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# Nursery delineation, movement patterns, and migration of the sandbar shark, Carcharhinus plumbeus, in the eastern shore of Virginia coastal bays and lagoons

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# NURSERY DELINEATION, MOVEMENT PATTERNS, AND MIGRATION OF THE SANDBAR SHARK, *Carcharhinus plumbeus*, IN THE EASTERN SHORE OF VIRGINIA COASTAL BAYS AND LAGOONS

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by

Christina L. Conrath 2005

APPROVAL SHEET

This dissertation is submitted in partial fulfillment of

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ABSTRACT

The identification and delineation of nursery areas and areas of aggregation of western North Atlantic sharks has been identified as a priority for future management efforts. The objectives of this project were to use fishery-independent methods to study the overwintering area of juvenile sandbar sharks, to spatially delineate the Eastern Shore nursery area, and to examine movement patterns and space use within this nursery area. Data from 21 satellite transmitters attached to large juvenile sandbar sharks revealed that these sharks primarily occurred off the outer banks of North Carolina, at deeper depths and colder water temperatures during the overwintering period (after November 1). The data from this project support the size and location of the closed area currently enacted by the Fishery Management Plan. The Eastern Shore of Virginia was found to be an important primary and secondary nursery area for this population of sandbar sharks. Within this nursery area sharks were most concentrated in Great Machipongo Inlet. Abundance of juvenile sandbar sharks was positively correlated to distance from the inlet and water temperature. Smaller juvenile sharks were more concentrated farther from the inlets and were more prevalent in the southern inlets. Juvenile sandbar shark movements were studied using passive acoustic telemetry. Juveniles tended to spend significantly more time farther from the inlets and their space use was positively correlated to time of day with a greater proportion of time spent in the acoustic array during the night time hours. Tidal currents were positively correlated with small scale movements but were unrelated to overall space use. The tracked sharks returned or remained within the array to a greater extent than would be predicted by random movements alone indicating these animals have some site attachment to these areas. Smaller sharks remained within the array area to a greater extent than larger sharks indicating they likely have smaller activity spaces. This study emphasizes the importance of both the Eastern Shore of Virginia nursery area and the overwintering area that occurs off the central coast of North Carolina as essential habitat for the western North Atlantic population of sandbar sharks.

NURSERY DELINEATION, MOVEMENT PATTERNS, AND MIGRATION OF THE SANDBAR SHARK, *Carcharhinus plumbeus*, IN THE EASTERN SHORE OF VIRGINIA COASTAL BAYS AND LAGOONS

INTRODUCTION

Sharks are harvested in significant numbers by commercial and recreational fisheries on the Atlantic and Gulf Coasts of the United States. The US recreational fishery for Atlantic sharks expanded considerably during the 1970s reaching a maximum in 1974-75, with 1,588,000 sharks caught in the Atlantic Ocean, Gulf of Mexico, and Caribbean Sea (Stone et al. 1998). Directed commercial fisheries for sharks in the western North Atlantic have been present intermittently since the 1930s but expanded rapidly during the 1980s with landings reaching a maximum value of over 7,100 metric tons in 1989 (Stone et al. 1998).

Sharks have life history traits that make them highly vulnerable to overfishing including late maturity, a small number of large offspring produced, and a low reproductive periodicity. Concerns over these life history traits and the expansion of the fishery prompted the five Atlantic Fishery Management Councils to request the Secretary of Commerce to develop a shark Fishery Management Plan (FMP) in 1989. NMFS implemented a FMP in 1993 that split the Atlantic shark species into three management groups: large coastal sharks, small coastal sharks, and pelagic sharks. The FMP established a yearly commercial quota of 2,436 metric tons for large coastal sharks and a recreational bag limit of four sharks per vessel for large coastal or pelagic shark species groups. Stock assessments that convened in 1994 and 1996 found no evidence of large coastal shark stock recovery, and in response to these results in 1997 the commercial quota was reduced by 50 percent to 1,285 mt dressed weight and the recreational bag limit to two large coastal, small coastal, or pelagic sharks combined per trip. The Sustainable Fisheries Act of 1996 amended the Magnuson-Stevens Act and requires NMFS to halt overfishing and rebuild overfished stocks, minimize bycatch and bycatch mortality to the extent practicable, and to identify and protect essential fish habitat. In 1998 the large coastal shark stock assessment found that these stocks were overfished and would not be rebuilt under the 1997 harvest levels. In 1999 NOAA Fisheries published the Final Management Plan for Atlantic Tunas, Swordfish, and Sharks that further reduced large coastal shark quotas, established ridgeback and non-ridgeback categories of large coastal sharks, reduced the recreational bag limit, and expanded the list of prohibited shark species. The resulting litigation led to another large coastal shark stock assessment in 2002, which led to an amendment of the 1999 management plan for large coastal shark stocks. The 2003 amendment to this management plan includes provisions to re-aggregate the large coastal complex, eliminate the commercial minimum size limit, lower the large coastal shark quota, establish regional commercial quotas and trimester fishing seasons, and add a time area closure off North Carolina (NMFS 1999, 2003).

Sandbar sharks are the principal species caught in the commercial shark fishery of the US Atlantic coast and are a significant fraction of the sharks caught in the coastal recreational fishery (NMFS 2003). The Virginia Institute of Marine Science (VIMS) longline program began in 1973 and has been tracking the abundance of coastal sharks in Virginia waters since that time. Standardized catch rates from the VIMS longline survey indicate a dramatic decline in sandbar shark abundance from 1974 to 1992. This decline was followed by a period of gradually increasing abundance until 1997 to 1998 when catch levels appear to stabilize at depressed levels well below the catch levels of the early 1980s.

The sandbar shark is a large coastal shark found globally in warm temperate and tropical waters. It is the most abundant large coastal shark found in the waters off the East Coast of the United States. The western North Atlantic population of sandbar sharks ranges from Cape Cod to the western Gulf of Mexico. This population migrates seasonally and segregates by sex for much of the year. In the summer, sandbar sharks are common from Long Island to West Palm Beach, Florida. In the winter months, sandbar sharks are common from the Carolinas around the tip of Florida to the western coast of Florida. Pregnant females migrate north to pup in nursery areas in the late spring and early summer (Springer 1960). Juveniles return to their natal nurseries during the summer months for as many as 10 years (Grubbs et al. in press, Mersen and Pratt 2001, Sminkey 1994). Springer (1960) found that the principal summer nursery areas for this population were shallow coastal waters from Long Island to Cape Canaveral with a secondary summer nursery in the northwestern Gulf of Mexico. More recent studies indicate that the principal summer nursery areas for this population have constricted and now occur from Great Bay, New Jersey to South Carolina with evidence of a small summer nursery occurring in the northeastern Gulf of Mexico (Mersen 1998, Carlson 1999). Larger juveniles appear to have a more widespread summer distribution with juveniles over 84 cm fork length being distributed as far north as Cape Cod, Massachusetts (Mersen 1998). Springer

(1960) reported the winter distribution of the juveniles of this population to be waters off of both Carolina coasts out to 75 fathoms (137 m). Recent studies indicate that while juveniles may range in the waters off both Carolina coasts in the winter months, the shallow waters off the central coast of North Carolina (Cape Hatteras to Cape Lookout) may be particularly important as an overwintering area for juvenile sandbar sharks of this population (Grubbs et al. in press, Mersen 1998, Jensen and Hopkins 2001).

Sandbar sharks are the most abundant member of the large coastal shark management group and have life history traits that make them potentially vulnerable to overexploitation. Male and female sandbar sharks have been found to mature at a length over 135 cm precaudal length, which corresponds to an age of 15 to 16 years (Sminkey and Musick 1995). Female sandbar sharks have a mean of 9 pups every other year, with a 9 to 12 month gestation period, and a year resting period between pregnancies (Springer 1960). The 1999 Highly Migratory Species (HMS) FMP stressed the importance of coastal nursery and pupping areas for large coastal sharks as essential fish habitat for these species. These areas may be particularly vulnerable to environmental and human influences. Information on where shark populations pup and how neonates and juveniles use nursery areas will help determine the habitat value of nursery areas (NMFS 2003).

*Objectives of the study*

The overall objective of this study was to add much needed knowledge about the summer nursery and overwintering habitat of neonate and juvenile sandbar sharks in the western North Atlantic. The first part of the study was focused on using a fishery independent technique (satellite telemetry) to examine the overwintering localities and habitat preferences of large juvenile sandbar sharks of this population. The second objective of the study was to spatially delineate the Eastern Shore of Virginia summer nursery area and to determine if the abundance of neonate or juvenile animals within the study area was correlated to physical parameters. The last objective of the project was to study the space use and movement patterns of juvenile sandbar sharks within this nursery area and to determine if the use and movement of these animals were correlated to physical parameters.

# CHAPTER 1

Investigations into the winter habitat of juvenile sandbar sharks, *Carcharhinus plumbeus*, using pop-up archival satellite transmitters (PSATs).

**Abstract**

Defining areas of aggregation and the continued study of overwintering areas and winter nurseries of US Atlantic shark species is important for current and future management efforts. Recent studies have found that the principal summer nursery areas of the western North Atlantic population of sandbar sharks occur in shallow coastal bays from New Jersey to South Carolina. The principal overwintering areas of this population are likely found off the North and South Carolina coasts. The primary objective of this project was to use a fishery independent method to examine the overwintering location and habitat preferences of large juvenile sandbar sharks. During the summer of 2003, 21 sandbar sharks captured within the Eastern Shore of Virginia bays and lagoons were outfitted with satellite transmitters that were programmed to detach during the winter of 2003/2004. Of the 21 transmitters, four transmitters did not report, 12 released prematurely, and five reported on time. Nine of the transmitters reported during the targeted overwintering period (November 2004 through February 2005). These transmitters reported a range of 18.9% to 34.1% of the expected 1,000 data lines. Only seven of these transmitters reported a good location before drifting offshore and only six of the transmitters reported habitat data from the over-wintering period. Data from these transmitters were used to examine winter habitat utilization and the overwintering localities of large juvenile sandbar sharks. Satellite pop-off locations during the overwintering period were concentrated in central North Carolina coastal waters. The sharks predominantly remained in waters

ranging from 18° to 22° C and in depths ranging from 0 to 50 m during this period. As the sharks migrated from the summer nursery area to the overwintering area daily mean temperatures decreased and daily mean depths increased.

**Introduction**

Migration can be generally defined as movement from one place to another. Some authors define 'true' migration as that migration which occurs between two widely separated and distinct areas (Landsborough Thompson 1942). The advantages of migration are thought to include the ability to exploit more resources, the avoidance of negative environmental conditions, improved reproductive success, and decreased predation (Dodson 1996, Dingle 1980, Harden-Jones 1968). Fish migration can be categorized into four different types: movement from marine water to fresh water to breed (anadromy), movement from fresh water to marine water to breed (catadromy), movement entirely within fresh water (potomadry), and movement entirely within salt water (oceanodromous) (Dingle 1980).

In temperate waters many oceanodromous migrations occur out of a favorable summer habitat when conditions become adverse in the winter months. Many temperate estuaries experience extreme temperature changes during the winter months. Chesapeake Bay has been shown to have temperature extremes that range from around freezing in the winter months up to 32° C during the summer months (Magnien 1999). As a result of the extreme temperature range only 10% of the fish that are found within Chesapeake Bay are year round residents, the majority of fish that occur here only do so when the physical conditions are favorable. Migratory fish come into Chesapeake Bay to feed, reproduce, or find shelter (Chesapeake Bay Program 1995).

Juvenile sandbar sharks migrate into Atlantic temperate estuaries like Chesapeake Bay during the summer months presumably to take advantage of an area with increased productivity and limited predation. However, there is a paucity of data demonstrating that these animals experience increased productivity due to the favorable conditions within these nurseries. The much smaller abundance of large predators within one of these nursery areas, the Chesapeake Bay, in comparison to nearby coastal waters has been documented by the Virginia Institute of Marine Science long term shark monitoring program.

The emigration of neonate and juvenile sharks from these Atlantic temperate estuaries during the winter months is likely a mechanism to avoid adverse environmental conditions that occur due to falling winter temperatures. Sandbar shark wintering areas in the western North Atlantic are less well studied than summer nursery areas but recent studies suggest sandbar sharks of this population winter in shallow waters off the Carolina coasts, with higher concentrations of animals possibly occurring off the central North Carolina coast (Mersen and Pratt 2001, Grubbs et al. in press, and Jensen and Hopkins 2001). Nearly all of the data collected about the location and importance of sandbar shark overwintering areas have been through tag and recapture or other fishery dependent studies. While these studies have provided valuable data there is the potential for biases in these data as they are dependent on existing fisheries. Recapture data may reflect fishery effort to a greater extent than fish abundance. While presumably these two factors are linked, sharks may occur outside of the fishing area that will not have a chance of being collected or recorded.

The development of marine satellite transmitters allowed researchers to study the movements of large fish in a fishery independent manner. In the late 1990s the pop-up archival satellite transmitter was developed. These transmitters can be programmed to release at a specific date, and to record the depth and temperature of animals during the period of time the transmitters are attached. In addition some of these transmitters collect light levels which can be used to determine the position of the shark by determining day length and time of sunrise and sunset (Arnold and Dewar 2001). However there is high degree of error associated with these position estimates (depending on tag type $\pm$ 0.5 to 1° for longitude and $\pm$ 1 to 10° for latitude) (Arnold and Dewar 2001) and this technique is generally only applied effectively to pelagic or oceanic fish that travel great distances. These transmitters have been developed for and most commonly used to study large pelagic sport fish (Lutcavage et al. 1999, Block et al. 2005, Horodysky and Graves 2005). However, in recent years the use of these transmitters to track elasmobranchs in both the pelagic and coastal environment has become more common (Loefer et al. 2005, Weng et al. 2005, and Grusha 2005).

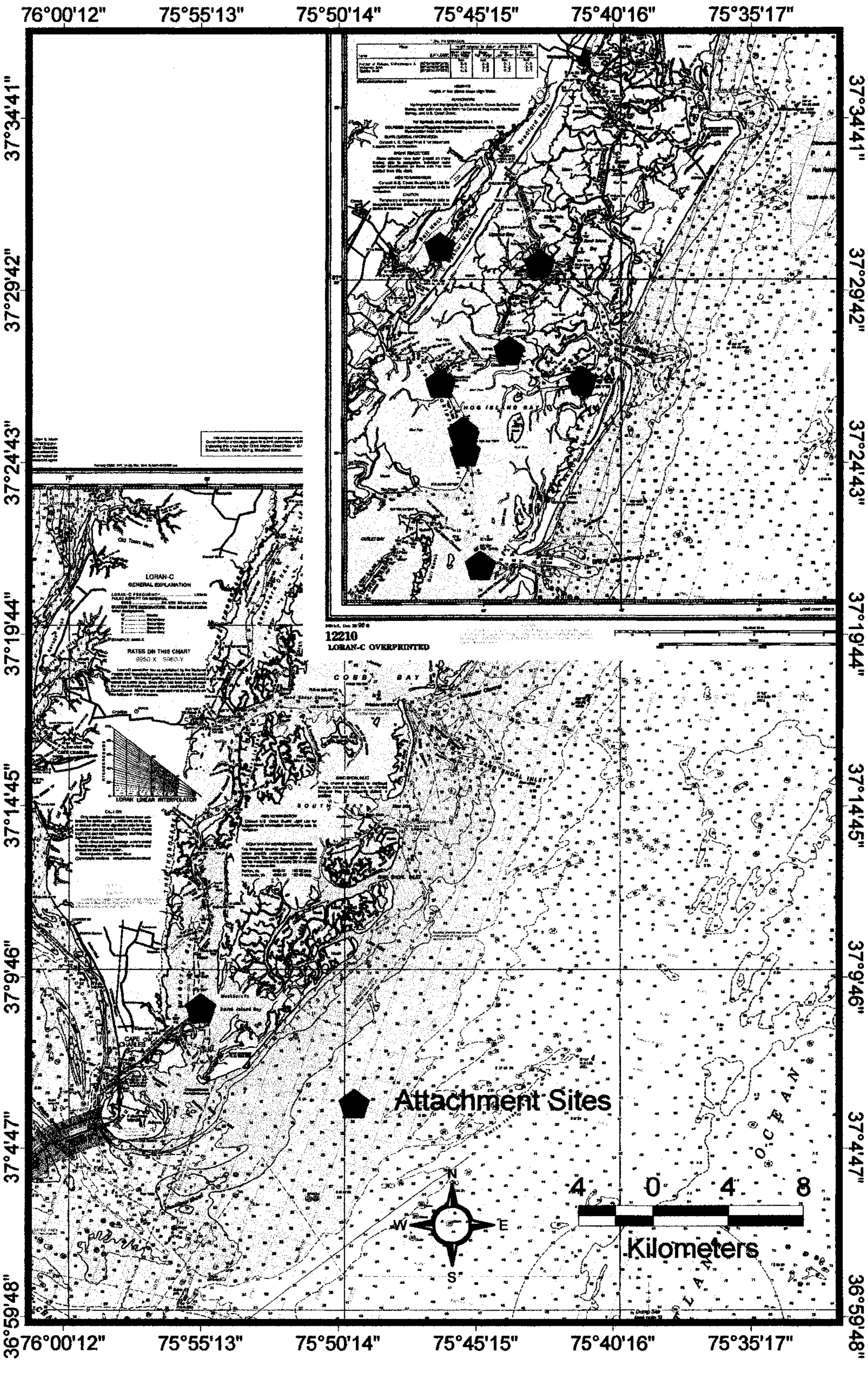
The use of satellite transmitters in this study allowed for the examination of winter migration, overwintering localities, and habitat preferences of large juvenile sandbar sharks in a fishery independent manner. The principal objectives of this study were to determine the overwintering locations of large juvenile sandbar sharks and to determine the depth and temperature habitat experienced by these animals throughout the overwintering period.

