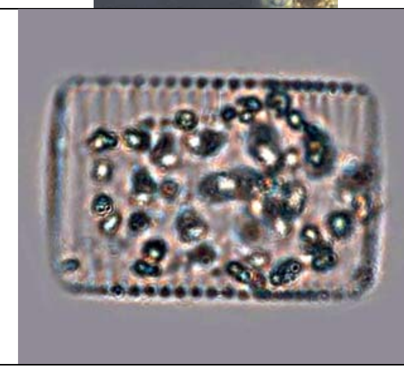
1. Phytoplankton (40 µm and cropped)

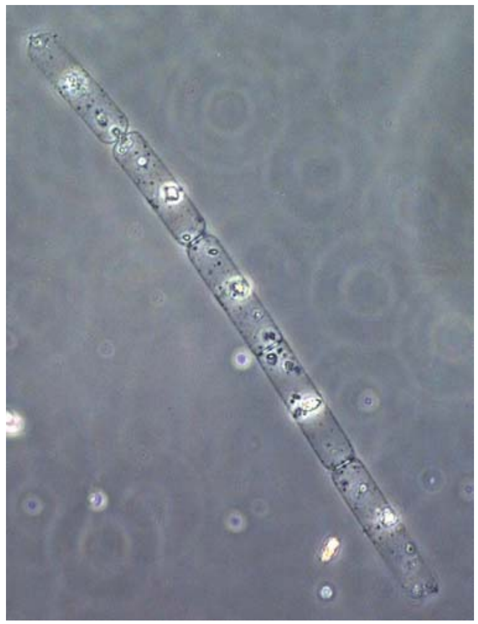
Bacillarophyta (centric diatoms)		**Bacillarophyta (pennate diatoms)**	
Guinardia delicatula		*Thalassiosira pacifica*	
Coscinodiscus radiatus		*Thalassiosira cf.*	

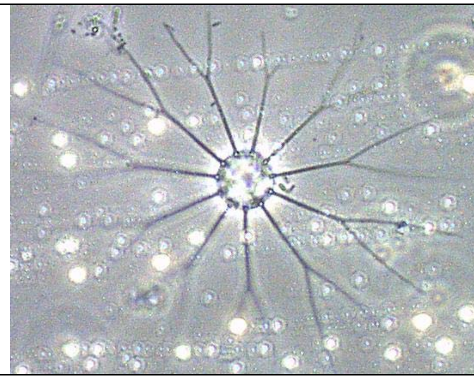
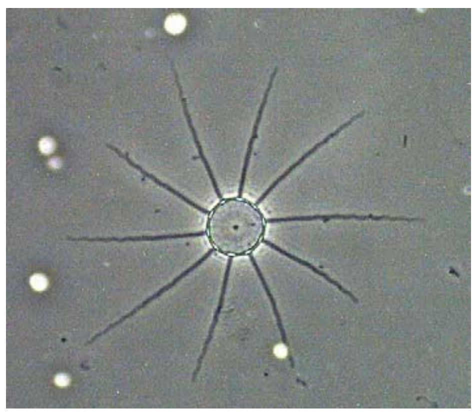
Ditylum brightwelli		*Melosira nummuloides*	
Chaetoceros danicus		*Rhizosolenia pungens*	

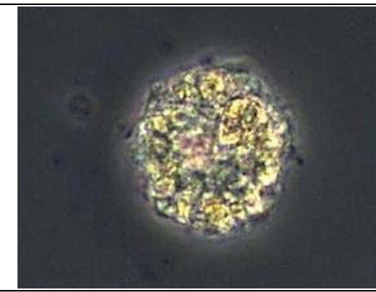
Chaetoceros didymus		*Rhizosolenia setigera*	
Chaetoceros curvisetus		*Rhiszosolenia imbricata*	

Chaetoceros decipiens		*Pleurosigma normanii*	
Chaetoceros lorenzianus		*Pleurosigma macrum*	
Chaetoceros affinis		*Odontella mobilensis*	

Chaetoceros spp. A		*Navicula directa*	
Chaetoceros spp. B		*Striatella unipuncta*	

Dactyliosolen fragillissimus		*Lithodesmium undulatum*	

Bacteriastrum furcatum		*Fragilaria striatula*	
Bacteriastrum hyalinum		*Skeletonema menzellii*	

Euglenophtya		**Haptophyta**	
Euglenophyta spp. A		*Corymbellus aureus*	

2. Seasonal chl a (µg/L), phaeo a (µg/L) and mean abundance (cells/L) per station.
(L = low, I = intermediate, M = moderate, H = high concentrations of chl *a,* phaeo and abundance cells).

Winter	mean chl *a*	mean phaeophytin	Mean total abundance	Summer	mean chl *a*	mean phaeophytin	Mean total abundance
1	0.0013 L	0.0003 L	$7 x 10^6$ I	1	0.0082 I	0.0071 I	$46 x 10^6$ I
2	0.0019 I	0.0001 L	$12 x 10^6$ M	2	0.0099 I	0.0087 I	$37 x 10^6$ I
3	0.0020 I	0.0010 L	$13 x 10^6$ M	3	0.0152 M	0.0106 I	$121 x 10^6$ H
4	0.0022 I	0.0011 L	$18 x 10^6$ H	4	0.0140 M	0.0128 M	$59 x 10^6$ I
5	0.0033 M	0.0021 I	$20 x 10^6$ H	5	0.0110 I	0.0102 I	$59 x 10^6$ I
7	0.0054 H	0.0041 H	$11 x 10^6$ M	7	0.0250 H	0.0252 H	$86 x 10^6$ M
8	0.0060 H	0.0047 H	$10 x 10^6$ I	8	0.0219 H	0.0217 H	$50 x 10^6$ I
9	0.0022 I	0.0012 L	$5 x 10^6$ L	9	0.0108 I	0.0103 I	$50 x 10^6$ I
10	0.0014 L	0.0009 L	$7 x 10^6$ I	10	0.0069 I	0.0059 L	$43 x 10^6$ I
11	0.0016 I	0.0009 L	$10 x 10^6$ I	11	0.0030 L	0.0013 L	$14 x 10^6$ L
12	0.0019 I	0.0011 L	$8 x 10^6$ I	12	0.0029 L	0.0015 L	$19 x 10^6$ L
Spring	mean chl *a*	mean phaeophytin	mean total abundance	Autumn	mean chl *a*	mean phaeophytin	mean total abundance
1	0.0016 I	0.0008 I	$2 x 10^5$ L	1	0.0018 I	0.0005 L	$9 x 10^6$ M
2	0.0016 I	0.0008 I	$1 x 10^6$ H	2	0.0028 I	0.0011 L	$3 x 10^6$ L
3	0.0020 I	0.0009 I	$5 x 10^4$ L	3	0.0025 I	0.0090 H	$12 x 10^6$ H
4	0.0022 I	0.0011 M	$6 x 10^5$ I	4	0.0023 I	0.0044 M	$8 x 10^5$ M
5	0.0019 I	0.0009 I	$9 x 10^5$ M	5	0.0033 M	0.0015 L	$5 x 10^6$ I
7	0.0027 M	0.0012 M	$1 x 10^6$ H	7	0.0060 H	0.0049 M	$3 x 10^6$ L
8	0.0044 H	0.0021 H	$5 x 10^5$ I	8	0.0043 M	0.0018 L	$4 x 10^6$ I
9	0.0016 I	0.0006 I	$7 x 10^5$ I	9	0.0034 M	0.0013 L	$12 x 10^6$ H
10	0.0013 I	0.0006 I	$4 x 10^5$ I	10	0.0031 M	0.0016 L	$11 x 10^6$ H
11	0.0013 I	0.0006 I	$5 x 10^5$ I	11	0.0021 I	0.0009 L	$3 x 10^6$ L
12	0.0012 I	0.0006 I	$3 x 10^5$ L	12	0.0020 I	0.0008 L	$9 x 10^6$ M