**Methods**

To determine the location of the overwintering grounds of large juvenile sandbar sharks in the western North Atlantic Ocean, 21 pop-up archival satellite transmitters were attached to sandbar sharks captured within the Eastern Shore of Virginia summer nursery area during 2003 (Figure 1-1). The satellite transmitters used were Pop-up Archival Transmitters (PAT) manufactured by Wildlife Computers (8345 154th Avenue NE, Redmond, WA 98052), 13 were PAT version 2, eight of the transmitters were PAT version 3. Juvenile sandbar sharks ranging in size from 121 to 144 cm total length caught by bottom set longline were brought on board the boat, measured, and a transmitter was attached. The transmitter was attached by drilling four holes into the first dorsal fin of the shark and securing a plastic plate to the dorsal fin using cable ties. The transmitter was then attached to the fin through the plate using 250-pound monofilament line and stainless steel crimps. The transmitters were programmed to detach from the sharks during the period between December 2003 and February 2004.

While attached to the animal the transmitters were programmed to take hourly temperature and depth readings binned into histograms of the following temperature and depth ranges: a. depth: 0 - 4, 4.5 - 6, 6.5 - 8, 8.5 - 10, 10.5 - 12, 12.5 -14, 14.5 - 16, 16.5-18. 18.5 - 20, 20.5 - 50, 50.5 - 1000 meters; b1. temperature: 0 - 5, 5.05 - 10, 10.05 - 15.0, 15.05 - 18, 18.05 - 20.00, 20.05 - 22, 22.05 - 24, 24.05 - 26, 26.05 - 28, 28.05 - 30, 30.05 - 32, 32.05 - 60°C or, b2. temperature: 0 - 5, 5.05 - 10,

Figure 1-1. The locations of transmitter attachment to large juvenile sandbar sharks in the Eastern Shore of Virginia's coastal bays and lagoons (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


76°00'12"
75°55'13"
75°50'14"
75°45'15"
75°40'16"
75°35'17"
37°34'41"
37°29'42"
37°24'43"
37°19'44"
37°14'45"
37°9'46"
37°4'47"
36°59'48"
12210
LORAN-C OVERPRINTED
Attachment Sites
4 0 4 8
Kilometers
N
W
E
S

10.05 - 12.5, 12.55 - 15, 15.05 - 17.5, 17.55 - 20, 20.05 - 22.5, 22.55 - 25, 25.05 - 27.5, 27.55 - 30, 30.05 - 32.5, 32.55 - 60°C. The first temperature binning was chosen to focus on the temperatures the sharks seemed most likely to inhabit (18° to 30°C). A second temperature binning strategy was used to ensure adequate coverage of the extreme portions of the temperature range due to the possibility that the sharks would occupy temperatures greater than expected during the summer months (30° to 35°C) and less than expected during the winter months (10° to 18°C). In addition, the transmitters recorded the temperatures associated with the minimum and maximum depths per day as well as at up to six depths in between the minimum and maximum to create depth temperature profiles.

The locations of the transmitters that released during the overwintering period and reported a good location before drifting offshore were used to examine the overwintering locations of large juvenile sandbar sharks of this population. The latitude and longitude coordinates reported by the transmitter were plotted on a chart and the distance from shore, nearest depth contours, and distance from the site of attachment were determined. The transmitter pop-off locations were compared with data from conventional tag returns in a previous study by Grubbs et al. (in press) to determine if the pop-off locations occurred within the same geographical area.

In order to compare winter habitat utilization with summer habitat utilization of these sharks two time periods were defined. The time period from November 1st until tag release was defined as the overwintering period, and the time period from tag attachment until September 15th, 2003 was defined as the summer nursery period. September 15th was chosen because juvenile sandbar sharks leave this nursery area between late September and the middle of October. Cumulative histograms of the mean frequency of all data collected by each transmitter were created to examine the depth and temperatures experienced by the sharks during these two periods of time.

The data from the depth temperature profiles were used to determine the maximum and minimum depth and temperatures these sharks experienced during the overwintering period. In addition, the data recorded in the depth temperature profiles were used to determine the daily mean temperature and depth each shark experienced. These values were compared from the time of tag attachment while the shark was in the summer nursery area to the time of tag release while the shark was in the overwintering area. A student's t-test was used to determine if the mean daily depths and temperatures experienced by the sharks were significantly different during the overwintering and summer nursery periods.

## Results

### *Transmitter performance*

The 21 satellite transmitters were programmed to detach during the period between December 2003 and February 2004. Of the 21 transmitters, four did not report (19%), twelve popped off early (57%), and five popped off on the scheduled day (24%). The first ten transmitters deployed were programmed to detach if the animal remained at a constant depth for more than eight days. It was later determined the sharks were not changing depth to a great enough extent while within the shallow Eastern Shore lagoons to use the constant depth release function. Four of the twelve early release transmitters released early due to being at constant depth. The cause of early release for the other eight transmitters is unknown and may have been due to pin failure, attachment failure, or biological activity damaging the transmitter. The version 3 PAT transmitter performed much more consistently than the version 2 PAT transmitter, with four of the eight version 3 transmitters releasing at the correct time (50%) and only one of the thirteen version 2 transmitters releasing at the correct time (8%). Data transmission for the transmitters was much poorer than expected with six (67%) of the nine overwintering period release transmitters reporting less than 10% of the expected 1000 data lines. The remaining three transmitters reported between 18.9% and 34.1% of the expected data. Three of the nine transmitters that released in the overwintering period had no usable habitat data from the overwintering period and only transmitted habitat data during the summer nursery period and the transition period (Sept $16^{th}$ – Oct $31^{st}$).

*Transmitter results*

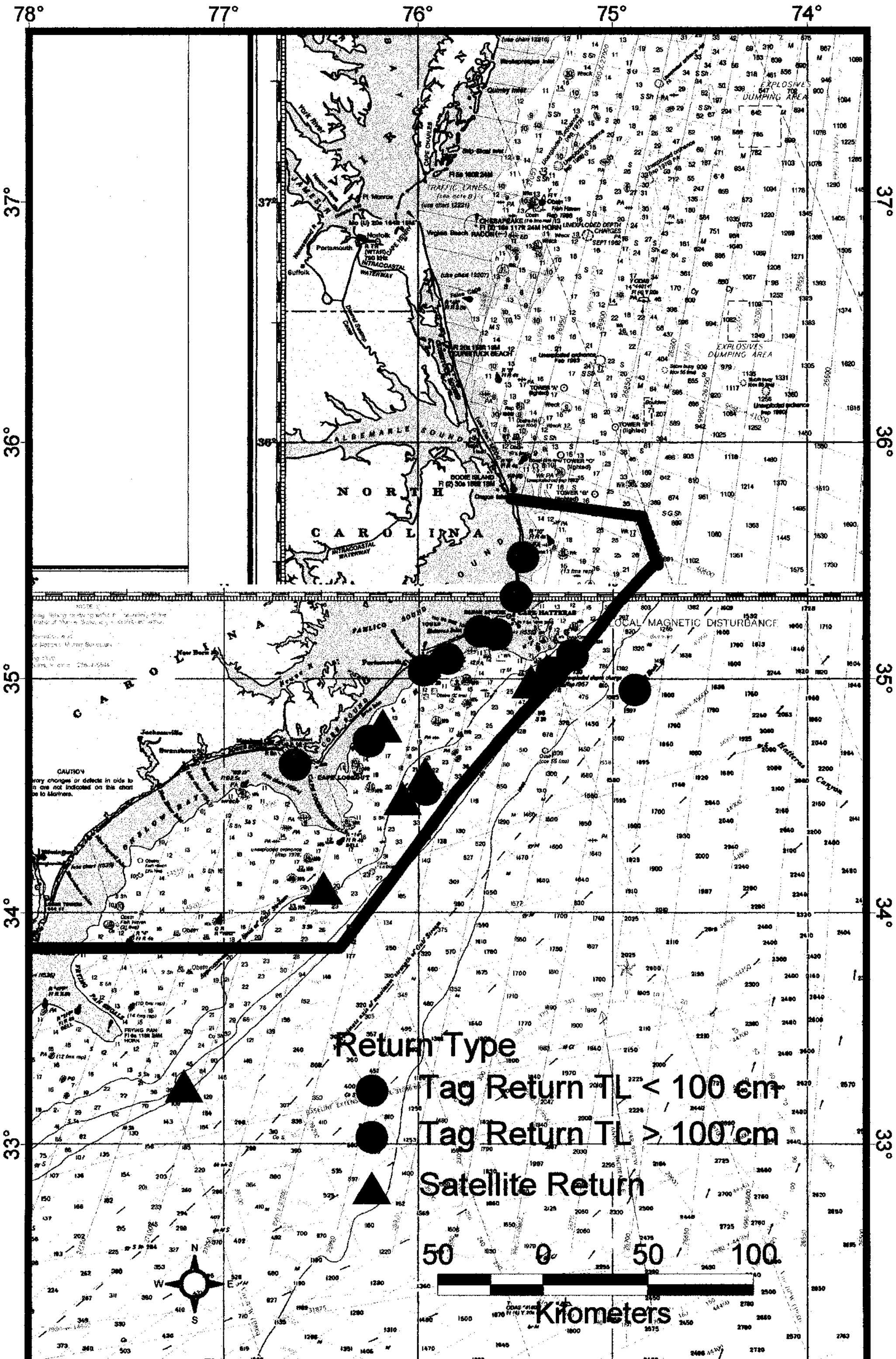
The objective of this study was to determine the winter habitat of these sharks and despite the high early pop off rate, nine (43%) of the transmitters released during the time period (November - February); we would expect these animals to occur in their overwintering area. Two satellite transmitters that released early during the winter months remained at the surface for eight days before transmitting and appear to have been transported by oceanic currents a considerable distance (over 900 km) before transmitting data. The location of these transmitters were not used to examine overwintering areas for these sharks but environmental data collected prior to the surfacing period was included in the habitat analysis. The remaining seven transmitters that surfaced and transmitted data in the winter months all popped up off the North Carolina coast between Cape Hatteras and 100 km southeast of the Cape

Fear River (Figure 1-2). The transmitters popped up in waters ranging from 14.4 to 92.2 km offshore and ranging in depths from 10 - 150 meters. These animals were found between 230 to 463 km from the transmitter attachment site within the summer nursery (Table 1-1).

The sharks were found in a wide range of water depths from the surface down to over 50 m during the winter months with the most common depth of occurrence being between 20 to 50 m (Figure 1-3). Sharks during this period occurred in all depth bins, even occurring in waters greater than 50 m deep and appear to have occupied a variety of depths throughout the overwintering period. In contrast these sharks exhibited a marked preference for shallow waters during the summer months with greater than 80 percent of the depth readings occurring in waters less than 12 m deep.

The transmitters recorded depths ranging from 0 to 172 m during the winter period, whereas during the summer period the transmitters recorded depths ranging from 0 to 24 m also indicating these animals occupy a much larger range of depths during the overwintering period. The depth profiles further reveal an increase in the mean depth of occurrence of these large juvenile sandbar sharks from the beginning of the tag deployment (July through September) to the time of pop-off (during November to February). The mean depth of occurrence for several of these sharks continued to increase until the time of transmitter release, potentially indicating these sharks continue moving into deeper waters throughout the late winter and

Figure 1-2. The locations of winter satellite transmitter pop-offs off the North Carolina coast (NOAA, Cape Sable to Cape Hatteras, #13003, 1:1,200,000 and NOAA, Cape Hatteras to Straits of Florida, #11009, 1:1,200,000).

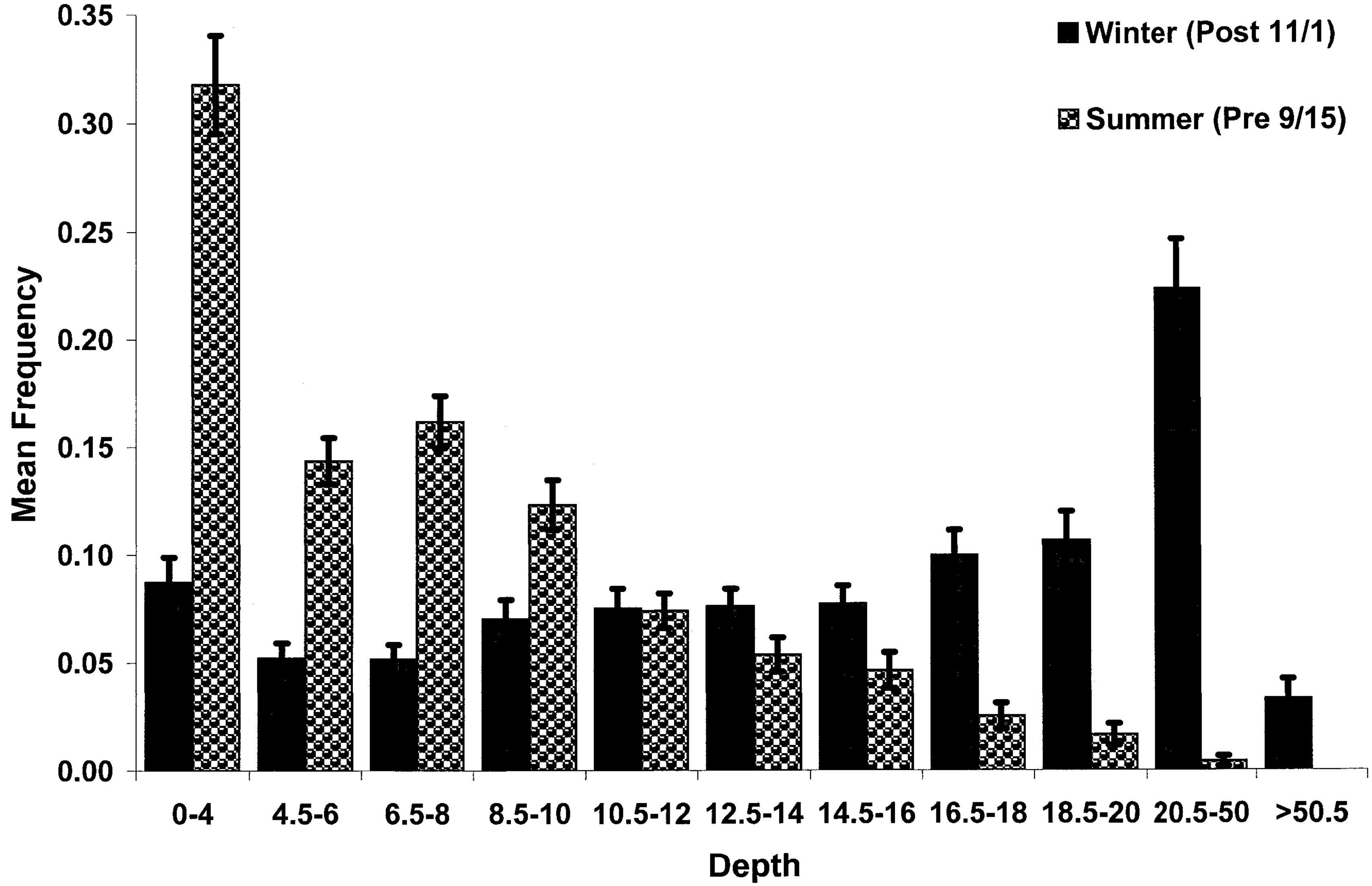


78°
77°
76°
75°
74°
37°
36°
35°
34°
33°
Return Type
Tag Return TL < 100 cm
Tag Return TL > 100 cm
Satellite Return
50
0
50
100
Kilometers

Table 1-1: Release locations and data are reported from the nine target time period releases. The depth column reports the map contours the pop-off locations occurred between. The PDT column represents data from the profile of depth and temperature during the overwintering period. Drifter refers to the transmitters that drifted for eight days before transmitting. The % data columns refer to the percent of data recovered from the transmitter during the summer and winter periods.

| Distance Offshore (km) | Nearest Land Point | Depth (fathoms) | Depth (meters) | Distance from attachment (km) | % Data summer | % Data winter | Date of Pop-Off *on time | PDT depth range (m) | PDT temp range C |
|---|---|---|---|---|---|---|---|---|---|
| 14.4 | E of Drum Inlet, NC | 10 to 20 | 18 to 37 | 294 | 16.5 | 0 | 12/13/03* | * | * |
| drifter | * | * | | * | 17.2 | 0 | 12/20/2003 | * | * |
| 51.5 | S of Cape Lookout, NC | 20 to 30 | 37 to 55 | 367 | 14.8 | 0 | 11/27/2003 | * | * |
| 33.3 | E of Cape Hatteras, NC | 20 to 30 | 37 to 55 | 254 | 16.2 | 21.3 | 01/07/04* | 0-48 | 16.0-25.4 |
| 92.2 | SE of Cape Fear, NC | 60 to 100 | 110 to 183 | 463 | 17.2 | 11.2 | 01/24/04* | 0-172 | 15.6-25.4 |
| 32.8 | E of Cape Lookout, NC | 20 to 30 | 37 to 55 | 289 | 16.0 | 1.9 | 02/04/04* | 0-168 | 17.2-23.6 |
| 49.4 | E of Cape Lookout, NC | 20 to 30 | 37 to 55 | 311 | 12.1 | 8.4 | 12/04/03 | 0-50 | 17.8-24.6 |
| 26.1 | E of Cape Hatteras, NC | 30 to 40 | 55 to 73 | 230 | 12.6 | 17.4 | 01/01/04* | 0-36 | 17.0-23.8 |
| drifter | * | * | | * | 0 | 9.3 | 12/05/03 | 0-40 | 16.8-22.6 |

Figure 1-3. Cumulative depth histogram of the satellite transmitters during the winter overwintering period and the summer nursery period (error bars are standard error of the mean).