3. Chlorophyll a and Phaeophytin a concentrations (µg/L) per sample date

sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
1-Dec-04	1C	1	winter	1	0.0017	0.0009
1-Dec-04	2C	1	winter	2	0.0027	0.0014
1-Dec-04	3C	1	winter	3	0.0021	0.0011
1-Dec-04	4C	1	winter	4	0.0018	0.0009
1-Dec-04	5C	1	winter	5	0.0029	0.0013
1-Dec-04	7C	1	winter	6	0.0081	0.0085
1-Dec-04	8C	1	winter	7	0.0053	0.0022
1-Dec-04	9C	1	winter	8	0.0021	0.0010
1-Dec-04	10C	1	winter	9	0.0013	0.0007
1-Dec-04	11C	1	winter	10	0.0014	0.0006
1-Dec-04	12C	1	winter	11	0.0009	0.0004
8-Dec-04	1D	1	winter	12	0.0024	0.0013
8-Dec-04	2D	1	winter	13	0.0023	0.0006
8-Dec-04	3D	1	winter	14	0.0029	0.0015
8-Dec-04	4D	1	winter	15	0.0035	0.0019
8-Dec-04	5D	1	winter	16	0.0038	0.0018
8-Dec-04	7D	1	winter	17	0.0035	0.0016
8-Dec-04	8D	1	winter	18	0.0031	0.0016
8-Dec-04	9D	1	winter	19	0.0032	0.0018
8-Dec-04	10D	1	winter	20	0.0019	0.0009
8-Dec-04	11D	1	winter	21	0.0011	0.0004
8-Dec-04	12D	1	winter	22	0.0004	0.0001
16-Dec-04	1E	1	winter	23	0.0043	0.0026
16-Dec-04	2E	1	winter	24	0.0041	0.0024
16-Dec-04	3E	1	winter	25	0.0050	0.0024
16-Dec-04	4E	1	winter	26	0.0045	0.0029

Continued...

sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
16-Dec-04	5E	1	winter	27	0.0047	0.0030
16-Dec-04	7E	1	winter	28	0.0077	0.0082
16-Dec-04	8E	1	winter	29	0.0092	0.0098
16-Dec-04	9E	1	winter	30	0.0026	0.0014
16-Dec-04	10E	1	winter	31	0.0016	0.0007
16-Dec-04	11E	1	winter	32	0.0008	0.0004
16-Dec-04	12E	1	winter	33	0.0011	0.0005
22-Dec-04	1F	1	winter	34	0.0023	0.0012
22-Dec-04	2F	1	winter	35	0.0006	0.0003
22-Dec-04	3F	1	winter	36	0.0018	0.0009
22-Dec-04	4F	1	winter	37	0.0014	0.0008
22-Dec-04	5F	1	winter	38	0.0037	0.0022
22-Dec-04	7F	1	winter	39	0.0032	0.0017
22-Dec-04	8F	1	winter	40	0.0075	0.0073
22-Dec-04	9F	1	winter	41	0.0031	0.0018
22-Dec-04	10F	1	winter	42	0.0025	0.0014
22-Dec-04	11F	1	winter	43	0.0025	0.0015
22-Dec-04	12F	1	winter	44	0.0011	0.0005
30-Dec-04	1G	1	winter	45	0.0013	0.0005
30-Dec-04	2G	1	winter	46	0.0007	0.0004
30-Dec-04	3G	1	winter	47	0.0006	0.0004
30-Dec-04	4G	1	winter	48	0.0011	0.0005
30-Dec-04	5G	1	winter	49	0.0040	0.0025
30-Dec-04	7G	1	winter	50	0.0105	0.0086
30-Dec-04	8G	1	winter	51	0.0106	0.0075

Continued…

sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
30-Dec-04	9G	1	winter	52	0.0020	0.0008
30-Dec-04	10G	1	winter	53	0.0023	0.0010
30-Dec-04	11G	1	winter	54	0.0013	-0.0032
30-Dec-04	12G	1	winter	55	0.0044	0.0028
6-Jan-05	1H	1	winter	56	0.0012	0.0005
6-Jan-05	2H	1	winter	57	0.0014	0.0008
6-Jan-05	3H	1	winter	58	0.0020	0.0009
6-Jan-05	4H	1	winter	59	0.0017	0.0009
6-Jan-05	5H	1	winter	60	0.0018	0.0009
6-Jan-05	7H	1	winter	61	0.0018	0.0013
6-Jan-05	8H	1	winter	62	0.0049	0.0022
6-Jan-05	9H	1	winter	63	0.0021	0.0012
6-Jan-05	10H	1	winter	64	0.0003	0.0001
6-Jan-05	11H	1	winter	65	0.0010	0.0005
6-Jan-05	12H	1	winter	66	0.0008	0.0002
15-Jan-05	1I	1	winter	67	0.0012	0.0006
15-Jan-05	2I	1	winter	68	0.0020	0.0009
15-Jan-05	3I	1	winter	69	0.0022	0.0011
15-Jan-05	4I	1	winter	70	0.0025	0.0005
15-Jan-05	5I	1	winter	71	0.0056	0.0028
15-Jan-05	7I	1	winter	72	0.0060	0.0032
15-Jan-05	8I	1	winter	73	0.0024	0.0013
19-Jan-05	1J	1	winter	74	0.0005	0.0003
19-Jan-05	2J	1	winter	75	0.0013	0.0007
19-Jan-05	3J	1	winter	76	0.0014	0.0005

Continued…						
sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
19-Jan-05	4J	1	winter	77	0.0014	0.0006
19-Jan-05	5J	1	winter	78	0.0013	0.0007
19-Jan-05	7J	1	winter	79	0.0026	0.0011
19-Jan-05	8J	1	winter	80	0.0037	0.0020
19-Jan-05	9J	1	winter	81	0.0012	0.0005
19-Jan-05	10J	1	winter	82	0.0012	0.0004
19-Jan-05	11J	1	winter	83	0.0014	0.0008
19-Jan-05	12J	1	winter	84	0.0020	0.0010
26-Jan-05	1K	1	winter	85	0.0008	0.0004
26-Jan-05	2K	1	winter	86	0.0014	0.0008
26-Jan-05	3K	1	winter	87	0.0013	0.0007
26-Jan-05	4K	1	winter	88	0.0008	0.0003
26-Jan-05	5K	1	winter	89	0.0024	0.0025
26-Jan-05	7K	1	winter	90	0.0090	0.0050
26-Jan-05	8K	1	winter	91	0.0118	0.0102
26-Jan-05	9K	1	winter	92	0.0011	0.0006
26-Jan-05	10K	1	winter	93	0.0009	0.0004
26-Jan-05	11K	1	winter	94	0.0003	0.0001
26-Jan-05	12K	1	winter	95	0.0006	0.0002
4-Feb-05	1L	1	winter	96	0.0005	0.0002
4-Feb-05	2L	1	winter	97	0.0010	0.0003
4-Feb-05	3L	1	winter	98	0.0022	0.0012
4-Feb-05	4L	1	winter	99	0.0041	0.0024
4-Feb-05	5L	1	winter	100	0.0054	0.0032
4-Feb-05	7L	1	winter	101	0.0010	0.0009

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
4-Feb-05	8L	1	winter	102	0.0011	0.0009
4-Feb-05	9L	1	winter	103	0.0037	0.0026
4-Feb-05	10L	1	winter	104	0.0043	0.0023
4-Feb-05	11L	1	winter	105	0.0031	0.0019
4-Feb-05	12L	1	winter	106	0.0036	0.0021
11-Feb-05	1M	1	winter	107	0.0021	-0.0054
11-Feb-05	2M	1	winter	108	0.0048	-0.0115
11-Feb-05	3M	1	winter	109	0.0026	0.0014
11-Feb-05	4M	1	winter	110	0.0022	0.0012
11-Feb-05	5M	1	winter	111	0.0082	0.0069
11-Feb-05	7M	1	winter	112	0.0116	0.0092
11-Feb-05	8M	1	winter	113	0.0155	0.0123
11-Feb-05	9M	1	winter	114	0.0020	0.0011
11-Feb-05	10M	1	winter	115	0.0029	0.0013
11-Feb-05	11M	1	winter	116	0.0017	0.0010
11-Feb-05	12M	1	winter	117	0.0033	0.0019
18-Feb-05	1N	1	winter	118	0.0003	0.0001
18-Feb-05	2N	1	winter	119	0.0005	0.0003
18-Feb-05	3N	1	winter	120	0.0005	0.0002
18-Feb-05	4N	1	winter	121	0.0005	0.0002
18-Feb-05	5N	1	winter	122	0.0008	0.0003
18-Feb-05	8N	1	winter	123	0.0006	0.0001
18-Feb-05	9N	1	winter	124	0.0005	0.0002
18-Feb-05	12N	1	winter	125	0.0046	0.0028
3-Mar-05	1O	1	winter	126	0.0008	0.0002