Mean Frequency
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Winter (Post 11/1)
Summer (Pre 9/15)
0-4
4.5-6
6.5-8
8.5-10
10.5-12
12.5-14
14.5-16
16.5-18
18.5-20
20.5-50
>50.5
Depth

early spring months (Figure 1-4). The mean daily depth the sharks occurred at during the overwintering period of 24.9 m (SE = 2.88) was significantly deeper than the mean depth the sharks occurred at during the summer nursery period of 3.7 m (SE = 0.24, student's t-test, $p < 0.0001$).

Two different temperature binnings were used to study the temperature utilization of these sharks, therefore data on each of these bins will be provided separately. These sharks were found in water temperatures that ranged from 10° to 26°C during the winter months with sharks tending to remain in water temperatures ranging between 18° to 22°C (Figures 1-5a and b). Both data sets show a peak in the proportional frequency of depth occurrence in 17.5° to 22°C temperature waters with over 60% of the depth readings falling within these temperature bins during the overwintering period. There is clearly a shift into colder waters during the overwintering period. During the summer months the animals show a preference for waters with temperatures ranging from 20° to 28°C.

The temperature-depth profiles recorded temperature readings ranging from 15.6° to 25.4°C during the overwintering period in contrast to temperature readings from 9.2° to 29.4°C during the summer months. The temperature profiles also show a decrease in the mean temperature of occurrence during the southern migration. A few of the sharks, however, were present in some low temperature waters during the end of July and the beginning of August. A cold water event took place around this time period and we measured temperatures less than 20°C in the surface waters of three out of twenty of our regular sampling sites in the Eastern Shore of Virginia lagoonal system during the time period between July 29th and August 8th (these sampling areas

Figure 1-4. Mean depths from the depth profiles from the onset of transmitter attachment until transmitter release.

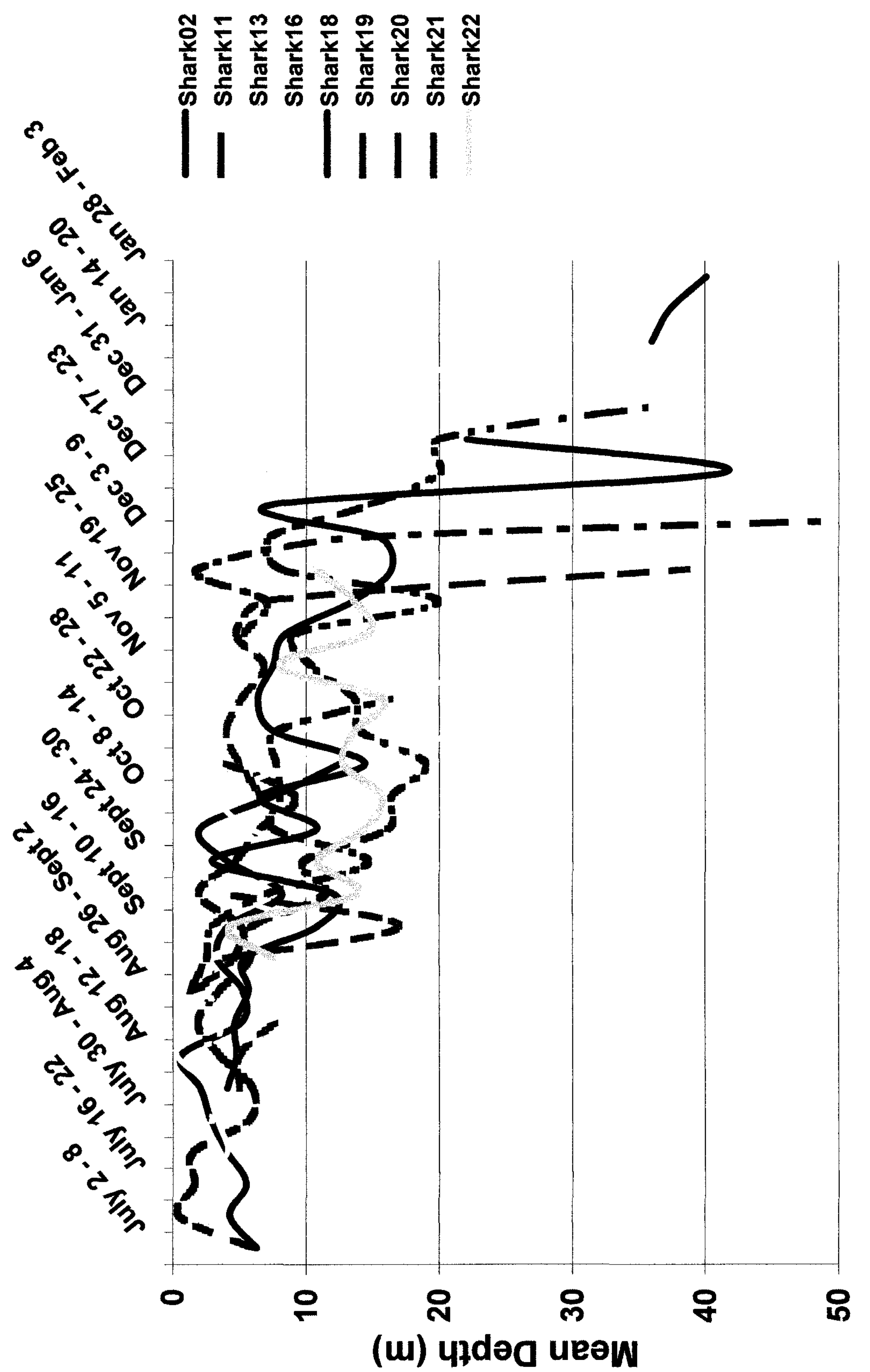
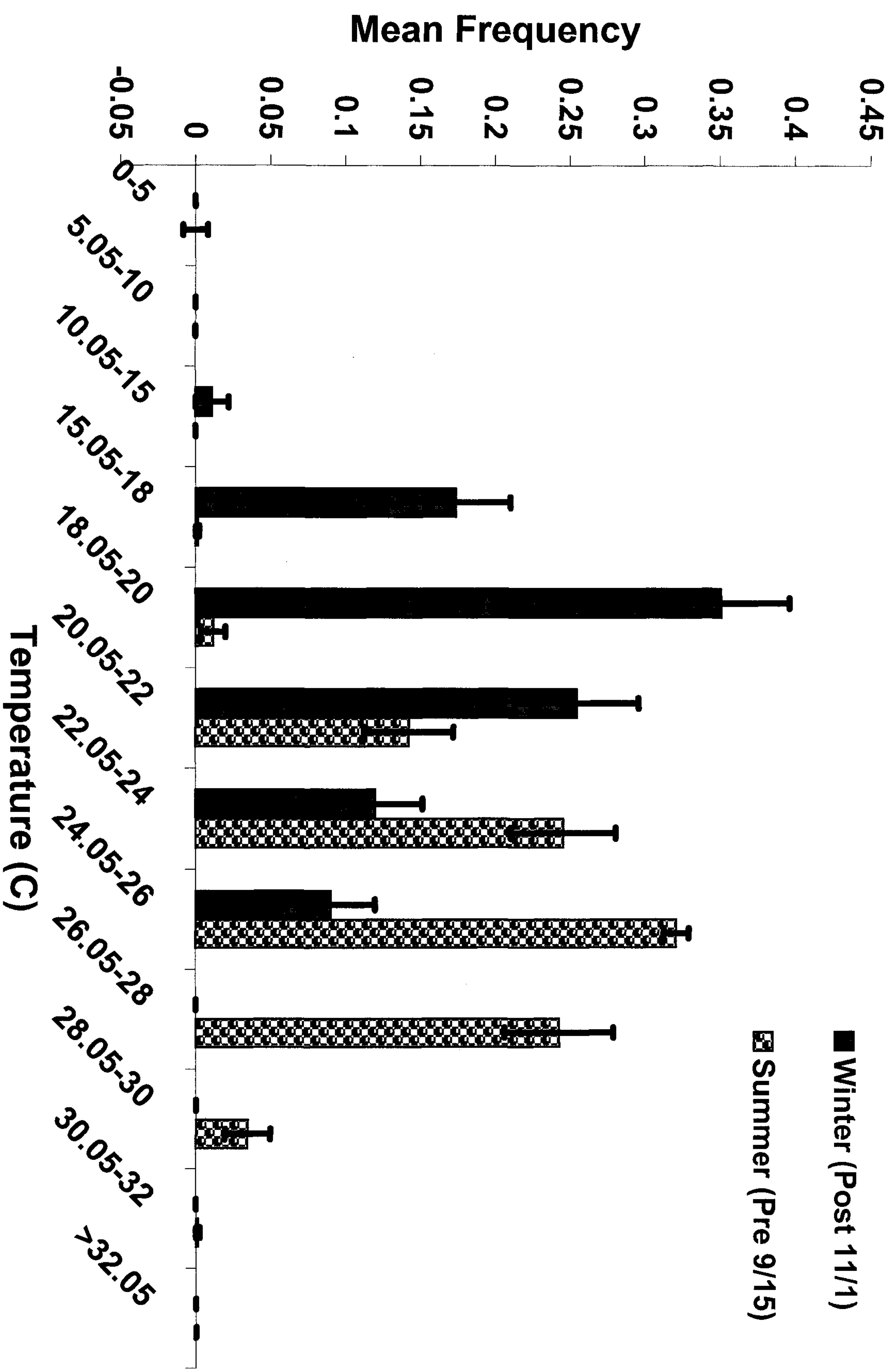
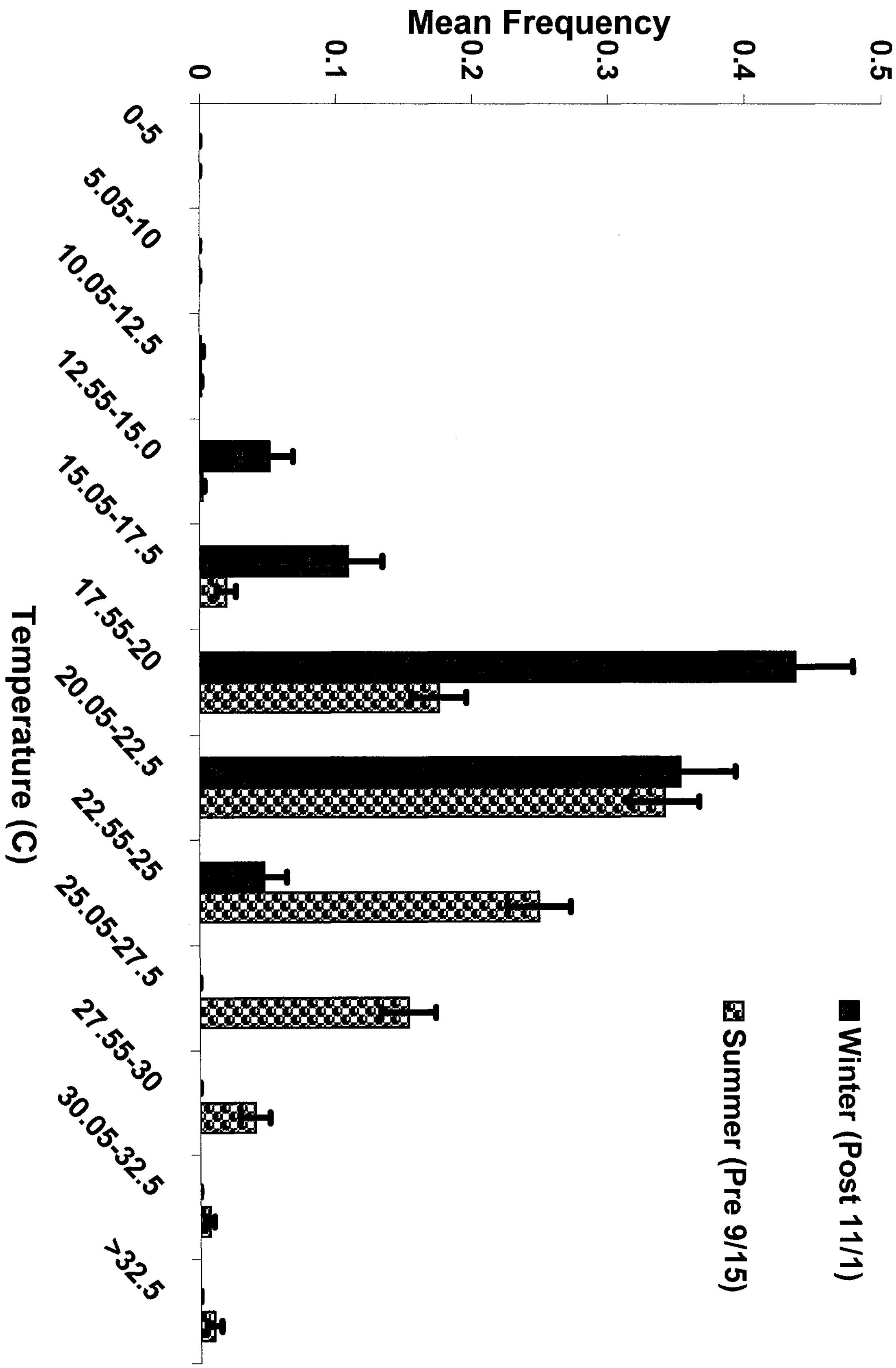

Mean Depth (m)
0
10
20
30
40
50
July 2 - 8
July 16 - 22
July 30 - Aug 4
Aug 12 - 18
Aug 26 - Sept 2
Sept 10 - 16
Sept 24 - 30
Oct 8 - 14
Oct 22 - 28
Nov 5 - 11
Nov 19 - 25
Dec 3 - 9
Dec 17 - 23
Dec 31 - Jan 6
Jan 14 - 20
Jan 28 - Feb 3
Shark02
Shark11
Shark13
Shark16
Shark18
Shark19
Shark20
Shark21
Shark22

Figure 1-5. Cumulative temperature histograms of the satellite transmitters during the overwintering period and the summer nursery period a) depth binning #1 and b) depth binning #2 (error bars are standard error of the mean).