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
3-Mar-05	2O	1	winter	127	0.0011	0.0004
3-Mar-05	3O	1	winter	128	0.0019	0.0010
3-Mar-05	4O	1	winter	129	0.0030	0.0016
3-Mar-05	5O	1	winter	130	0.0021	0.0011
3-Mar-05	7O	1	winter	131	0.0102	0.0086
3-Mar-05	8O	1	winter	132	0.0157	0.0147
3-Mar-05	9O	1	winter	133	0.0028	0.0017
3-Mar-05	10O	1	winter	134	0.0026	0.0021
3-Mar-05	11O	1	winter	135	0.0039	0.0021
3-Mar-05	12O	1	winter	136	0.0026	0.0014
10-Mar-05	1P	1	winter	137	0.0004	0.0002
10-Mar-05	2P	1	winter	138	0.0032	0.0021
10-Mar-05	3P	1	winter	139	0.0038	0.0024
10-Mar-05	4P	1	winter	140	0.0028	0.0014
10-Mar-05	5P	1	winter	141	0.0021	0.0013
10-Mar-05	7P	1	winter	142	0.0017	0.0010
10-Mar-05	8P	1	winter	143	0.0022	0.0015
10-Mar-05	9P	1	winter	144	0.0034	0.0022
10-Mar-05	10P	1	winter	145	0.0017	0.0010
10-Mar-05	11P	1	winter	146	0.0013	0.0007
10-Mar-05	12P	1	winter	147	0.0011	0.0006
24-Mar-05	1Q	1	winter	148	0.0006	0.0003
24-Mar-05	2Q	1	winter	149	0.0013	0.0008
24-Mar-05	3Q	1	winter	150	0.0005	0.0004
24-Mar-05	4Q	1	winter	151	0.0016	0.0011

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
24-Mar-05	5Q	1	winter	152	0.0022	0.0016
24-Mar-05	7Q	1	winter	153	0.0026	0.0014
24-Mar-05	8Q	1	winter	154	0.0014	0.0007
24-Mar-05	9Q	1	winter	155	0.0007	0.0004
24-Mar-05	10Q	1	winter	156	0.0009	0.0006
24-Mar-05	11Q	1	winter	157	0.0006	0.0004
24-Mar-05	12Q	1	winter	158	0.0006	0.0003
31-Mar-05	1R	1	winter	159	0.0010	0.0004
31-Mar-05	2R	1	winter	160	0.0016	0.0010
31-Mar-05	3R	1	winter	161	0.0015	0.0007
31-Mar-05	4R	1	winter	162	0.0022	0.0009
31-Mar-05	5R	1	winter	163	0.0025	0.0013
31-Mar-05	7R	1	winter	164	0.0021	0.0012
31-Mar-05	8R	1	winter	165	0.0013	0.0007
31-Mar-05	9R	1	winter	166	0.0017	0.0011
31-Mar-05	10R	1	winter	167	0.0018	0.0010
31-Mar-05	11R	1	winter	168	0.0012	0.0006
31-Mar-05	12R	1	winter	169	0.0019	0.0011
12-Apr-05	1S	2	spring	170	0.0014	0.0008
12-Apr-05	2S	2	spring	171	0.0015	0.0007
12-Apr-05	3S	2	spring	172	0.0019	0.0009
12-Apr-05	4S	2	spring	173	0.0030	0.0019
12-Apr-05	5S	2	spring	174	0.0028	0.0015
12-Apr-05	7S	2	spring	175	0.0032	0.0016
12-Apr-05	8S	2	spring	176	0.0033	0.0017

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
12-Apr-05	9S	2	spring	177	0.0009	0.0004
12-Apr-05	10S	2	spring	178	0.0015	0.0007
12-Apr-05	11S	2	spring	179	0.0012	0.0006
12-Apr-05	12S	2	spring	180	0.0013	0.0005
20-Apr-05	1T	2	spring	181	0.0016	0.0007
20-Apr-05	2T	2	spring	182	0.0019	0.0012
20-Apr-05	3T	2	spring	183	0.0018	0.0008
20-Apr-05	4T	2	spring	184	0.0017	0.0007
20-Apr-05	5T	2	spring	185	0.0007	0.0002
20-Apr-05	7T	2	spring	186	0.0028	0.0012
20-Apr-05	8T	2	spring	187	0.0044	0.0021
20-Apr-05	9T	2	spring	188	0.0012	0.0004
20-Apr-05	10T	2	spring	189	0.0011	0.0005
20-Apr-05	11T	2	spring	190	0.0012	0.0006
20-Apr-05	12T	2	spring	191	0.0010	0.0005
27-Apr-05	1U	2	spring	192	0.0007	0.0003
27-Apr-05	2U	2	spring	193	0.0005	0.0002
27-Apr-05	3U	2	spring	194	0.0003	0.0001
27-Apr-05	4U	2	spring	195	0.0017	0.0009
27-Apr-05	5U	2	spring	196	0.0007	0.0003
27-Apr-05	7U	2	spring	197	0.0009	0.0004
27-Apr-05	8U	2	spring	198	0.0036	0.0015
27-Apr-05	9U	2	spring	199	0.0002	0.0001
27-Apr-05	10U	2	spring	200	0.0007	0.0003
27-Apr-05	11U	2	spring	201	0.0012	0.0004

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
27-Apr-05	12U	2	spring	202	0.0012	0.0006
6-May-05	1V	2	spring	203	0.0020	0.0011
6-May-05	2V	2	spring	204	0.0021	0.0010
6-May-05	3V	2	spring	205	0.0013	0.0005
6-May-05	4V	2	spring	206	0.0012	0.0006
6-May-05	5V	2	spring	207	0.0022	0.0011
6-May-05	7V	2	spring	208	0.0037	0.0016
6-May-05	8V	2	spring	209	0.0058	0.0029
6-May-05	9V	2	spring	210	0.0022	0.0008
6-May-05	10V	2	spring	211	0.0013	0.0006
6-May-05	11V	2	spring	212	0.0013	0.0006
6-May-05	12V	2	spring	213	0.0014	0.0007
11-May-05	1W	2	spring	214	0.0025	0.0012
11-May-05	2W	2	spring	215	0.0023	0.0010
11-May-05	3W	2	spring	216	0.0046	0.0019
11-May-05	4W	2	spring	217	0.0035	0.0015
11-May-05	5W	2	spring	218	0.0029	0.0012
11-May-05	7W	2	spring	219	0.0027	0.0010
11-May-05	8W	2	spring	220	0.0048	0.0022
11-May-05	9W	2	spring	221	0.0032	0.0014
11-May-05	10W	2	spring	222	0.0020	0.0010
11-May-05	11W	2	spring	223	0.0018	0.0009
11-May-05	12W	2	spring	224	0.0012	0.0006
2-Jun-05	1X	3	summer	225	0.0028	0.0014
2-Jun-05	2X	3	summer	226	0.0032	0.0019

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
2-Jun-05	3X	3	summer	227	0.0025	0.0009
2-Jun-05	4X	3	summer	228	0.0028	0.0014
2-Jun-05	5X	3	summer	229	0.0055	0.0031
2-Jun-05	7X	3	summer	230	0.0031	0.0014
2-Jun-05	8X	3	summer	231	0.0046	0.0023
2-Jun-05	9X	3	summer	232	0.0015	0.0008
2-Jun-05	10X	3	summer	233	0.0019	0.0007
2-Jun-05	11X	3	summer	234	0.0018	0.0006
2-Jun-05	12X	3	summer	235	0.0027	0.0014
9-Jun-05	Y1	3	summer	236	0.0017	0.0005
9-Jun-05	Y2	3	summer	237	0.0019	0.0007
9-Jun-05	Y3	3	summer	238	0.0020	0.0006
9-Jun-05	Y4	3	summer	239	0.0025	0.0010
9-Jun-05	Y5	3	summer	240	0.0026	0.0010
9-Jun-05	Y7	3	summer	241	0.0022	0.0005
9-Jun-05	Y8	3	summer	242	0.0026	0.0008
9-Jun-05	Y9	3	summer	243	0.0046	0.0022
9-Jun-05	Y10	3	summer	244	0.0023	0.0008
9-Jun-05	Y11	3	summer	245	0.0016	0.0006
9-Jun-05	Y12	3	summer	246	0.0020	0.0009
15-Jun-05	Z1	3	summer	247	0.0017	0.0008
15-Jun-05	Z2	3	summer	248	0.0024	0.0014
15-Jun-05	Z3	3	summer	249	0.0027	0.0015
15-Jun-05	Z4	3	summer	250	0.0028	0.0015
15-Jun-05	Z5	3	summer	251	0.0025	0.0011

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
15-Jun-05	Z7	3	summer	252	0.0036	0.0019
15-Jun-05	Z8	3	summer	253	0.0031	0.0014
15-Jun-05	Z9	3	summer	254	0.0029	0.0008
15-Jun-05	Z10	3	summer	255	0.0031	0.0008
15-Jun-05	Z11	3	summer	256	0.0038	0.0023
15-Jun-05	Z12	3	summer	257	0.0014	0.0007
22-Jun-05	AA1	3	summer	258	0.0025	0.0005
22-Jun-05	AA2	3	summer	259	0.0029	0.0007
22-Jun-05	AA3	3	summer	260	0.0020	0.0007
22-Jun-05	AA4	3	summer	261	0.0033	0.0014
22-Jun-05	AA5	3	summer	262	0.0030	0.0012
22-Jun-05	AA7	3	summer	263	0.0257	0.0251
22-Jun-05	AA8	3	summer	264	0.0153	0.0150
22-Jun-05	AA9	3	summer	265	0.0019	0.0009
22-Jun-05	AA10	3	summer	266	0.0029	0.0011
22-Jun-05	AA11	3	summer	267	0.0024	0.0011
22-Jun-05	AA12	3	summer	268	0.0018	0.0008
5-Jul-05	AB1	3	summer	269	0.0024	0.0012
5-Jul-05	AB2	3	summer	270	0.0030	0.0014
5-Jul-05	AB3	3	summer	271	0.0025	-0.0006
5-Jul-05	AB4	3	summer	272	0.0024	0.0011
5-Jul-05	AB5	3	summer	273	0.0095	0.0085
5-Jul-05	AB7	3	summer	274	0.0464	0.0442
5-Jul-05	AB8	3	summer	275	0.0482	0.0542
5-Jul-05	AB9	3	summer	276	0.0126	0.0121

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
5-Jul-05	AB10	3	summer	277	0.0051	0.0031
5-Jul-05	AB11	3	summer	278	0.0024	0.0011
5-Jul-05	AB12	3	summer	279	0.0037	0.0019
21-Jul-05	AD1	3	summer	280	0.0035	0.0020
21-Jul-05	AD2	3	summer	281	0.0025	0.0014
21-Jul-05	AD3	3	summer	282	0.0058	0.0027
21-Jul-05	AD4	3	summer	283	0.0095	0.0084
21-Jul-05	AD5	3	summer	284	0.0208	0.0191
21-Jul-05	AD7	3	summer	285	0.0053	0.0004
21-Jul-05	AD8	3	summer	286	0.0066	0.0027
21-Jul-05	AD9	3	summer	287	0.0063	0.0036
21-Jul-05	AD10	3	summer	288	0.0005	0.0004
21-Jul-05	AD11	3	summer	289	0.0024	0.0012
21-Jul-05	AD12	3	summer	290	0.0002	0.0001
28-Jul-05	AE1	3	summer	291	0.0010	0.0005
28-Jul-05	AE2	3	summer	292	0.0027	0.0014
28-Jul-05	AE3	3	summer	293	0.0063	0.0039
28-Jul-05	AE4	3	summer	294	0.0135	0.0131
28-Jul-05	AE5	3	summer	295	0.0096	0.0085
28-Jul-05	AE7	3	summer	296	0.0215	0.0198
28-Jul-05	AE8	3	summer	297	0.0502	0.0427
28-Jul-05	AE9	3	summer	298	0.0194	0.0170
28-Jul-05	AE10	3	summer	299	0.0123	0.0115
28-Jul-05	AE11	3	summer	300	0.0022	0.0008
28-Jul-05	AE12	3	summer	301	0.0033	0.0025

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
6-Aug-05	AF1	3	summer	302	0.0007	0.0002
6-Aug-05	AF2	3	summer	303	0.0056	0.0032
6-Aug-05	AF3	3	summer	304	0.0047	0.0017
6-Aug-05	AF4	3	summer	305	0.0045	0.0022
6-Aug-05	AF5	3	summer	306	0.0147	0.0132
6-Aug-05	AF7	3	summer	307	0.0558	0.0658
6-Aug-05	AF8	3	summer	308	0.0239	0.0215
6-Aug-05	AF9	3	summer	309	0.0325	0.0357
6-Aug-05	AF10	3	summer	310	0.0122	0.0108
6-Aug-05	AF11	3	summer	311	0.0028	0.0012
6-Aug-05	AF12	3	summer	312	0.0043	0.0026
12-Aug-05	AG1	3	summer	313	0.0080	0.0071
12-Aug-05	AG2	3	summer	314	0.0179	0.0176
12-Aug-05	AG3	3	summer	315	0.0097	0.0090
12-Aug-05	AG4	3	summer	316	0.0178	0.0173
12-Aug-05	AG5	3	summer	317	0.0043	0.0024
12-Aug-05	AG7	3	summer	318	0.0128	0.0118
12-Aug-05	AG8	3	summer	319	0.0352	0.0336
12-Aug-05	AG9	3	summer	320	0.0031	0.0019
12-Aug-05	AH10	3	summer	321	0.0017	0.0008
12-Aug-05	AG11	3	summer	322	0.0016	0.0005
12-Aug-05	AG12	3	summer	323	0.0035	0.0018
19-Aug-05	AH1	3	summer	324	0.0115	0.0114
19-Aug-05	AH2	3	summer	325	0.0199	0.0181
19-Aug-05	AH3	3	summer	326	0.0247	0.0230

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
19-Aug-05	AH4	3	summer	327	0.0217	0.0219
19-Aug-05	AH5	3	summer	328	0.0130	0.0131
19-Aug-05	AH7	3	summer	329	0.0176	0.0154
19-Aug-05	AH8	3	summer	330	0.0417	0.0381
19-Aug-05	AH9	3	summer	331	0.0269	0.0246
19-Aug-05	AH10	3	summer	332	0.0193	0.0177
19-Aug-05	AH11	3	summer	333	0.0063	0.0029
19-Aug-05	AH12	3	summer	334	0.0041	0.0017
25-Aug-05	AI1	3	summer	335	0.0626	0.0572
25-Aug-05	AI2	3	summer	336	0.0590	0.0547
25-Aug-05	AI3	3	summer	337	0.0880	0.0836
25-Aug-05	AI4	3	summer	338	0.0504	0.0535
25-Aug-05	AI5	3	summer	339	0.0464	0.0436
25-Aug-05	AI7	3	summer	340	0.1156	0.1179
25-Aug-05	AI8	3	summer	341	0.0455	0.0484
25-Aug-05	AI9	3	summer	342	0.0201	0.0171
25-Aug-05	AI10	3	summer	343	0.0105	0.0097
25-Aug-05	AI11	3	summer	344	0.0043	0.0009
25-Aug-05	AI12	3	summer	345	0.0038	0.0020
15-Sep-05	AK1	3	summer	346	0.0068	0.0024
15-Sep-05	AK2	3	summer	347	0.0039	0.0022
15-Sep-05	AK3	3	summer	348	0.0023	0.0003
15-Sep-05	AK4	3	summer	349	0.0305	0.0303
15-Sep-05	AK5	3	summer	350	0.0080	0.0079
15-Sep-05	AK7	3	summer	351	0.0042	-0.0013

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
15-Sep-05	AK8	3	summer	352	0.0036	0.0000
15-Sep-05	AK9	3	summer	353	0.0075	0.0064
15-Sep-05	AK10	3	summer	354	0.0145	0.0132
15-Sep-05	AK11	3	summer	355	0.0046	0.0024
15-Sep-05	AK12	3	summer	356	0.0036	0.0016
29-Sep-05	AL1	3	summer	357	0.0013	0.0004
29-Sep-05	AL2	3	summer	358	0.0033	0.0014
29-Sep-05	AL3	3	summer	359	0.0443	0.0405
29-Sep-05	AL4	3	summer	360	0.0203	0.0179
29-Sep-05	AL5	3	summer	361	0.0030	0.0019
29-Sep-05	AL7	3	summer	362	0.0118	0.0102
29-Sep-05	AL8	3	summer	363	0.0044	0.0023
29-Sep-05	AL9	3	summer	364	0.0009	0.0004
29-Sep-05	AL10	3	summer	365	0.0033	0.0014
29-Sep-05	AL11	3	summer	366	0.0031	0.0012
29-Sep-05	AL12	3	summer	367	0.0025	0.0008
5-Oct-05	AM1	4	autumn	368	0.0018	0.0001
5-Oct-05	AM2	4	autumn	369	0.0022	0.0002
5-Oct-05	AM3	4	autumn	370	0.0018	0.0006
5-Oct-05	AM4	4	autumn	371	0.0019	0.0004
5-Oct-05	AM5	4	autumn	372	0.0027	0.0008
5-Oct-05	AM7	4	autumn	373	0.0029	0.0008
5-Oct-05	AM8	4	autumn	374	0.0034	0.0012
5-Oct-05	AM9	4	autumn	375	0.0022	0.0004
5-Oct-05	AM10	4	autumn	376	0.0019	0.0006