Mean Frequency
-0.05
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
0-5
5.05-10
10.05-15
15.05-18
18.05-20
20.05-22
22.05-24
24.05-26
26.05-28
28.05-30
30.05-32
>32.05
Temperature (C)
Winter (Post 11/1)
Summer (Pre 9/15)

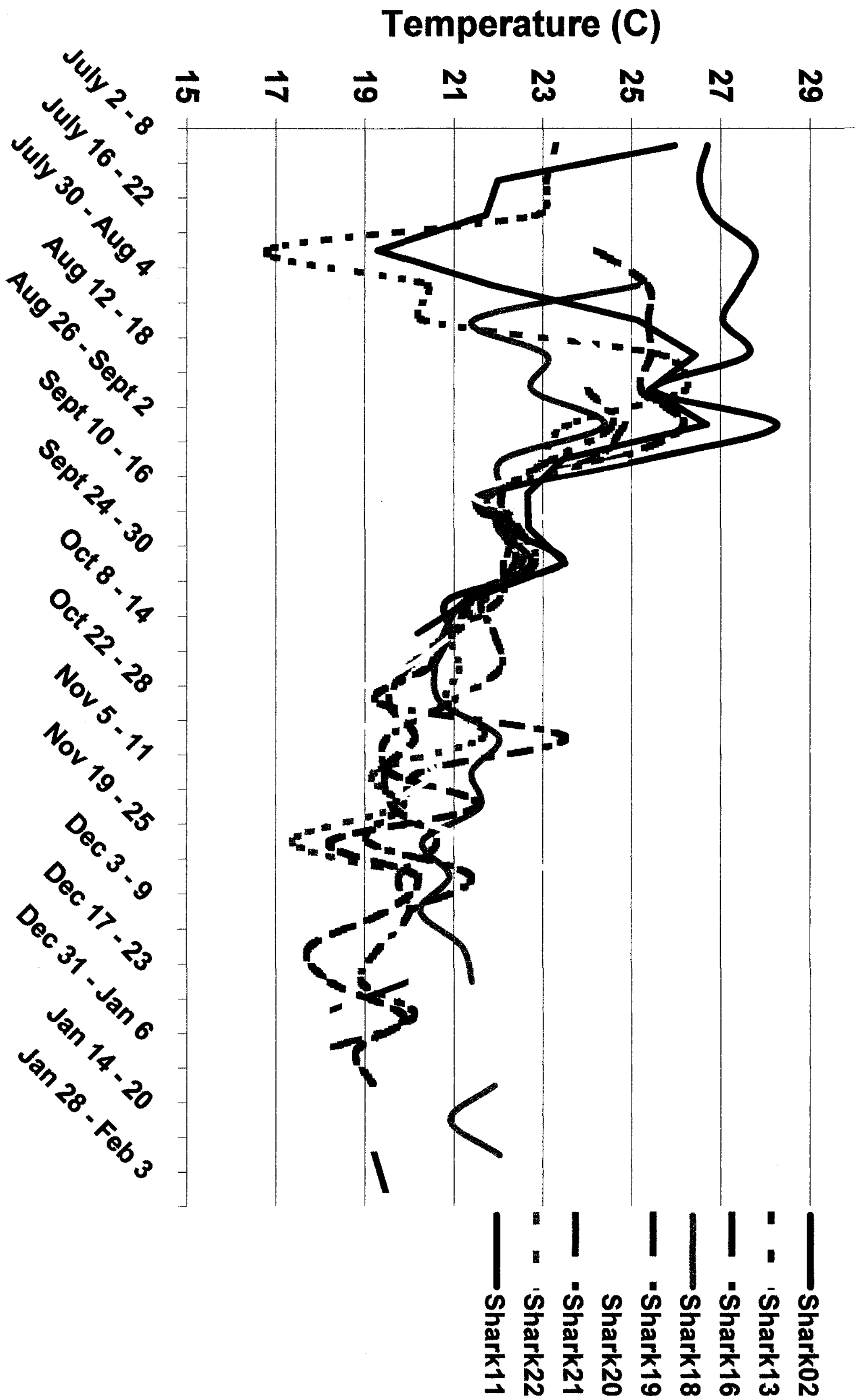

Mean Frequency
0
0.1
0.2
0.3
0.4
0.5
0-5
5.05-10
10.05-12.5
12.55-15.0
15.05-17.5
17.55-20
20.05-22.5
22.55-25
25.05-27.5
27.55-30
30.05-32.5
>32.5
Temperature (C)
Winter (Post 11/1)
Summer (Pre 9/15)

had temperatures ranging between 23.9° and 29.3°C in the sampling periods prior to and after the cold water event sampling) (Figure 1-6). This cold water event appears to have been localized to waters near the inlet as sites greater than a few kilometers from the inlet inside the lagoonal system had near normal temperatures. This possibly indicates these sharks were closer to the inlet or in coastal waters and the other sharks outfitted with transmitters that did not record these cold temperatures were further up into the lagoonal system. The mean temperature experienced by the sharks during the overwintering period of 19.9°C (SE = 0.19) was significantly colder than the mean temperature experienced during the summer nursery period of 23.9°C (SE = 0.23, student's t-test, $p < 0.0001$).

**Discussion**

Conventional tag return data from Chesapeake and Delaware Bay studies indicate sandbar shark wintering areas occur in shallow waters off the Carolina coasts, with higher concentrations of animals occurring off the central North Carolina coast (Grubbs et al. in press. Mersen and Pratt 2001). Jensen and Hopkins (2001) studied shark bycatch from October and November 1996 to 1998 and 2000, during Spanish mackerel and king mackerel sinknet fishing at Cape Hatteras, North Carolina. It was determined the Cape Hatteras region was an important overwintering area for sandbar and dusky sharks. Neonate and juvenile sandbar sharks began to arrive in this area during the last two weeks in October and remained in the region from Cape Hatteras to Cape Lookout in large numbers through the month of May. During the course of the study they had 77 sandbar shark tag recaptures, 73 of which were recaptured within

Figure 1-6. Mean temperatures from the temperature profiles from the onset of transmitter attachment until transmitter release.



Temperature (C)
15
17
19
21
23
25
27
29
July 2 - 8
July 16 - 22
July 30 - Aug 4
Aug 12 - 18
Aug 26 - Sept 2
Sept 10 - 16
Sept 24 - 30
Oct 8 - 14
Oct 22 - 28
Nov 5 - 11
Nov 19 - 25
Dec 3 - 9
Dec 17 - 23
Dec 31 - Jan 6
Jan 14 - 20
Jan 28 - Feb 3
Shark02
Shark13
Shark16
Shark18
Shark19
Shark20
Shark21
Shark22
Shark11

the sampling period in the same region they were tagged in, three returns were animals tagged in the Delaware Bay summer nursery, and one return was an animal tagged in the Chesapeake Bay summer nursery. Mersen and Pratt (2001) reported three recaptures of sandbar sharks tagged in Delaware Bay that were recaptured during the winter months. All three recaptures occurred off the coast of North Carolina. Mersen and Pratt (2001) further report winter tag recaptures of neonate sandbar sharks off the coast of North Carolina that were from age-0 animals initially tagged in New Jersey during the summer months. These three studies relied upon fishery dependent fish capture or tag recoveries and reporting by observers or commercial fishermen and there is the potential for apparent patterns to reflect fishing activity and not fish abundance. However, this study using fishery independent techniques also found that large juveniles were concentrated within the same area off the southern outer banks of North Carolina.

Our study found those large juveniles with successful satellite transmitter pop offs during the course of the winter months occurred in the region from Cape Hatteras to Cape Lookout. These animals were found to occur within 100 km of the shore and in waters from 10 to 200 m deep. When compared to the Grubbs et al. (in press) conventional tag-recapture study, we found that these large juvenile sandbar sharks occurred within the same locations as those juvenile sandbar sharks that were recaptured at a size greater than 100 cm total length (TL) and further offshore from those juvenile sandbar sharks recaptured at a size less than 100 cm TL (Figure 1-2). We estimated size at recapture when not known or questionable by applying the growth equation for sandbar sharks determined by Sminkey and Musick (1995). We then determined the age at tagging, added the time at liberty to determine the age at recapture, and then used the same equation to calculate the estimated size at recapture.

Large juvenile sandbar sharks of this population occupied a deeper and colder environment during the winter months than during the summer months. There was a shift in temperatures of occurrence from predominately 20° to 28°C to predominantly 17° to 22°C between the summer and overwintering periods. There was also a shift in the depth regime from predominantly less than 10 meters to predominantly over 20 meters from the summer to the overwintering periods. A colder habitat in combination with less available resources presumably results in less productivity during the winter months. This pattern is likely prevalent in many temporate species that migrate large distances between their summer and winter habitats. Grusha (2005) applied satellite transmitters to cownose rays that were programmed to detach in the spring months. She found that cownose rays captured in Chesapeake Bay, Virginia overwintered in the Florida area, with animals occurring in colder and deeper waters in the winter months than during the summer months and a gradual shift in the climatic regime experienced by these rays.

The 2003 Amendment 1 to the 1999 Final Fishery Management plan for Atlantic Tunas, Swordfish and Sharks includes a time area closure that encompasses the area between Cape Hatteras to the north and Cape Fear to the south, out to the sixty fathom line off the coast of North Carolina (Figure 1-2). This area is closed to directed shark bottom longline fishing during the months of January to July. Six of the seven pop-off locations for these sharks occurred within the area encompassed by the closed area. In addition, all of the conventional tag returns with the exception of one age-10 animal occurred within the closed area during the overwintering period. There has been a significant emphasis on the delineation and protection of summer nursery areas for this species. While juvenile sandbar sharks may experience increased productivity during the nursery period, their summer nursery habitat is quite extensive in comparison to their overwintering grounds. The concentration of both small and large juvenile sandbar sharks within this coastal area may make the population more vulnerable to overfishing within the overwintering area. This study reconfirms the importance of shallow North Carolina coastal waters as an overwintering area for juvenile sandbar and supports the size and scope of the winter closed area enacted by the 2003 management amendment.

# CHAPTER 2

# A delineation of the Eastern Shore of Virginia summer nursery habitat of juvenile sandbar sharks, *Carcharhinus plumbeus*

**Abstract**

The identification and delineation of pupping and nursery areas of Atlantic sharks has been identified as an important information need for future management efforts. Recent studies have found the principal summer nursery areas of the western North Atlantic population of sandbar sharks occur in shallow coastal bays from New Jersey to South Carolina. The primary objective of this project was to spatially delineate the summer nursery for sandbar sharks that occurs in the coastal bays and lagoons of the Eastern Shore of Virginia. To accomplish this, twenty sites were chosen within an area that spanned 70 km from Magothy Bay to the south and Wachapreague Inlet to the north for repetitive sampling using longline gear. These sampling locations were situated within four inlets from south to north: Sand Shoal Inlet, Great Machipongo Inlet, Quinby Inlet, and Wachapreague Inlet. Sites were sampled monthly using a 50 hook longline set, baited with Atlantic menhaden, and soaked for two hours. The mean catch rate at each site during the peak nursery season varied from 5.6 to 22.2 sharks per 100 hooks. Despite the high catch rates throughout the study area, there was significantly higher abundance in Great Machipongo Inlet and there was a significant positive correlation between abundance and both distance from the inlet and bottom temperature. Neonates, small juveniles, and large juveniles were present throughout the sampling area, but there were significant differences in the relative abundance of each age class with inlet and with distance from the inlet. Neonates and small juveniles tended to be concentrated further from the inlets and larger juveniles

tended to be concentrated closer to the inlets. Neonates were more concentrated in the southern two inlets, likely indicating a higher frequency of pupping occurs within these areas. Small juveniles were abundant throughout the study area except in Quinby Inlet. Large juveniles were more concentrated in the middle two inlets, Great Machipongo and Quinby Inlets. The catch rates of neonate and juvenile sandbar sharks within this area were comparable to those of the nearby Chesapeake Bay though a larger number of juveniles greater than 100 cm total length were caught within the Eastern Shore lagoons. This study indicates that the Eastern Shore of Virginia's bays and lagoons function as important primary and secondary nursery grounds for this species and fit the criteria to be included in future management measures as a habitat area of particular concern (HAPC).

**Introduction**

Castro (1993) defined shark nursery areas as, "geographically discrete parts of a species range where the gravid females of most species of coastal sharks deliver their young or deposit their eggs and where their young spend their first weeks, months, or years." Nurseries are often defined as primary or secondary types, where primary nursery areas are those in which parturition occurs and the young remain for a short period of time and secondary nurseries are those in which juveniles occur after leaving the primary nursery and before reaching maturity (Bass 1978). Springer (1967) found that shark nursery areas most often occur in shallow waters outside the normal geographic range of mature male sharks and that females did not feed while traveling into these areas to pup. It was proposed that the availability of suitable nursery habitat may be a density dependent factor in controlling the size of shark populations. The use of shallow coastal areas by various species as a nursery may be dependent upon and unique to the particular life history of the species. Branstetter (1990) found that species which produce relatively small or slow growing young utilize protected nursery areas whereas species that produce large or fast growing young can utilize areas that afford little protection.

Nursery areas are generally thought to be places where growth and survival of juveniles are enhanced through a lower risk of predation and a higher availability of food resources. The role of the nursery area likely varies from species to species and location to location, though two recent studies stress the importance of these areas as a refuge from predators. Heupel and Hueter (2002) in a study on juvenile blacktip sharks in Terra Ceia Bay, Florida found no correlation between prey density and shark activity within geographic zones, indicating predator avoidance may be a more important factor than prey density in the use of this nursery area by blacktip sharks. Bush and Holland (2002) found that food was actually limiting for juvenile scalloped hammerheads in Kaneohe Bay (Oahu, Hawaii) and that these sharks may be existing at consumption levels below maintenance ration. They suggest this nursery area may provide protection from some larger carcharhinid shark predators.

Specific examples of studies that focus on delineating and studying elasmobranch nursery areas are rare in the literature. A few studies describe areas that function as nursery grounds for multiple species. Castro (1993) studied the Bulls Bay shark nursery in South Carolina, which functions as a nursery for nine different shark species. The role of this area as a nursery was described for each of these nine species. Simpfendorfer and Milward (1993) described the use of the Cleveland Bay nursery in Northern Australia by eight species of carcharhinid and sphyrnid sharks. The variance to mean ratio of catch rates was calculated to determine if distribution of each species was aggregated, random, or uniform. It was found that four of the species utilized the nursery area as a seasonal primary nursery and at least three of the species used this area as a year-round combined primary and secondary nursery. The authors suggested the use of communal nursery areas may reduce predation.

More commonly studies describe a specific nursery area of a single shark species and frequently these studies focus on the presence of neonate or juvenile animals within an area to define the nursery area without further study into the physical factors that affect the use of the nursery. Some research has focused on the role of juvenile sharks as part of local ecosystems. Clark (1971) studied the nursery habitat of scalloped hammerheads found in Kaneohe Bay. This area is a known pupping area for this species and a concentrated sampling study was conducted to determine the role of these pups in the bay community. It was estimated that as many as 10,000 scalloped hammerhead pups may pass through this area in a year indicating these animals likely have a large impact on the community. More commonly research has focused on the qualitative assessment of where nursery grounds occur, often by opportunistically noting the presence of these animals as bycatch in fisheries or netting programs. Van der Molen and Caille (2001) studied the use of the bay, Bahia Engano (Patagonia, Argentina), by smoothhound sharks, *Mustelus schmitti*, by measuring sharks captured as bycatch in the shrimp fishery that occurs in this area. Juvenile and neonate *M. schmitti* were found in this area from late spring to mid autumn. Smale (2002) studied the nursery areas of the sandtiger shark, *Carcharias taurus*, off the

South African coast. By examining records from the National Marine Linefish System for catch, species, locality, and size, it was found that the Eastern Cape functions as both a primary and secondary nursery for this shark.

Studies of sandbar shark summer nursery areas have been conducted for various locations in the western North Atlantic Ocean and the Gulf of Mexico. Carlson (1999) found that neonate and juvenile sandbar sharks occur in the northeastern Gulf of Mexico indicating that sandbar sharks pup in this region. While the primary summer nursery areas for this species are thought to be in the western North Atlantic, future research may reveal the importance of nursery areas in the Gulf of Mexico. Sandbar sharks are one of the species reported to occur in the communal nursery of Bulls Bay, South Carolina. Gravid female sandbar sharks were caught in Bulls Bay during the first week of June with embryos ranging in size from 48 to 64 cm. Neonate and juveniles were common there until late September (Castro 1993).

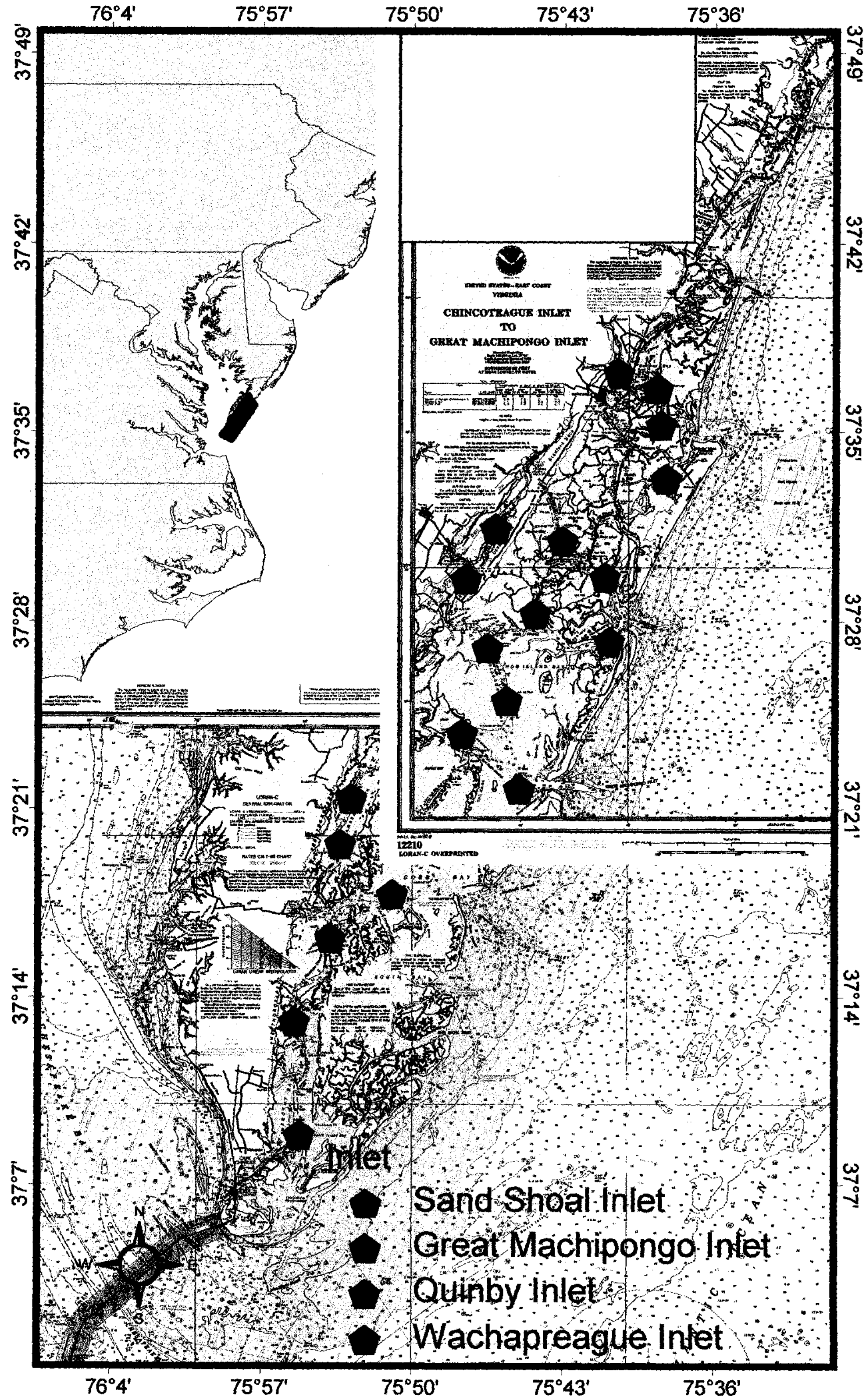
The two primary summer nurseries of this population are thought to occur in the Chesapeake and Delaware bays. High abundances of neonate and juvenile sharks have been shown to occur within each of these areas. Recent studies have attempted to use physical parameters to define the use of these nurseries both spatially and temporally (Mersen and Pratt 2001, Grubbs and Musick in press). The Eastern Shore of Virginia summer nursery for this species occurs from the mouth of Magothy Bay to the north along the coast of Virginia. This nursery lies between the Chesapeake Bay and Delaware Bay nurseries and is known to function as nursery habitat for juvenile and neonate sandbar sharks based on the VIMS longterm shark monitoring program. However, the importance of this area as a sandbar shark nursery has not been extensively studied. The principal objectives of this project were to delineate the spatial use of the Eastern Shore of Virginia summer sandbar shark nursery, to determine how physical parameters affect the use of this nursery area, and to examine how different size classes of sandbar sharks use the nursery area.