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sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
5-Oct-05	AM11	4	autumn	377	0.0022	0.0008
5-Oct-05	AM12	4	autumn	378	0.0022	0.0009
19-Oct-05	AN1	4	autumn	379	0.0012	0.0003
19-Oct-05	AN2	4	autumn	380	0.0012	0.0002
19-Oct-05	AN3	4	autumn	381	0.0017	0.0005
19-Oct-05	AN4	4	autumn	382	0.0017	0.0005
19-Oct-05	AN5	4	autumn	383	0.0027	0.0009
19-Oct-05	AN7	4	autumn	384	0.0058	0.0022
19-Oct-05	AN8	4	autumn	385	0.0047	0.0019
19-Oct-05	AN9	4	autumn	386	0.0023	0.0007
19-Oct-05	AN10	4	autumn	387	0.0020	0.0008
19-Oct-05	AN11	4	autumn	388	0.0016	0.0003
19-Oct-05	AN12	4	autumn	389	0.0015	0.0005
26-Oct-05	AO1	4	autumn	390	0.0016	0.0005
26-Oct-05	AO2	4	autumn	391	0.0046	0.0021
26-Oct-05	AO3	4	autumn	392	0.0011	0.0003
26-Oct-05	AO4	4	autumn	393	0.0032	0.0015
26-Oct-05	AO5	4	autumn	394	0.0037	0.0014
26-Oct-05	AO7	4	autumn	395	0.0125	0.0101
26-Oct-05	AO8	4	autumn	396	0.0039	0.0015
26-Oct-05	AO9	4	autumn	397	0.0063	0.0034
26-Oct-05	AO10	4	autumn	398	0.0065	0.0033
26-Oct-05	AO11	4	autumn	399	0.0018	0.0009
26-Oct-05	AO12	4	autumn	400	0.0017	0.0007
2-Nov-05	AP1	4	autumn	401	0.0032	0.0013

Continued…						
sample date	sample station	season category	season	sample number	chlorophyll *a*	phaeophytin
2-Nov-05	AP2	4	autumn	402	0.0042	0.0016
2-Nov-05	AP3	4	autumn	403	0.0059	0.0032
2-Nov-05	AP4	4	autumn	404	0.0037	0.0017
2-Nov-05	AP5	4	autumn	405	0.0050	0.0024
2-Nov-05	AP7	4	autumn	406	0.0033	0.0014
2-Nov-05	AP8	4	autumn	407	0.0050	0.0021
2-Nov-05	AP9	4	autumn	408	0.0040	0.0016
2-Nov-05	AP10	4	autumn	409	0.0037	0.0020
2-Nov-05	AP11	4	autumn	410	0.0031	0.0015
2-Nov-05	AP12	4	autumn	411	0.0023	0.0011
11-Nov-05	AQ1	4	autumn	412	0.0012	0.0005
11-Nov-05	AQ2	4	autumn	413	0.0019	0.0008
11-Nov-05	AQ3	4	autumn	414	0.0020	0.0005
11-Nov-05	AQ4	4	autumn	415	0.0007	0.0002
11-Nov-05	AQ5	4	autumn	416	0.0024	0.0010
11-Nov-05	AQ7	4	autumn	417	0.0053	0.0024
11-Nov-05	AQ8	4	autumn	418	0.0045	0.0024
11-Nov-05	AQ9	4	autumn	419	0.0024	0.0010
11-Nov-05	AQ10	4	autumn	420	0.0012	0.0005
11-Nov-05	AQ11	4	autumn	421	0.0018	0.0008
11-Nov-05	AQ12	4	autumn	422	0.0022	0.0010

APPENDIX D

METEOROLOGICAL AND TIDAL DATA

Meteorological data

Date	Minimum Temperature (°C)	Mean Temperature (°C)	Maximum Temperature (°C)	Mean Sea Level Pressure (cm)	Total Precipitation (cm)	Mean Wind Speed (kmph)	Maximum Sustained Wind (kmph)	Maximum Wind Gust (kmph)	Wind Direction
2-Nov-04	19.00	21.50	27.00	75.77	5.28	22.22	41.83		NNW
3-Nov-04	13.89	15.56	19.39	76.30	2.90	25.55	46.47		WNW
9-Nov-04	16.72	19.89	23.28	76.78	0.00	13.52	17.86		ENE
10-Nov-04	18.89	23.06	27.22	76.43	0.03	15.93	16.09		SE
18-Nov-04	20.00	21.33	22.00	76.38	0.46	16.85	24.14		West
19-Nov-04	22.00	22.89	24.00	76.23	0.00	14.08	15.93		East
30-Nov-04	9.00	16.00	23.00	76.30	0.05	27.59	43.44		NW
1-Dec-04	7.00	9.78	13.00	77.06	0.00	19.81	24.14		NNE
7-Dec-04	16.72	19.61	22.78	76.12	0.10	15.74	22.53		NNW
8-Dec-04	13.89	18.11	22.78	76.23	0.00	12.04	20.92		East
15-Dec-04	5.00	8.67	14.39	77.57	0.00	21.66	25.58		ENE
16-Dec-04	8.89	14.06	17.78	76.94	0.05	28.33	40.39		NE
21-Dec-04	17.00	18.06	21.00	76.05	2.39	20.55	27.19		SE
22-Dec-04	8.00	15.89	20.00	75.72	0.76	22.96	35.40		WNW
29-Dec-04	15.00	17.11	19.39	76.99	0.30	15.56	22.53		ESE
30-Dec-04	16.00	17.56	20.00	76.71	0.00	18.70	20.92		ESE
11-Jan-05	17.00	19.44	24.00	76.30	0.03	15.56	19.31		SSE
12-Jan-05	16.72	19.33	22.78	75.77	0.00	17.78	20.92		SE
14-Jan-05	7.78	10.89	15.00	77.04	0.05	31.47	33.79		NNE
15-Jan-05	6.11	10.11	12.78	77.34	0.00	20.00	22.53		NNE

Continued…

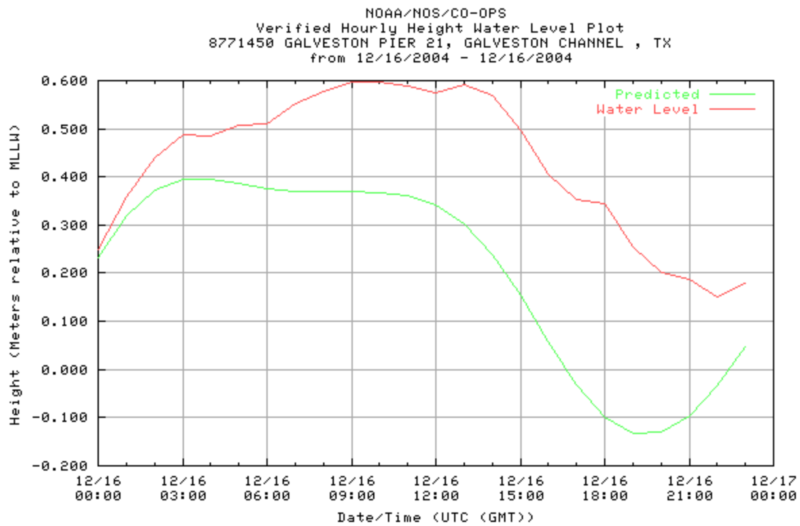
Date	Minimum Temperature (°C)	Mean Temperature (°C)	Maximum Temperature (°C)	Mean Sea Level Pressure (cm)	Total Precipitation (cm)	Mean Wind Speed (kmph)	Maximum Sustained Wind (kmph)	Maximum Wind Gust (kmph)	Wind Direction
18-Jan-05	4.00	9.33	13.00	77.67	0.00	19.44	20.92		NE
19-Jan-05	10.00	13.61	19.39	77.27	0.00	12.78	15.93		ESE
25-Jan-05	11.72	15.06	20.61	76.58	0.00	13.52	24.14		South
26-Jan-05	15.61	18.72	25.00	76.12	0.00	18.89	22.53		SSW
3-Feb-05	8.11	8.78	11.00	77.09	0.00	23.33	27.19		North
4-Feb-05	6.72	8.33	10.61	77.24	0.00	14.45	20.92		NE
10-Feb-05	7.78	11.06	15.00	77.06	0.00	27.96	35.40		NNE
11-Feb-05	10.00	12.06	15.61	77.27	0.00	9.62	12.87		NE
17-Feb-05	14.00	16.33	19.00	76.53	0.00	20.74	29.12		NNE
18-Feb-05	12.00	14.44	16.00	76.91	0.00	20.00	22.53		ENE
2-Mar-05	10.00	15.61	19.39	76.33	2.84	26.29	40.39		NE
3-Mar-05	10.61	13.22	16.11	76.30	0.25	19.63	25.58		NNE
9-Mar-05	13.28	17.39	23.28	76.23	0.00	12.97	30.57		NW
10-Mar-05	10.00	15.89	20.00	76.33	0.00	13.34	24.14		SSE
23-Mar-05	15.00	18.61	23.89	76.05	0.00	14.63	19.31		NNE
24-Mar-05	16.00	18.89	23.00	75.97	0.00	15.56	19.31		ESE
30-Mar-05	19.00	21.28	24.00	75.64	0.00	15.93	19.31		SE
31-Mar-05	19.00	20.78	24.00	75.69	0.00	13.52	17.86		NE
11-Apr-05	20.00	23.00	26.72	75.49	0.20	21.85	29.12		ESE
12-Apr-05	15.61	22.11	28.28	75.92	0.00	10.56	19.31		NW
19-Apr-05	20.61	22.06	25.61	76.33	0.00	22.40	24.14		SE
20-Apr-05	21.00	22.56	25.00	76.23	0.00	19.63	22.53		ESE
26-Apr-05	19.00	22.22	26.00	75.64	1.04	18.15	25.58		WNW
27-Apr-05	17.00	21.72	26.00	76.23	0.00	15.00	20.92		SE
5-May-05	16.00	20.61	24.00	76.73	0.00	14.63	15.93		East