**Methods**

The sampling for this project occurred in the Eastern Shore of Virginia coastal bays and lagoons between Fisherman's Island to the south, where the lagoons are connected to Chesapeake Bay and Wachapreague Inlet to the north (Figure 2-1). The study area consists of constricted tidal creeks bounded by marsh and barrier islands to the east and the Eastern Shore of Virginia to the west. The constricted nature of water flow results in high tidal current velocities and little structure within the water column. Therefore, temperature, salinity, dissolved oxygen and other physical parameters tend to be homogenous vertically throughout the water column. These creeks also possess a large amount of macroalgae in the spring and summer months which is transported by the strong tidal currents and may contribute to hypoxic events within the nursery area.

In order to delineate the nursery, twenty longline sampling sites were chosen to maximize spatial coverage within the study area as well as to sample as many different habitats as possible. During the summers of 2003 and 2004, these sites were set with a 50 hook monofilament longline, using 12/0 circle hooks, baited with Atlantic menhaden, and set for 2 hours. Each longline site was set once every four weeks between the end of May and the end of October. All live juvenile sandbar sharks were

Figure 2-1. Longline sampling locations, 2003 and 2004, in the Eastern Shore of Virginia coastal bays and lagoons. Sampling occurred in: Sand Shoal Inlet, Great Machipongo Inlet, Quinby Inlet, and Wachapreague Inlet (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


76°4'
75°57'
75°50'
75°43'
75°36'
37°49'
37°42'
37°35'
37°28'
37°21'
37°14'
37°7'
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
LORAN-C OVERPRINTED
Inlet
Sand Shoal Inlet
Great Machipongo Inlet
Quinby Inlet
Wachapreague Inlet

measured and tagged with a VIMS juvenile shark tag and each adult sandbar shark was tagged with a NMFS M-type tag. At each longline sampling site a YSI 600 XL sonde (YSI Incorporated 1725 Brannum Lane Yellow Springs, OH 45387) was used to measure water temperature, salinity, and dissolved oxygen at 1 m intervals from the surface to the bottom of the water column. In addition the tidal phase and current direction, distance from the inlet, and start and end depth of the set were determined at each site.

Catch per unit effort (CPUE) was calculated as the number of sharks caught per 100 hooks and was determined for each longline set. A non parametric Kruskal-Wallis test was used to determine if there was a difference in abundance between our four sampling areas. The Kruskal-Wallis test was used due to the non-normality of the catch rate data set even when these data were transformed. A principal components analysis (PCA) was calculated for the physical factors of bottom temperature, bottom salinity, bottom dissolved oxygen, depth, and distance from the inlet to determine if physical factors varied in relation to each other and to determine if sampling sites could be defined using a reduced number of physical parameters. PCA is a matrix technique that calculates eigenvalues and eigenvectors from the covariance matrix of the parameters. By ordering the eigenvalues one can determine which parameters explain the greatest amount of the variance in the data. The PCA and Kruskal Wallis tests were performed using Minitab statistical software (Quality Plaza 1829 Pine Hall Road State College, PA 16801-3008).

To examine the spatial use of the nursery area, Spearman's rank correlation (rho) was calculated between CPUE and each physical parameter (surface temperature, bottom temperature, bottom salinity, bottom dissolved oxygen, distance to the inlet, tidal phase, water depth). The Spearman's rank test was conducted using Minitab statistical software (Quality Plaza 1829 Pine Hall Road State College, PA 16801-3008). Spearman's rank correlation was chosen again due to the non-normality of the data and because this test is known to be less sensitive to outliers. Results from this test were used to determine which variables best explain the abundance distribution. CPUE was modeled as a function of the parameters that were significantly related to catch rates using classification and regression tree analysis (CART) with Dtreg data mining software (http://www.dtreg.com/index.htm). The regression tree split the data into binary pairs in such a fashion that each subsequent split explained the greatest amount of variance in the data. To test the accuracy of the regression tree the relative error was calculated using 10-fold cross validation estimation. The data were divided into 10 subsets of nearly equal size and trees were constructed using the data minus each subset which was used to determine a mean error estimate (Breiman, et al. 1984). Classification error rate as a function of tree size is averaged for the ten trees and the tree was pruned to the tree size that minimizes this classification error rate or cross validation cost. This study used methods comparable to those used by Grubbs and Musick (in press) for the Chesapeake Bay summer nursery to determine if the same parameters define habitat use of this nursery area.

During the time period of the study two satellite transmitters that had been attached to large juvenile sandbar sharks (TL = 124 and 127 cm) within the lagoonal system popped-off prematurely of their programmed overwintering date and were recovered. These transmitters archived temperature and depth data every two minutes while attached to the shark. These data were used to examine actual temperature and depths utilized by these sharks.

Catch per unit effort was calculated at each site for three defined size classes: neonates which were defined as those animals less than 71 cm total length (TL), small juveniles which were defined to be those animals between 71 – 90 cm TL (this size class likely includes those animals that were age-1 or age-2), and large juveniles were defined to be those animals larger than 90 cm TL (including those animals age-3 or greater). Simple correspondence analysis was used to examine the effect of abundance of size class by sampling site. The computer program SAS proc corresp procedure (Version 9.1.3 for Windows, SAS Institute Inc., Cary, NC, USA) was used to calculate the correspondence analysis and associated chi square significance values. Correspondence analysis is a technique which derives eigenvalues and eigenvectors from a matrix obtained from a contingency table. The resultant components were plotted to reveal potential relationships between abundance of size class and inlet and distance from the inlet.

**Results**

During the summers of 2003 and 2004, 1,159 sandbar sharks were captured within the Eastern Shore lagoons ranging in size from 53 cm to an estimated 215 cm TL. In general, high catch rates of neonate and juvenile sandbar sharks were found throughout the nursery area with mean catch rates by sampling site ranging from 5.6 to 22.2 sharks per 100 hooks during peak nursery usage (from June through September). Each size class was caught at every location with the exception of one site in Wachapreague Inlet where no large juveniles were captured. Neonate and juvenile sandbar sharks were captured in waters ranging from 14.8° to 30.4°C, in salinities ranging from 24.4 to 32.3 ppt, in dissolved oxygen levels ranging from 3.38 to 9.90 ppm, and in depths ranging from 1.1 to 15.1 m. Bottom temperature of all sets ranged from 13.0° to 30.4°C, bottom salinity of all sets ranged from 17.1 to 32.6 ppt, bottom dissolved oxygen levels ranged from 3.38 to 10.23 ppm, and bottom depth ranged from 1.1 to 15.5 m (Appendix 1). The mean catch rates of neonate and juvenile sharks combined were highest at three sites in Great Machipongo Inlet and there was a trend of higher abundance in more southern localities (Figure 2-2). There were significant differences in the abundance of neonate and juvenile sharks in the four sampling areas leading to the rejection of the null hypothesis of equal abundance throughout the sampling region (Kruskal Wallis, $p < 0.001$). However, using a nonparametric multiple comparison test, only the Machipongo Inlet area had significantly higher abundance than the other three areas (with unequal sample size and tied ranks tested at $Q_{\alpha=0.05, k=4}$) (Figure 2-3).

The principal components analysis revealed principal component one explained about 44% of the variance and was related to a distance from the inlet effect (Table 2-1). The other principal components explained 20% of the variance or less. The first principal component related distance from the inlet positively with temperature and distance from the inlet negatively with dissolved oxygen, salinity, and depth (Figure 2-4). This indicated that as distance from the inlet increased, temperature increased whereas salinity, dissolved oxygen and depth decreased within the study area.

Figure 2-2. Mean catch per unit effort (sharks/100 hooks) at each sampling site (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).

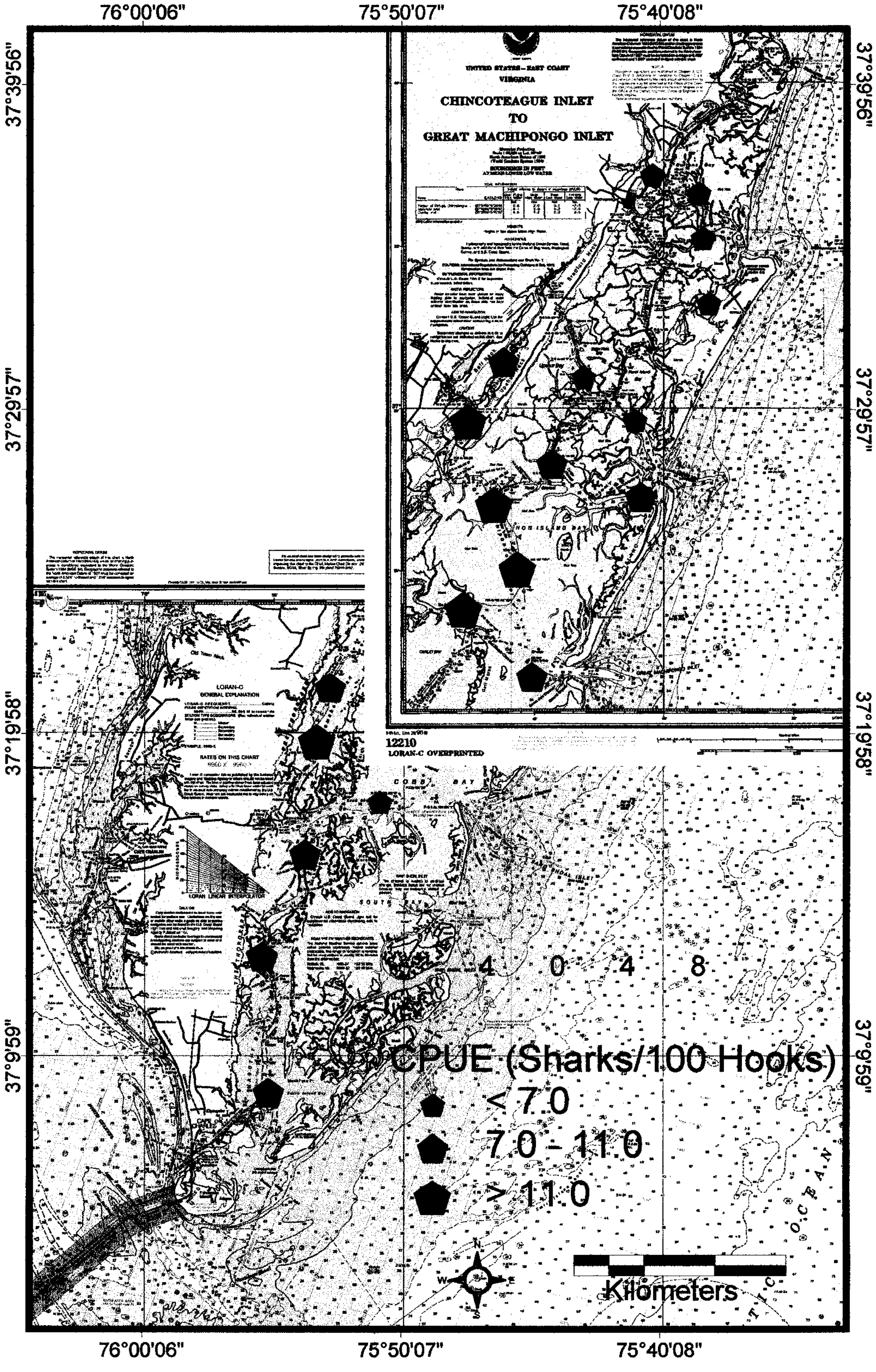

76°00'06"
75°50'07"
75°40'08"
37°39'56"
37°29'57"
37°19'58"
37°9'59"
UNITED STATES – EAST COAST
VIRGINIA
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
LORAN-C OVERPRINTED
LORAN-C
GENERAL EXPLANATION
LORAN LINEAR INTERPOLATOR
4 0 4 8
CPUE (Sharks/100 Hooks)
< 7.0
7.0 - 11.0
> 11.0
Kilometers
N
W
E
S

Figure 2-3. Catch per unit effort by Inlet, SSI = Sand Shoal Inlet (error bars are standard error of the mean).

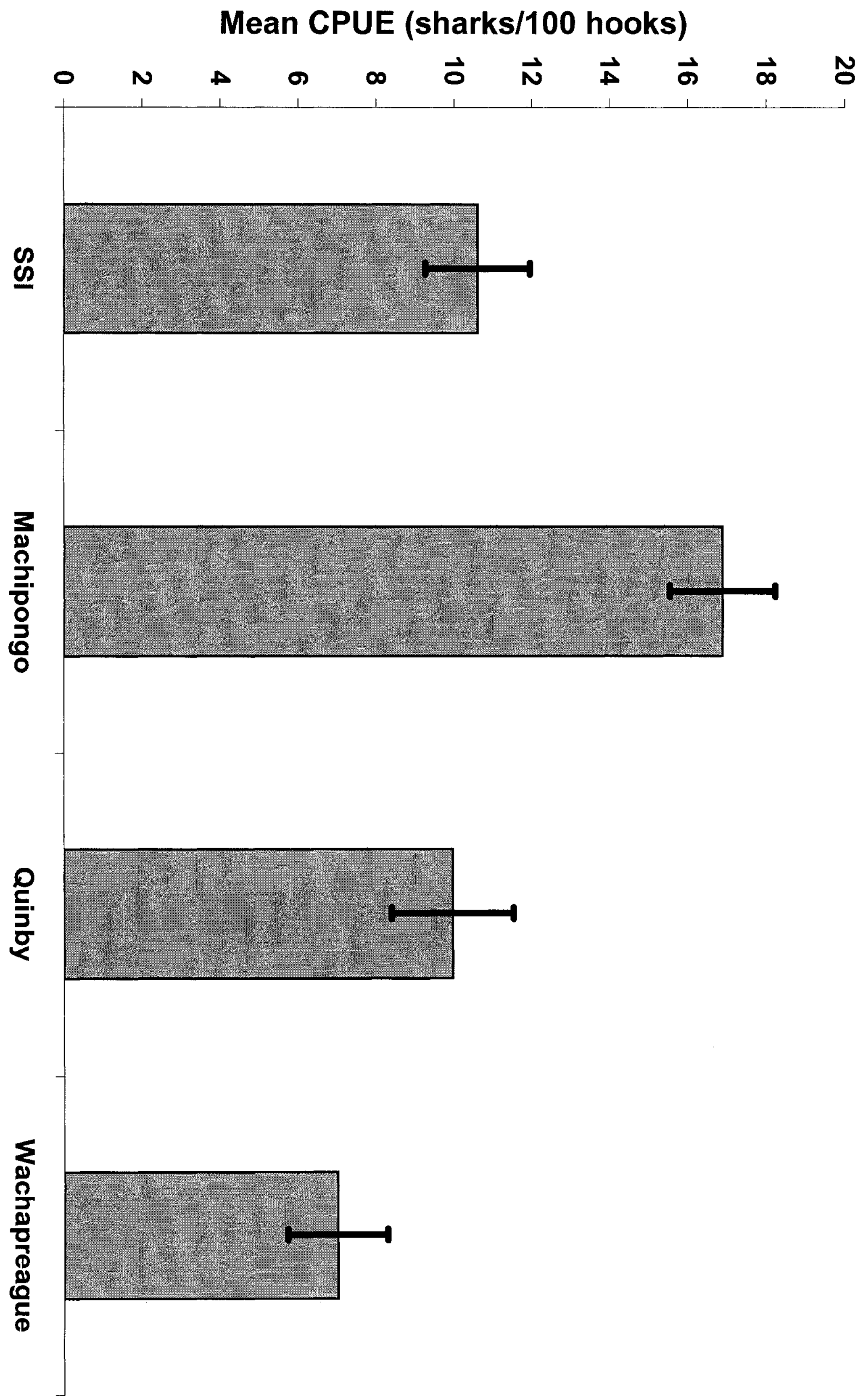
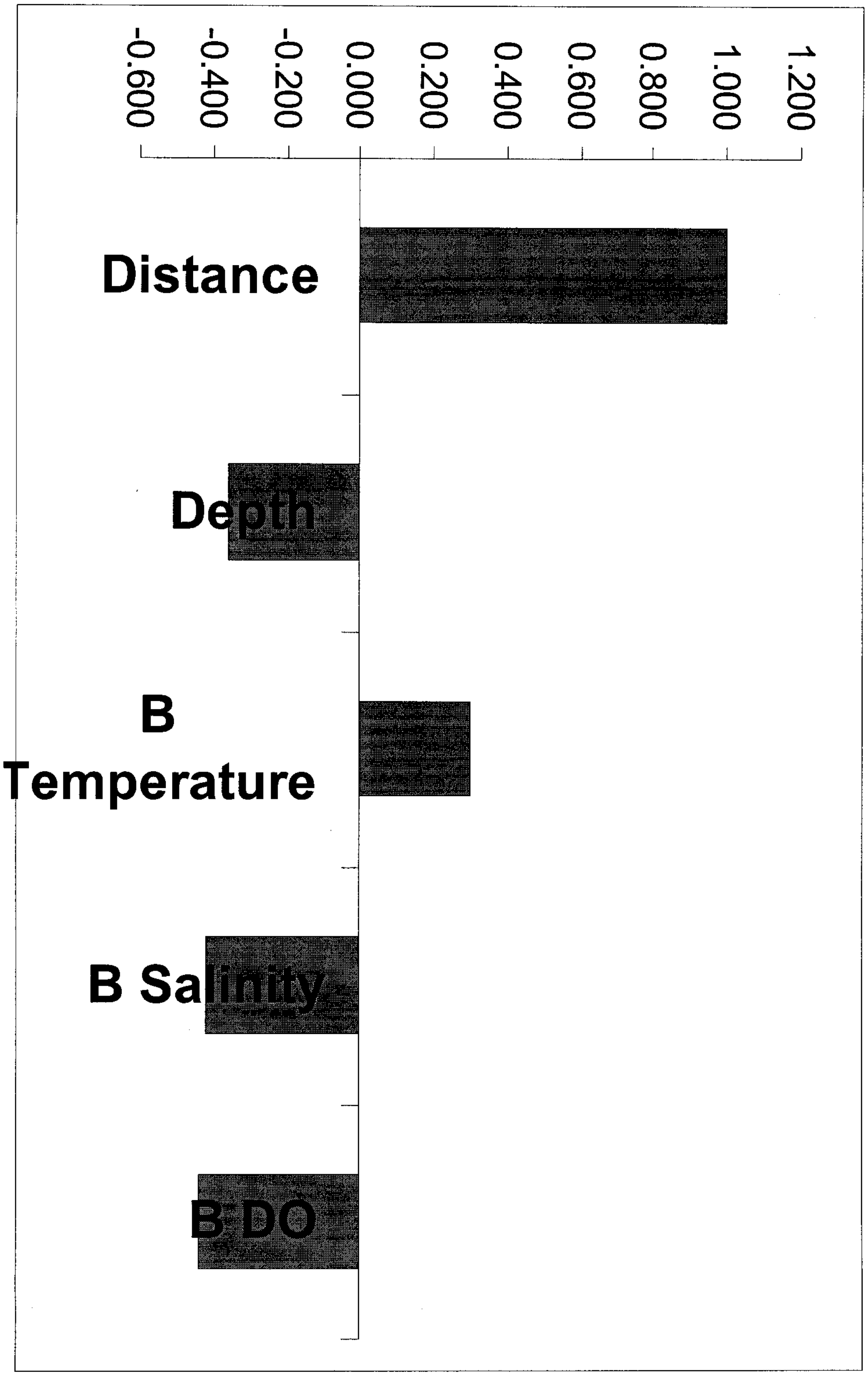

Mean CPUE (sharks/100 hooks)
0
2
4
6
8
10
12
14
16
18
20
SSI
Machipongo
Quinby
Wachapreague

Table 2-1. Principal components analysis table with the eigenvalue, the proportion of variance explained, and the cumulative variance explained for each principal component.

| PC | Eigenvalue | Proportion | Cumulative |
|---|---|---|---|
| 1 | 2.18 | 0.435 | 0.435 |
| 2 | 1.00 | 0.200 | 0.635 |
| 3 | 0.832 | 0.167 | 0.802 |
| 4 | 0.525 | 0.105 | 0.907 |
| 5 | 0.466 | 0.032 | 1.00 |

Figure 2-4. Principal components analysis results, scores are plotted for each variable for the first principal component.


-0.600
-0.400
-0.200
0.000
0.200
0.400
0.600
0.800
1.000
1.200
Distance
Depth
B Temperature
B Salinity
B DO

A Spearman's rank correlation was calculated to see if catch per unit effort was correlated with any of the following physical parameters: bottom temperature, bottom salinity, bottom dissolved oxygen, distance from the inlet, maximum water depth, inlet location, year, tidal phase and current direction. The only four parameters that were significantly correlated with catch rate were inlet, bottom temperature, bottom dissolved oxygen, and distance from the inlet. Bottom temperature was positively correlated with catch rate whereas bottom dissolved oxygen and distance were negatively correlated with catch rate (Table 2-2). The increase in abundance at larger distances from the inlet and higher temperatures corresponds with the PCA results, which revealed a positive relationship between distance and temperature and a negative relationship between distance and dissolved oxygen.

However, when these four parameters (inlet, distance, bottom temperature, and bottom dissolved oxygen) were used in a regression tree to determine if they could be used to predict areas within the nursery of higher abundance, the resulting unpruned tree has 37 nodes and only explains 63.8% of the total variance in the data set. When the tree was pruned to the minimum validation error the tree only had three nodes with the only split occurring due to station grouping, with Great Machipongo once again separating out from the other three station groups. This tree however only explained 11.4% of the variance found within the data set. This result reconfirmed the high numbers of juvenile sharks that occurred within Great Machipongo Inlet but indicates the regression tree was unable to predict areas within the nursery of higher abundance effectively based on physical parameters. This was likely due to the relatively high abundance of these animals throughout the nursery area during the summer months.

Table 2-2. Spearman's Rank Correlation Coefficient for each physical parameter related to abundance, ** indicates parameters with a significant relationship to CPUE.

| Variable | Correlation Coefficient | Significance | N |
|---|---|---|---|
| **Bottom Temp** | **0.220** | **0.002**** | **190** |
| **Bottom DO** | **-0.180** | **0.013**** | **190** |
| **Inlet** | **-0.164** | **0.022**** | **196** |
| **Distance** | **0.157** | **0.028**** | **196** |
| **Year** | **0.061** | **0.398** | **196** |
| **Bottom Salinity** | **0.056** | **0.444** | **190** |
| **Max. Depth** | **0.047** | **0.517** | **196** |
| **Current** | **0.020** | **0.777** | **196** |
| **Tide** | **-0.019** | **0.793** | **196** |

Two satellite transmitters attached during the overwintering study that prematurely released during the summer months were recovered during the fall of 2003. One of these transmitters (shark #12) was attached on July 29th and detached from the animal on August 23rd, the other transmitter (shark #17) was attached on August 5th and detached from the animal on August 18th. These transmitters recorded depth and temperature readings every 2 minutes. Daily mean temperatures of the water these sharks occurred in ranged between 19.2° to 26.7°C for shark #12 and 20.8° to 26.6°C for shark #17 (Figure 2-5). There was a dip in temperatures recorded by the transmitter attached to the shark #12 during the end of July, corresponding to a cold water event that is documented in chapter one. Daily mean depths of the water these two sharks occurred in ranged between 1.7 to 7.3 m for shark #12 and 4.2 to 8.3 m for shark #17 (Figure 2-6).

There were local differences in the relative abundance of each of the three size classes of sandbar sharks within this nursery area. Neonate sharks were more abundant in the southern inlets particularly in Machipongo Inlet, likely due to increased pupping within these southern areas. Machipongo Inlet in particular is a known pupping area as several adult females were captured within this region in recent years by VIMS shark researchers (Figure 2-7). Small juveniles were more widely distributed but appear to be somewhat more concentrated at greater distances from the inlets (Figure 2-8). Large juveniles were concentrated in Great Machipongo and Quinby inlets and appeared to be concentrated closer to the inlet mouths (Figure 2-9). Regardless that all size classes were found within each inlet, each inlet appeared to have a unique pattern of abundance of the size classes (Table 2-3a). Sand Shoal

Figure 2-5. Mean daily temperatures from two satellite transmitters recovered from large juvenile sandbar sharks (error bars are standard error of the mean).

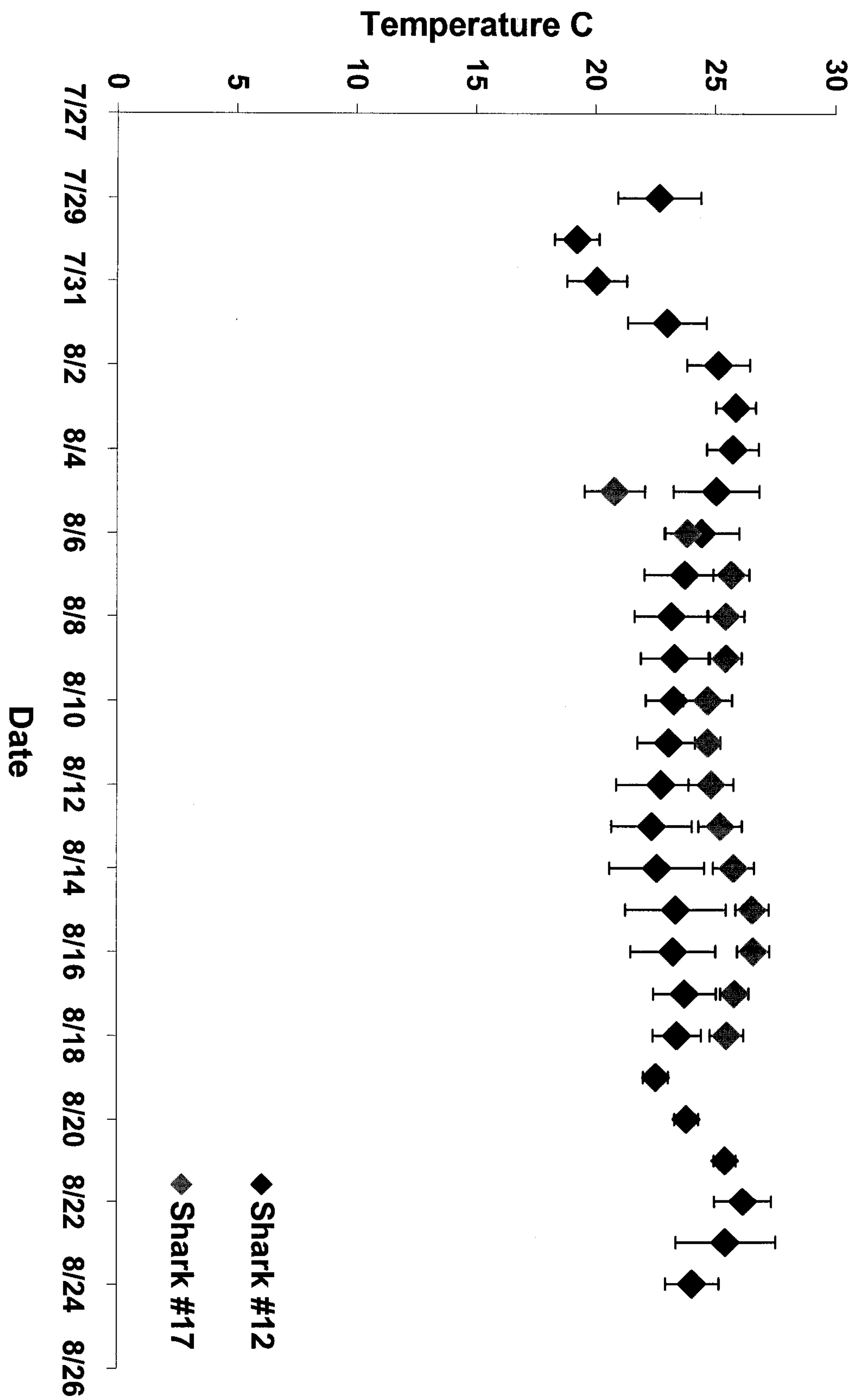

Temperature C
0
5
10
15
20
25
30
7/27
7/29
7/31
8/2
8/4
8/6
8/8
8/10
8/12
8/14
8/16
8/18
8/20
8/22
8/24
8/26
Date
Shark #12
Shark #17

Figure 2-6. Mean daily depths from two satellite transmitters recovered from large juvenile sandbar sharks (error bars are standard error of the mean).

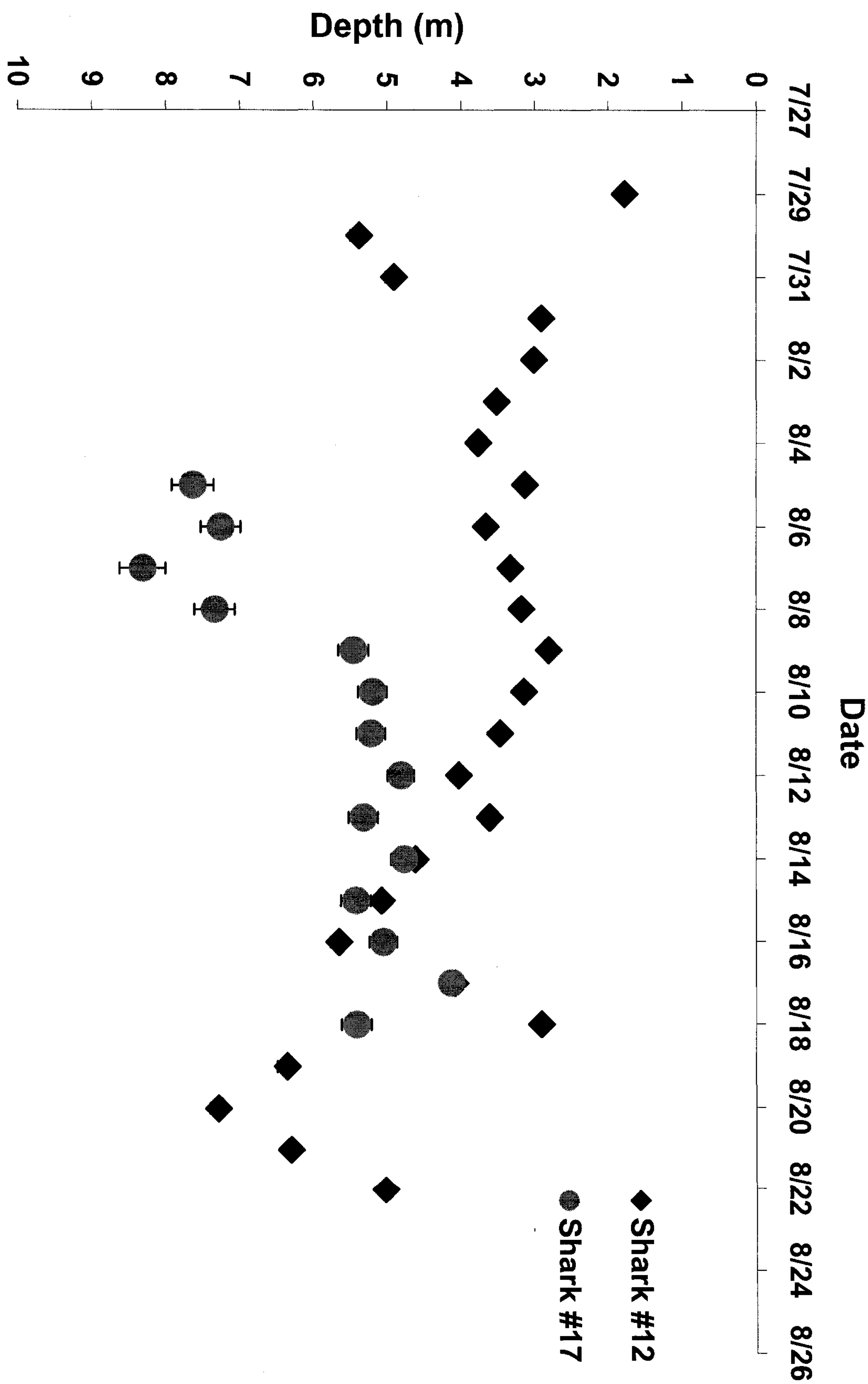

Depth (m)
Date
Shark #12
Shark #17

Figure 2-7. Neonate (TL < 71 cm) abundance by station, with low (CPUE < 1.0), medium (CPUE 1. 0 – 4. 0), and high (CPUE > 4.0) abundance noted by station (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).