Continued…

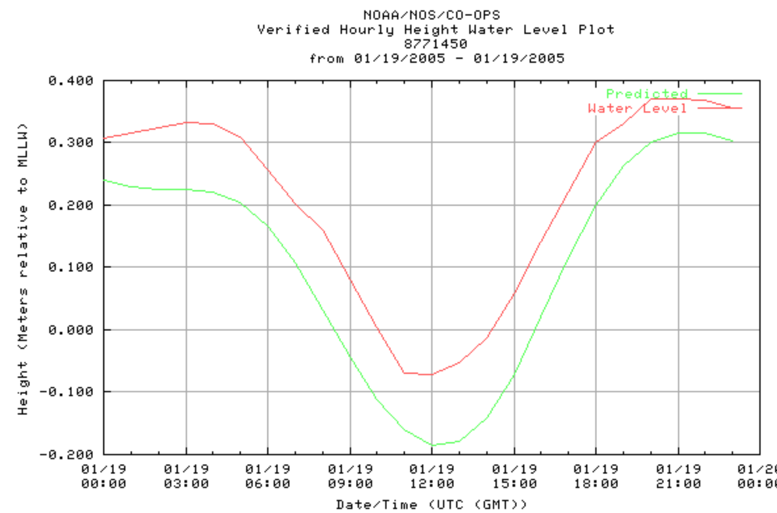
Date	Minimum Temperature (°C)	Mean Temperature (°C)	Maximum Temperature (°C)	Mean Sea Level Pressure (cm)	Total Precipitation (cm)	Mean Wind Speed (kmph)	Maximum Sustained Wind (kmph)	Maximum Wind Gust (kmph)	Wind Direction
6-May-05	17.78	21.39	25.61	76.58	0.00	12.78	19.31		East
10-May-05	22.78	24.06	26.72	76.12	0.00	18.15	20.92		SE
11-May-05	22.78	24.33	27.22	76.10	0.00	21.29	24.14		ESE
1-Jun-05	21.72	26.06	30.61	75.62	0.00	12.41	32.18		WNW
2-Jun-05	23.28	27.28	30.61	75.67	0.48	7.96	17.86		SSE
4-Jun-05	26.72	28.39	31.11	75.69	0.00	24.26	27.19		SE
5-Jun-05	26.72	28.39	31.11	75.84	0.00	19.63	22.53		SE
14-Jun-05	27.00	29.72	32.00	75.97	0.00	15.00	19.31		SSE
15-Jun-05	26.72	29.78	33.28	76.07	0.00	10.36	17.86		SSW
21-Jun-05	26.00	29.11	33.00	76.35	0.00	11.30	15.93		East
22-Jun-05	26.11	29.11	32.22	76.38	0.00	11.67	19.31		ENE
4-Jul-05	28.89	30.78	33.89	76.10	0.00	21.66	22.53		SSE
5-Jul-05	27.22	30.56	34.39	76.15	0.00	13.89	24.14		ESE
20-Jul-05	29.00	30.67	33.00	76.15	0.00	22.96	24.14		East
21-Jul-05	28.89	30.44	32.78	76.35	0.00	16.67	19.31		ESE
27-Jul-05	26.72	29.89	33.28	76.15	0.00	12.97	19.31		SSW
28-Jul-05	27.78	30.28	35.00	76.23	0.00	14.08	17.86		SW
5-Aug-05	26.11	28.56	31.72	76.30	0.03	8.14	14.32		SSE
6-Aug-05	26.72	29.50	34.39	76.30	0.00	10.93	14.32		NW
18-Aug-05	28.89	30.56	33.89	76.10	0.00	15.56	19.31		SSE
19-Aug-05	28.89	30.78	33.89	76.17	0.00	18.70	20.92		SSE
24-Aug-05	27.22	30.28	33.28	75.95	0.00	8.88	17.86		SSE
25-Aug-05	28.00	29.83	32.00	76.12	0.00	9.62	15.93		ENE
26-Aug-05	27.78	30.39	34.39	76.05	0.00	10.36	15.93		East
14-Sep-05	27.22	29.33	32.22	76.10	0.00	19.07	19.31		SSE

Continued…									
Date	Minimum Temperature (°C)	Mean Temperature (°C)	Maximum Temperature (°C)	Mean Sea Level Pressure (cm)	Total Precipitation (cm)	Mean Wind Speed (kmph)	Maximum Sustained Wind (kmph)	Maximum Wind Gust (kmph)	Wind Direction
15-Sep-05	28.00	29.72	32.00	76.15	0.03	23.14	25.58		South
23-Sep-05	26.00	28.44	30.00	75.39	3.40	33.89	62.75	88.88	North
24-Sep-05	25.56	29.44	33.33		1.60				NE
25-Sep-05	29.00	33.50	38.00	75.77	0.00	24.44	27.19	38.89	South
28-Sep-05	27.78	29.56	32.22	75.95	0.00	15.74	19.31		South
29-Sep-05	26.72	29.50	32.78	76.07	0.00	12.78	22.53		NNE
4-Oct-05	24.00	28.06	31.00	76.12	0.18	24.81	33.79	44.25	ENE
5-Oct-05	26.72	28.61	31.11	76.00	1.17	21.11	20.92	27.77	ENE
18-Oct-05	20.00	24.22	29.39	76.23	0.00	7.59	12.87		SSW
19-Oct-05	21.11	24.67	28.28	76.15	0.00	9.99	15.93		SE
25-Oct-05	11.72	16.22	21.11	76.73	0.00	13.34	15.93		NNW
26-Oct-05	13.00	17.67	23.00	76.48	0.00	9.44	15.93		ENE
1-Nov-05	13.00	17.11	22.00	76.71	1.93	29.07	36.85		NNW
2-Nov-05	13.00	17.44	22.00	76.94	0.00	12.41	17.86		ENE
10-Nov-05	21.72	24.11	28.89	76.56	0.00	8.70	15.93		South
11-Nov-05	20.00	22.56	25.00	76.48	1.47	14.82	20.92		ENE

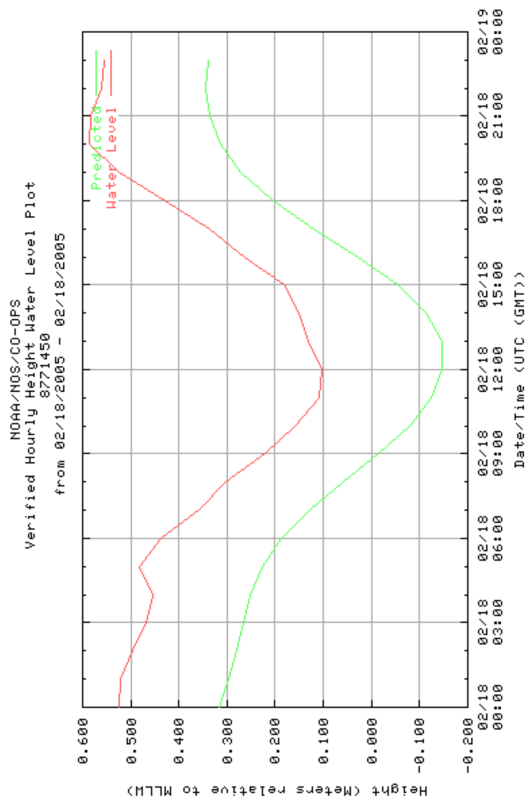
Tidal data



NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450 GALVESTON PIER 21, GALVESTON CHANNEL , TX
from 12/16/2004 - 12/16/2004
Predicted
Water Level
Height (Meters relative to MLLW)
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
12/16 00:00
12/16 03:00
12/16 06:00
12/16 09:00
12/16 12:00
12/16 15:00
12/16 18:00
12/16 21:00
12/17 00:00
Date/Time (UTC (GMT))



NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 01/19/2005 - 01/19/2005
Predicted
Water Level
Height (Meters relative to MLLW)
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
01/19 00:00
01/19 03:00
01/19 06:00
01/19 09:00
01/19 12:00
01/19 15:00
01/19 18:00
01/19 21:00
01/20 00:00
Date/Time (UTC (GMT))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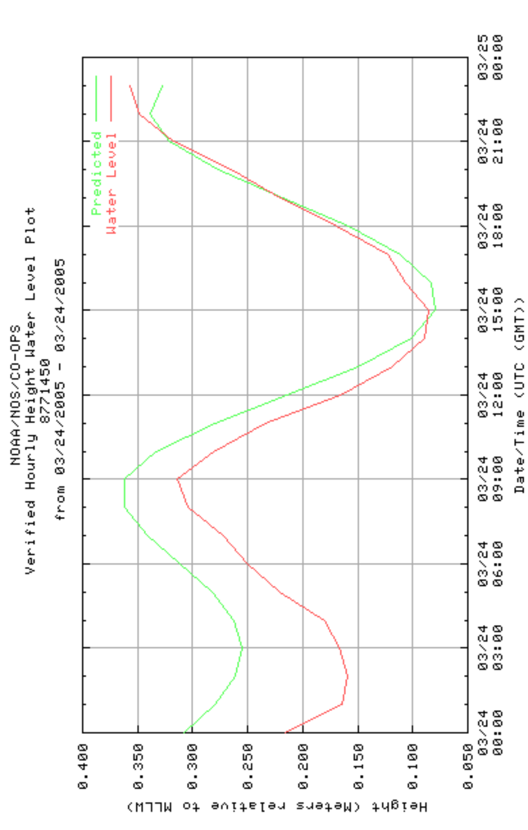
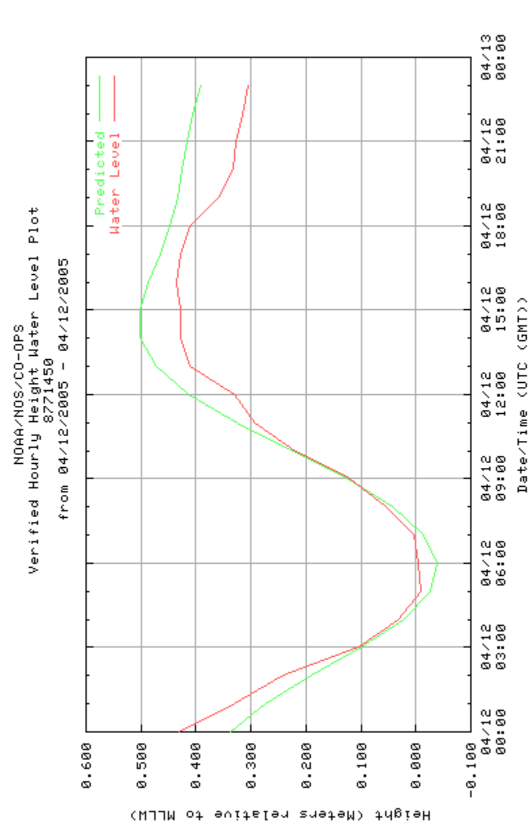
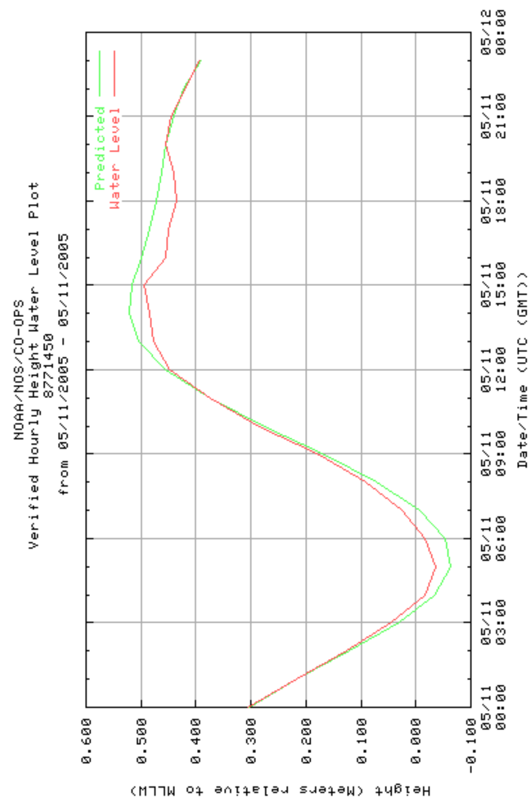
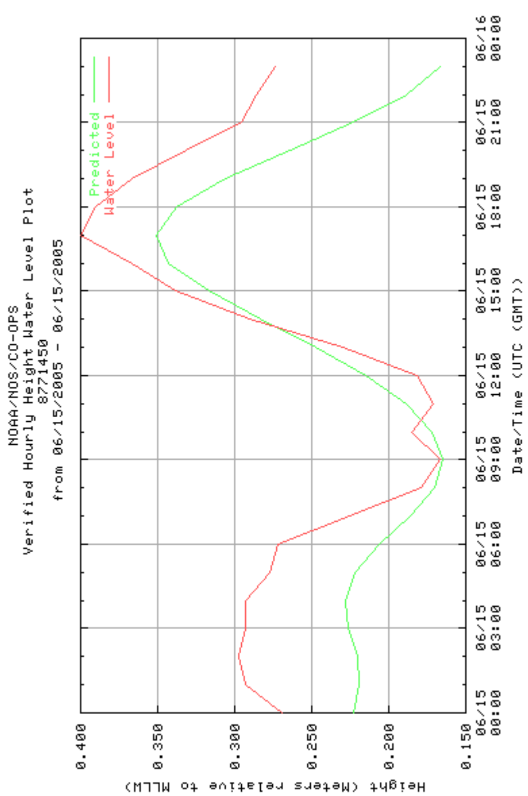
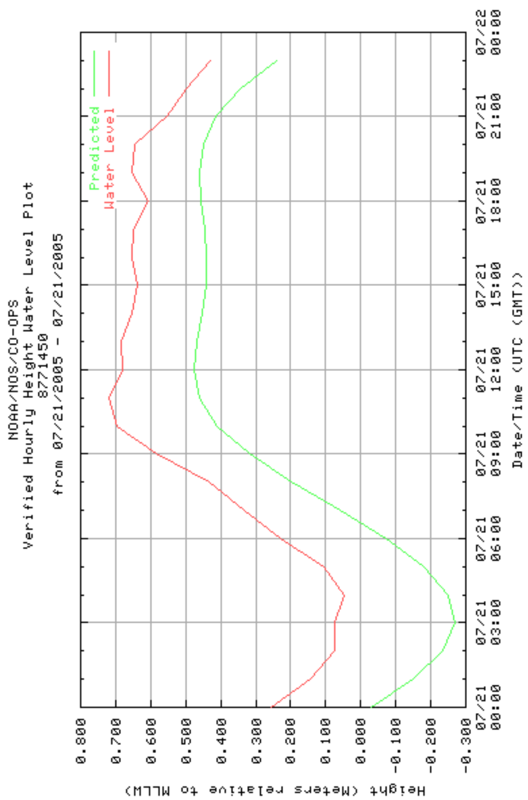
Verified Hourly Height Water Level Plot
8771450
from 02/18/2005 - 02/18/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
-0.200
02/18 00:00
02/18 03:00
02/18 06:00
02/18 09:00
02/18 12:00
02/18 15:00
02/18 18:00
02/18 21:00
02/19 00:00

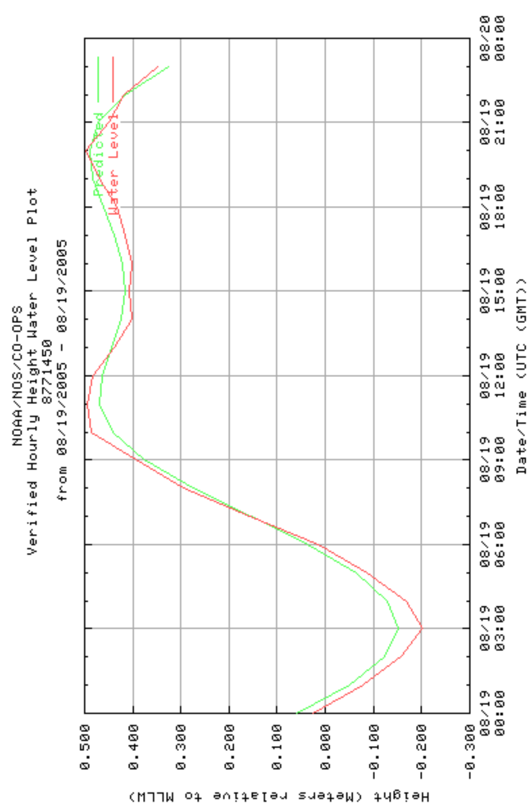

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 03/24/2005 - 03/24/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))
0.400
0.350
0.300
0.250
0.200
0.150
0.100
0.050
03/24 00:00
03/24 03:00
03/24 06:00
03/24 09:00
03/24 12:00
03/24 15:00
03/24 18:00
03/24 21:00
03/25 00:00