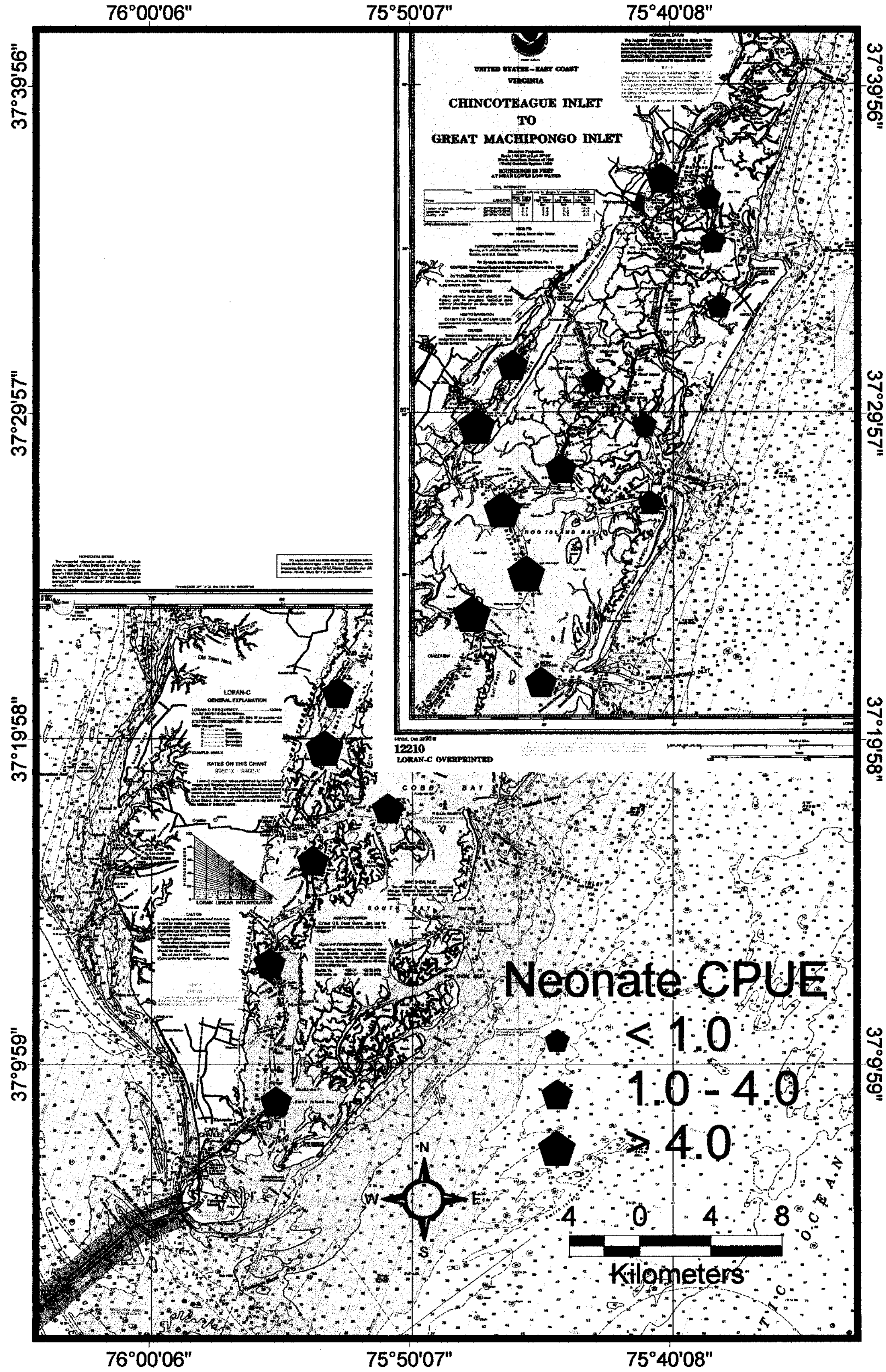
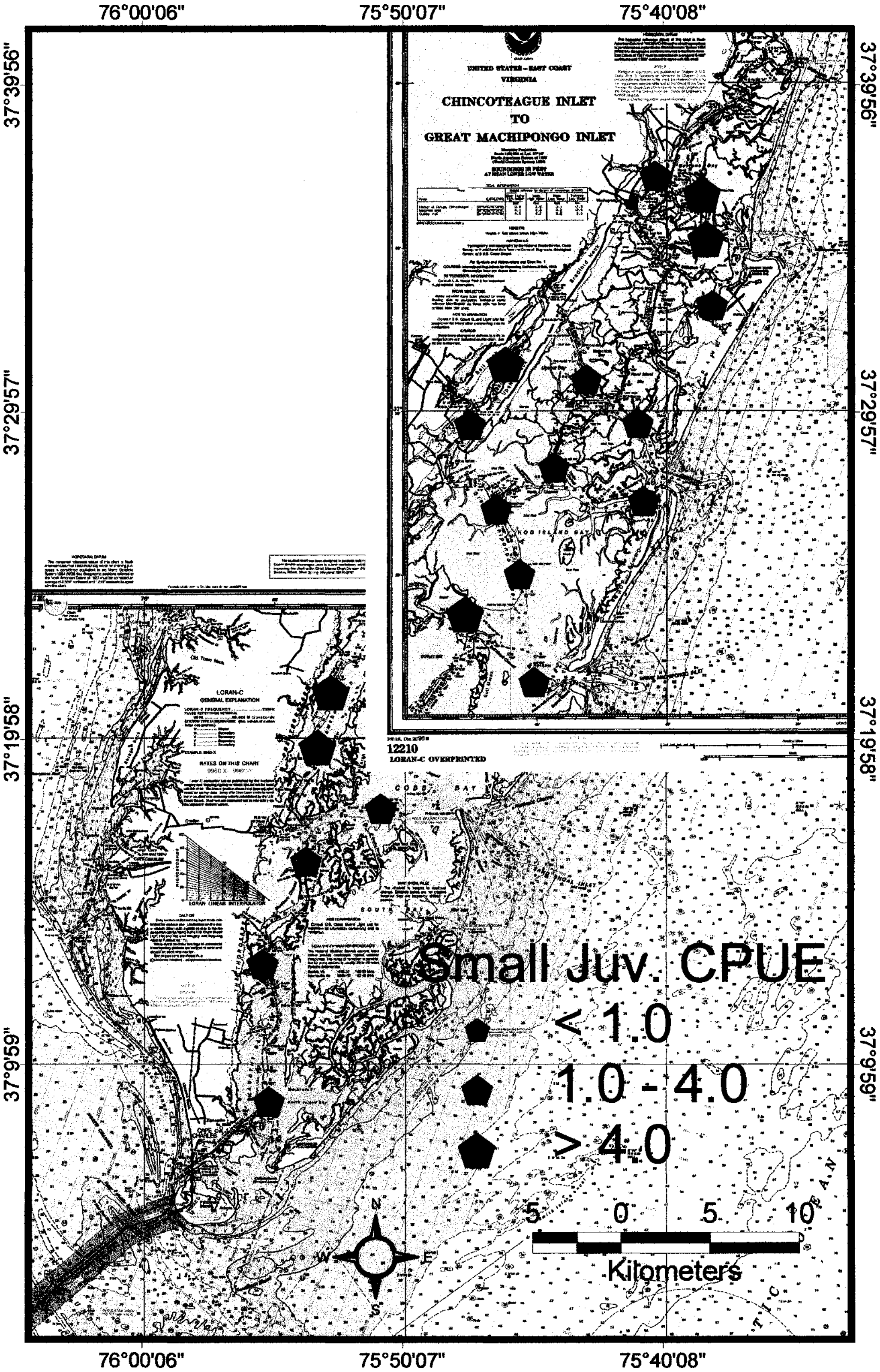
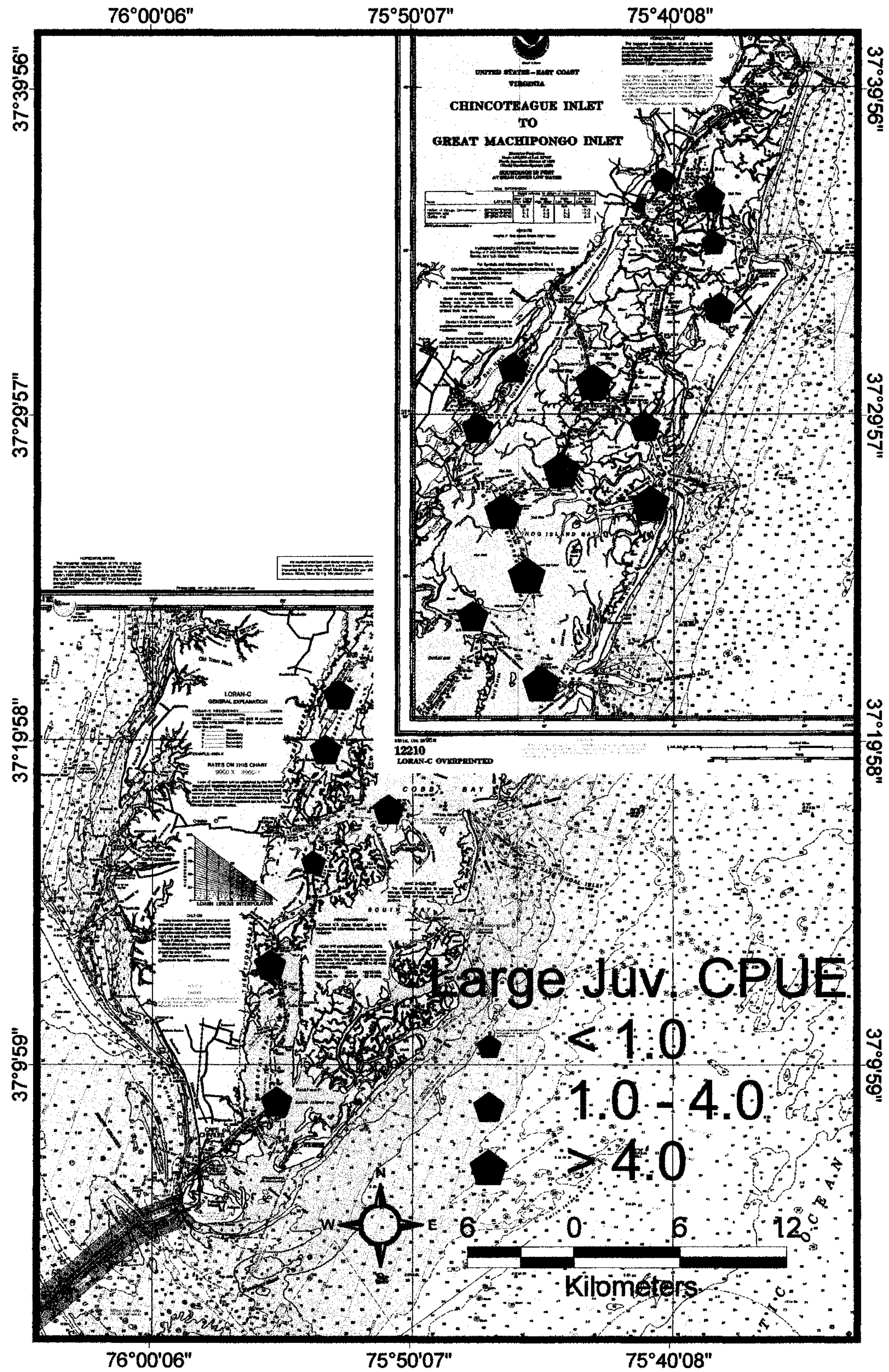

76°00'06"
75°50'07"
75°40'08"
37°39'56"
37°29'57"
37°19'58"
37°9'59"
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
LORAN-C OVERPRINTED
Neonate CPUE
< 1.0
1.0 - 4.0
> 4.0
N
S
E
W
4 0 4 8
Kilometers

Figure 2-8. Small juvenile (71 ≤ TL ≤ 90 cm) abundance by station, with low (CPUE < 1.0), medium (CPUE 1. 0 – 4. 0), and high (CPUE > 4.0) abundance noted by station (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).



76°00'06"
75°50'07"
75°40'08"
37°39'56"
37°29'57"
37°19'58"
37°9'59"
UNITED STATES - EAST COAST
VIRGINIA
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
LORAN-C OVERPRINTED
LORAN-C
GENERAL EXPLANATION
RATES ON THIS CHART
LORAN LINEAR INTERPOLATOR
Small Juv. CPUE
< 1.0
1.0 - 4.0
> 4.0
5
0
5
10
Kilometers
N
E
S
W

Figure 2-9. Large juvenile (TL > 90 cm) abundance by station, with low (CPUE < 1.0), medium (CPUE 1. 0 – 4. 0), and high (CPUE > 4.0) abundance noted by station (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


76°00'06"
75°50'07"
75°40'08"
37°39'56"
37°29'57"
37°19'58"
37°9'59"
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
LORAN-C OVERPRINTED
LORAN-C
GENERAL EXPLANATION
RATES ON THIS CHART
Large Juv. CPUE
< 1.0
1.0 - 4.0
> 4.0
N
W
E
S
6
0
6
12
Kilometers

Inlet was dominated by neonate and small juvenile size classes, Great Machipongo Inlet had all size classes present in relatively high abundance, Quinby Inlet only had large juveniles present in high abundance, and Wachapreague Inlet only had small juveniles present in high abundance. Again all size classes were found at all distances from the inlet, but it appeared that neonate and small juveniles were more concentrated farther from the inlet and that large juveniles were more concentrated closer to the inlets (Table 2-3b).

Correspondence analysis results also indicated a significant relationship between abundance of size class and sampling site, again showing that neonates grouped with Sand Shoal Inlet and Machipongo Inlet, small juveniles grouped with Wachapreague inlet and large juveniles grouped with Quinby and Machipongo Inlets ($X^2 = 563.4 >> X^2_{(df=38,\ a=0.05)} = 53.4$) (Figure 2-10). The correspondence analysis results also indicated a significant relationship between abundance of size class and distance from the inlet with neonates and small juveniles grouping with the inner sites furthest from the inlets and large juveniles grouping with the outer sites closest to the inlets (Figure 2-11).

**Discussion**

Studies of sandbar shark summer nursery areas have been conducted for various locations in the western North Atlantic Ocean and the Gulf of Mexico. The northern extent of sandbar shark nursery grounds in the western North Atlantic was found to be Great Bay New Jersey (Mersen 1998). Sandbar sharks were one of the species reported to use the communal nursery of Bulls Bay, South Carolina as both a primary and secondary nursery (Castro 1993). In addition, areas off the western

Table 2-3. Contingency table for a. for size class vs. inlet location and b. size class vs. distance from the inlet.

a.

| Inlet | All sizes | Neonates | Small Juveniles | Large Juveniles |
|---|---|---|---|---|
| Sand Shoal | 10.61 ± 1.34 | 4.00 ± 0.776 | 4.43 ± 0.840 | 2.18 ± 0.448 |
| Great Machipongo | 16.88 ± 1.35 | 5.21 ± 0.758 | 4.44 ± 0.705 | 7.24 ± 1.13 |
| Quinby | 9.95 ± 1.56 | 1.20 ± 0.410 | 2.45 ± 0.557 | 6.30 ± 1.33 |
| Wachapreague | 7.00 ± 1.28 | 1.00 ± 0.295 | 4.20 ± 1.03 | 1.80 ± 0.558 |

b.

| Distance (km) | All sizes | Neonates | Small Juveniles | Large Juveniles |
|---|---|---|---|---|
| 1.0 – 2.9 | 8.35 ± 1.10 | 1.07 ± 0.253 | 3.16 ± 0.646 | 4.12 ± 0.836 |
| 3.0 – 4.9 | 14.63 ± 1.45 | 3.76 ± 0.726 | 3.93 ± 0.822 | 6.94 ± 1.08 |
| 6.0 – 7.9 | 12.54 ± 1.56 | 4.50 ± 0.963 | 4.54 ± 0.716 | 3.50 ± 1.02 |
| > 8.0 | 13.00 ± 2.02 | 5.00 ± 0.948 | 5.07 ± 1.26 | 2.93 ± 0.938 |

Figure 2-10. Simple Correspondence Analysis results for size class abundance vs. sampling site emphasizing inlet location.