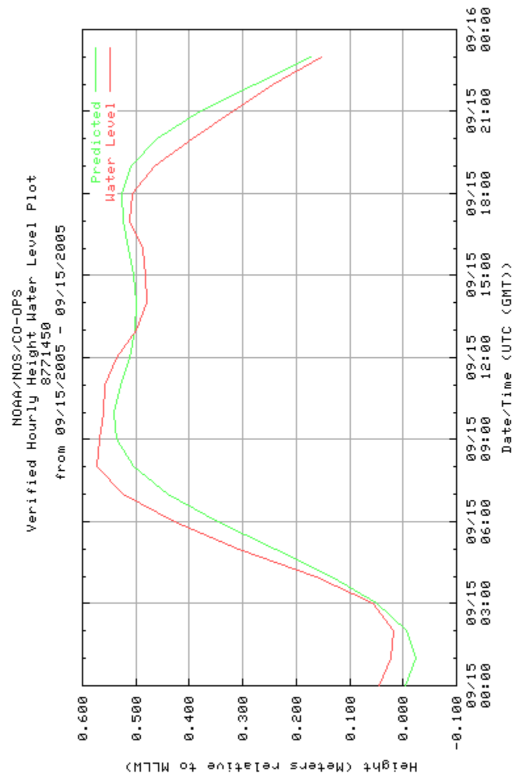

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 04/12/2005 - 04/12/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
04/12 00:00
04/12 03:00
04/12 06:00
04/12 09:00
04/12 12:00
04/12 15:00
04/12 18:00
04/12 21:00
04/13 00:00

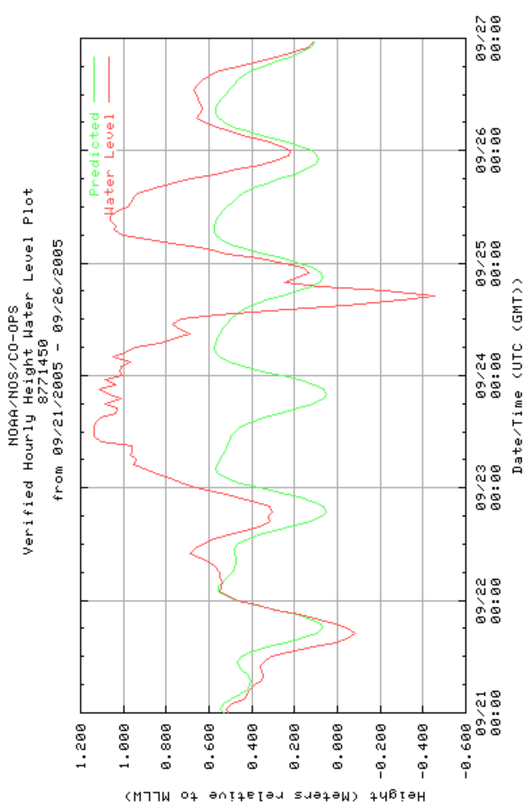

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 05/11/2005 - 05/11/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))
0.600
0.500
0.400
0.300
0.200
0.100
0.000
-0.100
05/11 00:00
05/11 03:00
05/11 06:00
05/11 09:00
05/11 12:00
05/11 15:00
05/11 18:00
05/11 21:00
05/12 00:00

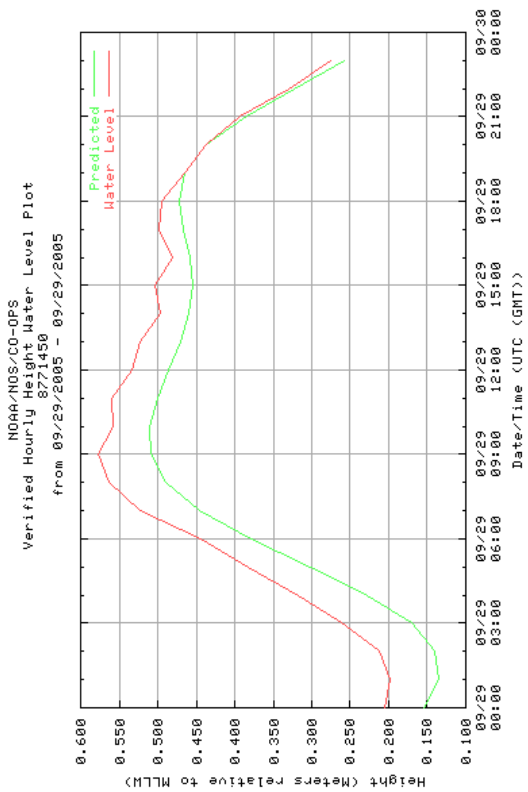

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 06/15/2005 - 06/15/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))

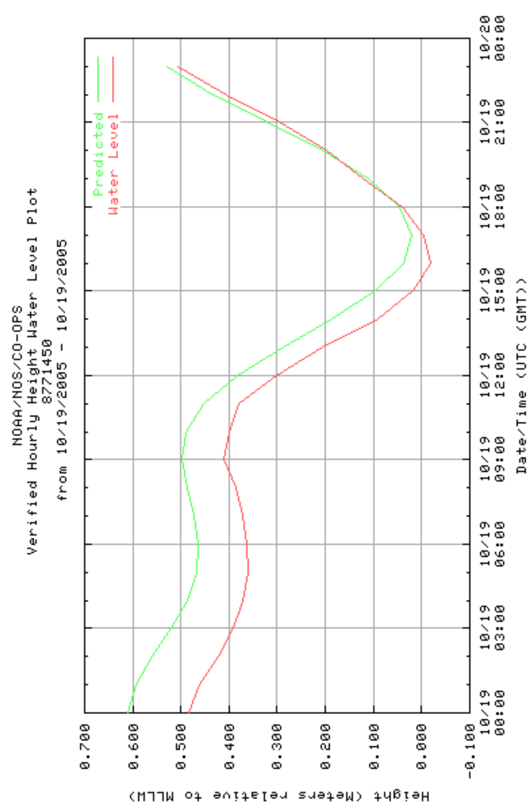

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 07/21/2005 - 07/21/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))

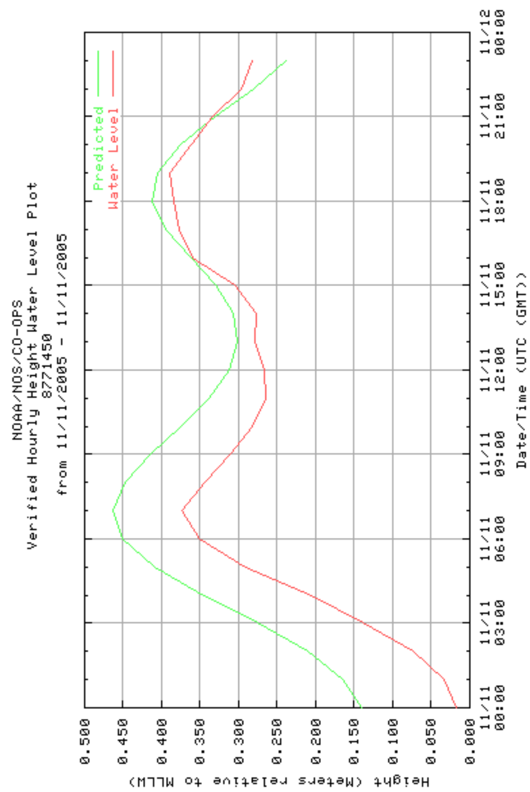

NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 08/19/2005 - 08/19/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))


NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 09/15/2005 - 09/15/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))


NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 09/21/2005 - 09/26/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))


NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 09/29/2005 - 09/29/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))


NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 10/19/2005 - 10/19/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))


NOAA/NOS/CO-OPS
Verified Hourly Height Water Level Plot
8771450
from 11/11/2005 - 11/11/2005
Predicted
Water Level
Height (Meters relative to MLLW)
Date/Time (UTC (GMT))

APPENDIX E

AUGUST FISH KILL DATA

Dead fry Menhadden located in back of canal off of Lake Madeline

Closer view of dead fry Menhadden located in back of canal off of Lake Madeline

Adult Menhadden – approximately 20 to 25 centimeters in length

Fry Menhadden – approximately 7 centimeters in length

Adult Ribbonfish – approximately 1 meter in length

Adult Stripped Mullet – approximately 30 centimeters in length

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