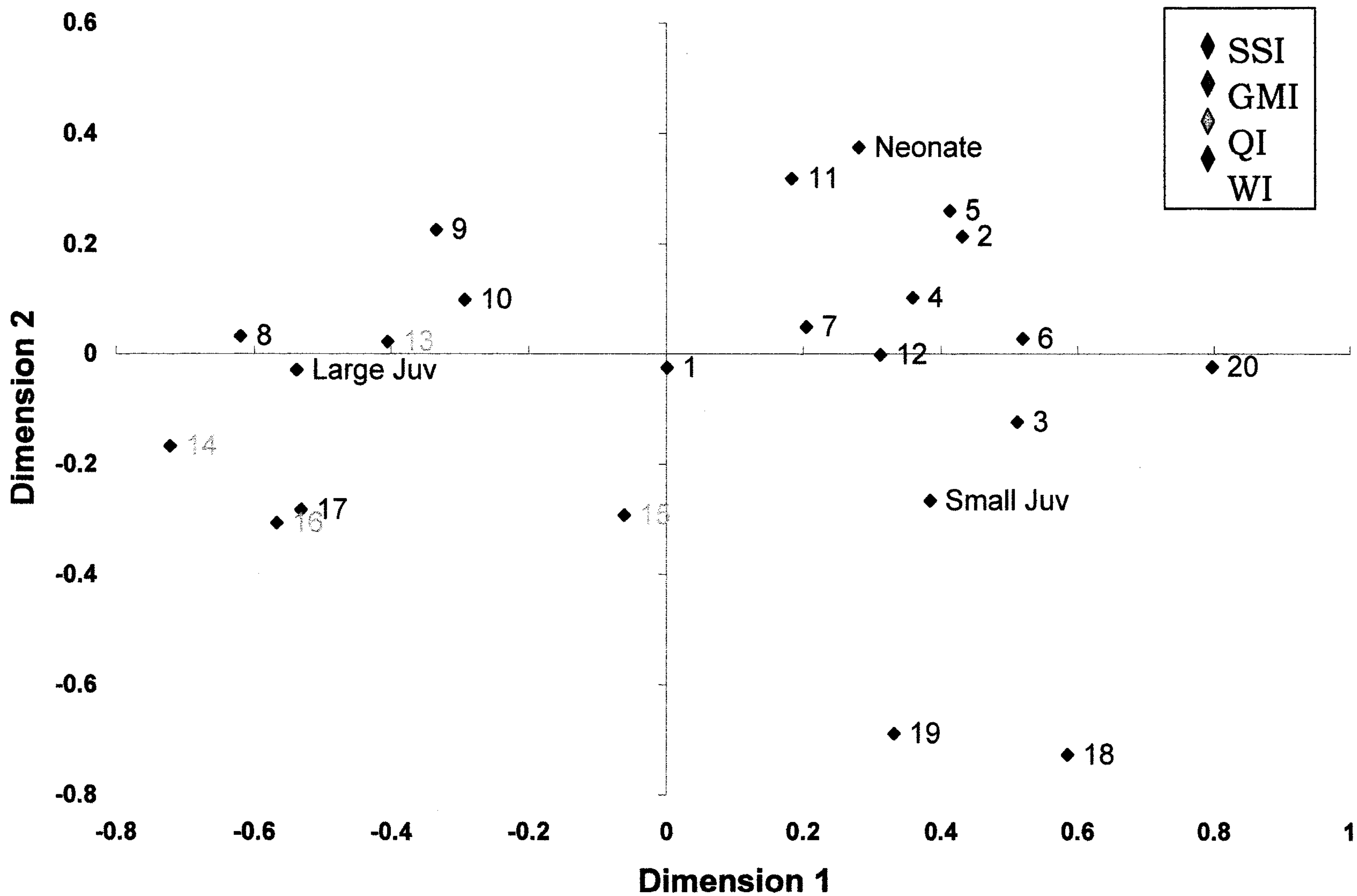
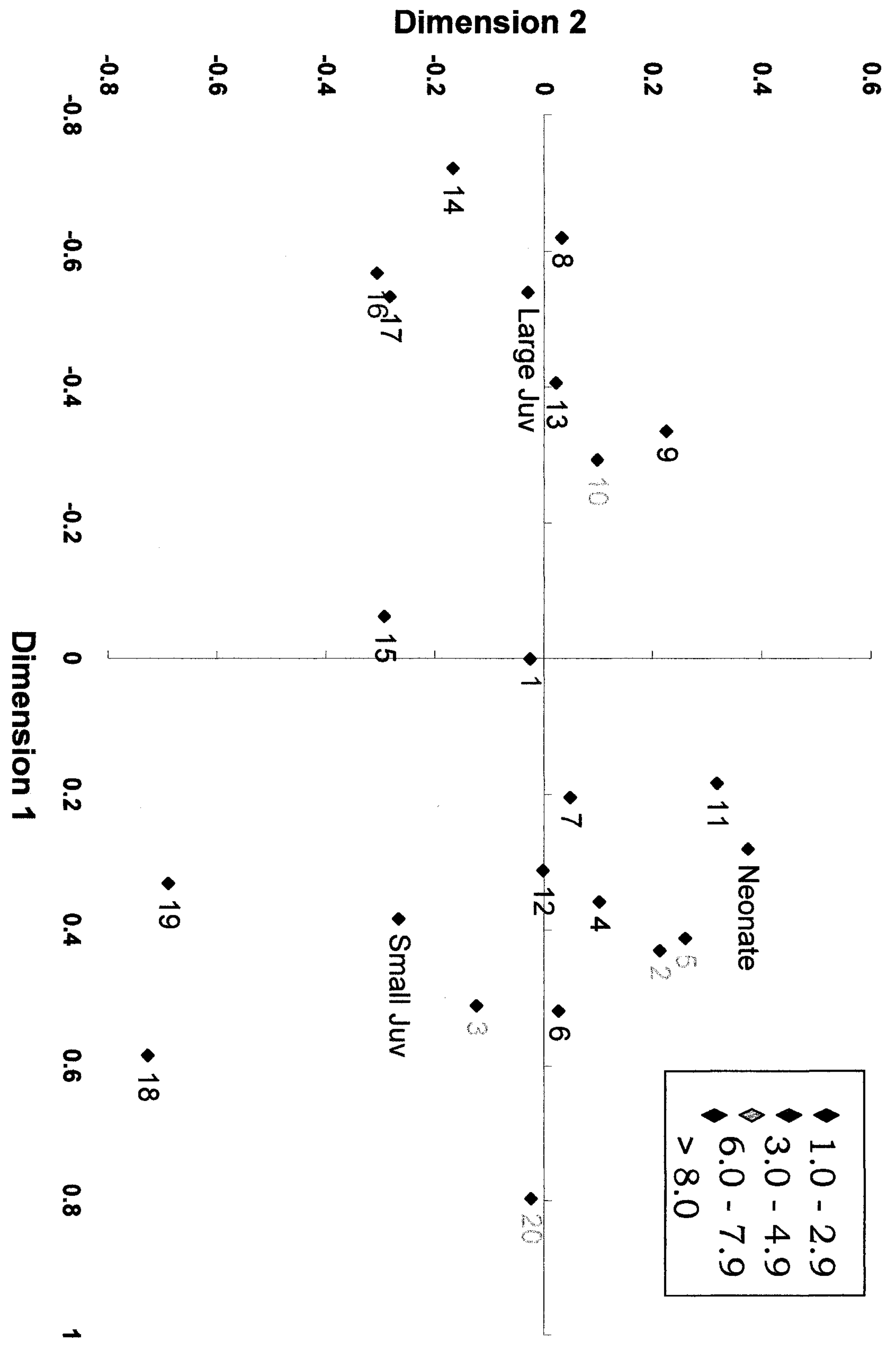

SSI
GMI
QI
WI
Neonate
11
5
2
9
10
4
7
8
13
12
6
Large Juv
1
20
14
3
17
16
15
Small Juv
19
18
Dimension 2
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
Dimension 1

Figure 2-11. Simple Correspondence Analysis results for size class abundance vs. sampling site, emphasizing distance from the inlet.



Dimension 2
Dimension 1
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
14
8
16
17
Large Juv
13
9
10
15
1
11
7
Neonate
12
4
5
2
Small Juv
3
6
19
18
20
1.0 - 2.9
3.0 - 4.9
6.0 - 7.9
> 8.0

Florida coast have been recently found to act as sandbar shark nursery area and neonates and juvenile sandbar sharks occur in small numbers in the northeastern Gulf of Mexico (Hueter and Tyminski 2002, Carlson 1999). While there is the potential for neonate and juvenile summer nursery areas to occur in shallow protected waters from New Jersey to the eastern Gulf of Mexico, the two primary nursery grounds for the species are thought to occur in the Chesapeake and Delaware Bays off the mid Atlantic bight.

Neonate and juvenile sandbar sharks were present in high abundance throughout the Eastern Shore of Virginia nursery area during the summer months of 2003 and 2004. The high catch rates of neonate and juvenile sandbar sharks throughout the region indicate that this is an important primary and secondary nursery area. In addition three adult pregnant female sandbar sharks were captured in Machipongo Inlet during June of 2003 during the sampling for this project and several additional pregnant and post partum females were captured within this area during ancillary sampling trips. Eight of ten adult female sandbar sharks captured by the VIMS long-term longline survey in 2003 and 2004 were captured in Great Machipongo Inlet. This survey sampled eight standard stations and ancillary stations in Virginia coastal waters, Chesapeake Bay and the Eastern Shore lagoons, on a monthly basis. The southern inlet areas, where the concentration of neonates was highest, likely serves as an important pupping ground for this population of sandbar sharks.

The Magnuson-Stevenson Act requires each fishery management plan developed under the act to delineate essential fish habitat for the species under consideration. Essential fish habitat is defined as "those waters and substrates necessary to fish for spawning, breeding, feeding or growth to maturity." Habitat areas of particular concern (HAPC) are a subset of the essential fish habitat and are areas that serve vital ecological functions or are areas particularly vulnerable to habitat degradation. To be designated as a HAPC one or more of the following criteria must be shown, "importance of the ecological function provided by the habitat, extent to which the habitat is sensitive to human-induced environmental degradation, whether, and to what extent, development activities are, or will be, stressing the habitat type, or the rarity of the habitat type (NMFS 2002)." The Eastern Shore of Virginia's bays and lagoons fit the first criteria of a HAPC as this area serves as a pupping ground and provides primary and secondary nursery habitat for the sandbar shark. This area is also sensitive to environmental degradation and recent eutrophication of the area has led to the increased abundance of floating macroalgae within these waters. Our water quality measurements in the area reveal a daily oxygen minimum that occurs and hypoxic conditions are a potential effect of this increasing macroalgae load within the water column.

Mersen and Pratt (2001) conducted a study of the Delaware Bay summer sandbar shark nursery which also acts as a pupping ground and a primary and secondary nursery area for this population. Neonate and juvenile sandbar sharks were captured from June through October that ranged in size from 48 to 130 cm total length. Individual sharks occurred in waters ranging from 15.4 to 28.5° C and in salinities that ranged from 22.8 to 30.3 ppt. The spatial distribution of juvenile sandbar sharks in Delaware Bay was uniform across the varying values of the physical parameters of salinity, depth, surface temperature, or tidal cycle. There were some spatial differences, however, with the highest abundance of sandbar sharks occurring along the southwest coast of Delaware Bay. The authors suggested these differences were likely due to a higher amount of pupping occurring within this area. Grubbs and Musick (in press) studied the Chesapeake Bay sandbar shark summer nursery. In contrast to Delaware Bay and the current study, most of the physical parameters measured were correlated to catch rates based on a Spearman's rank correlation. Areas of high and low sandbar shark abundance were successfully delineated with a regression tree using only two of these parameters. Neonate and juvenile sandbar sharks were most abundant in areas of salinity greater than 20.5 ppt and in depths greater than 5.5 m.

The Eastern Shore of Virginia is connected to the Chesapeake Bay at the mouth of Magothy Bay in the southern portion of the Eastern Shore lagoonal system. Despite the close physical connection of these two areas, they have quite different physical properties. Chesapeake Bay is the largest estuary in the United States. Approximately half of the volume of water in the Chesapeake Bay enters the bay from the Atlantic Ocean. The remaining half of the water drains into the bay from a 64,000 square mile drainage basin or watershed, with freshwater entering the bay from springs, streams, creeks, and rivers. Due to estuarine circulation created by this mix of salt and freshwater, stratification occurs particularly in the spring and summer due to increased freshwater inputs and the warming of surface waters (Chesapeake Bay Program 1995). Tidal range in Chesapeake Bay ranges from a minimum of 0.32 m near Annapolis to a maximum of 0.88 m near the mouth of the Bay (Chesapeake Bay

Coastal Prediction Center 2005). The Eastern Shore area consists of narrow deep channels and shallow mud flats that create strong tidal currents, this area has a tidal range of approximately 0.94 to 1.4 meters (NOAA Tidal Current Prediction Center 2003). The strength of the tidal currents in these areas tends to homogenize the water column and very little stratification occurs in this area. Water temperature was measured at the surface and bottom of the water column at almost every sampling set, on 244 occasions throughout the summer of 2003 and 2004. The temperature difference between surface and bottom waters was less than 1°C at over 94% of the sampling sets (range = 0.0° to 2.9°C, mean = 0.2°C, SE = 0.028). Likely the most significant physical difference between the Chesapeake Bay and the Eastern Shore lagoonal system is salinity. Salinity in the Eastern Shore of Virginia remains near to coastal values, all of our sampling sites remained above 30 ppt throughout the summer except two sites that dropped to less than 20 ppt on one sampling occasion after a significant rain event. In contrast, the freshwater inputs to the Chesapeake Bay act to lessen the salinity of the Bay with salinity values that range from freshwater to nearly coastal salinity at the mouth of the Bay (Chespeake Bay Program 1995). Sandbar shark nursery areas occur in waters in the Bay from the mouth to areas with salinity as low as 20.5 ppt (Grubbs and Musick in press).

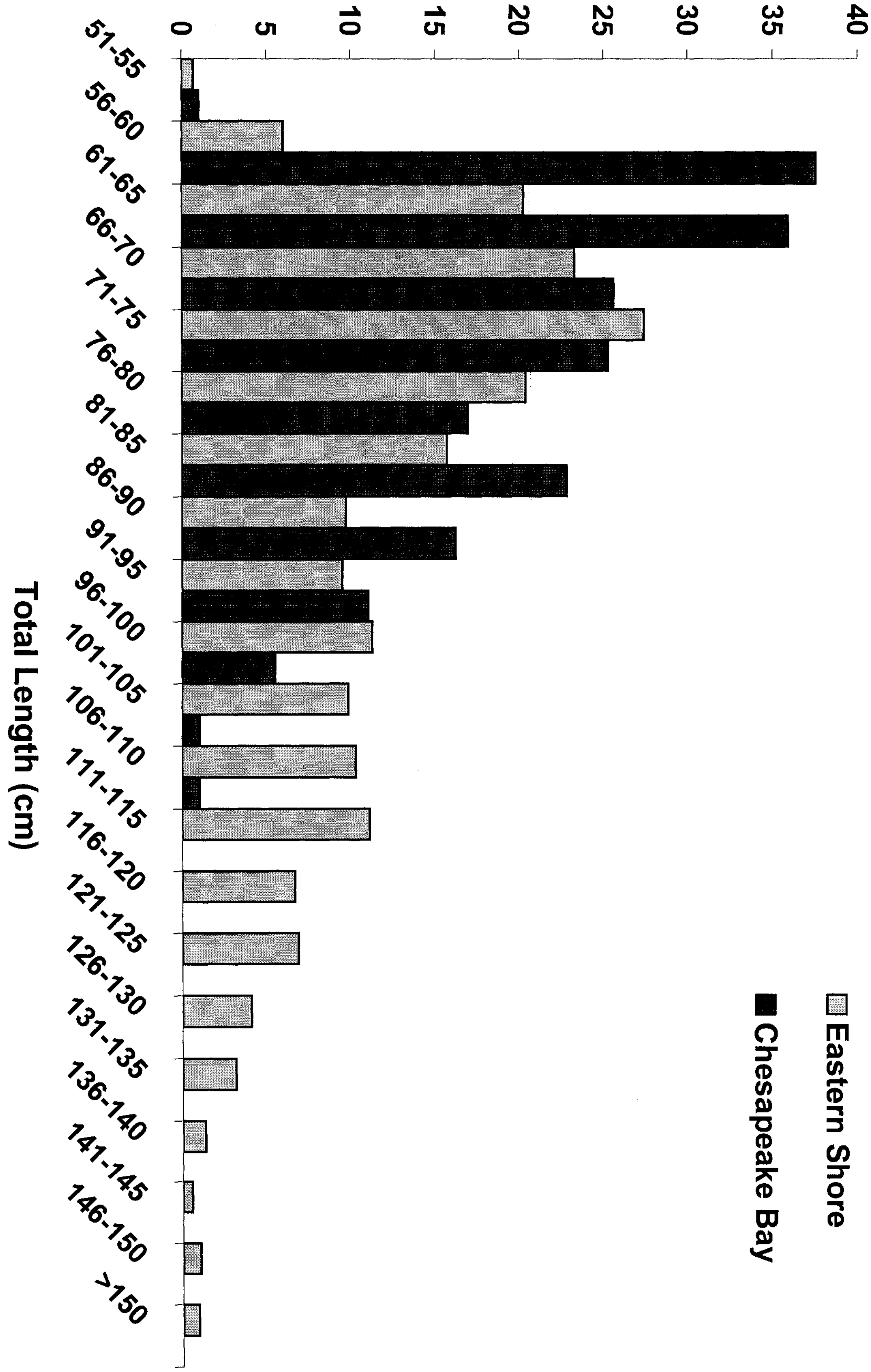
Unlike the Chesapeake Bay study, we were unable to delineate areas of high and low abundance within the Eastern Shore nursery using physical parameters. This was likely due to the greater homogeneity in physical parameters that occurs within this area. The lack of a salinity gradient may be particularly important. Salinity may act as a barrier to larger predatory sharks entering the Chesapeake Bay nursery

(Musick, personal communication). Neonate and juvenile sandbars may have increased tolerance to these lower salinities which allow them to escape predation. The lack of predators within this area may allow young sandbar sharks to occupy deeper waters than would be feasible in more saline nursery areas. The catch rate of juvenile sandbar sharks in Chesapeake Bay and the Eastern Shore of Virginia coastal lagoons were not significantly different during the summers of 2003 and 2004 (student's t-test, $p = 0.276$). The mean CPUE in this study during peak nursery usage, which was defined as the period between June and September for each station, ranged from 5.6 to 22.2 sharks per one hundred hooks, with an overall mean of 11.7 sharks per 100 hooks (196 sets, 20 locations, SE = 0.74). VIMS standard Chesapeake Bay longline sites during the summers of 2003 and 2004, during peak nursery usage, using only comparable hook types, had a mean catch rate of 14.6 sharks per 100 hooks (19 sets, 3 locations, SE = 2.89). These values were not significantly different and indicate a comparable abundance of juvenile sharks found within these two areas. The Chesapeake Bay sandbar shark nursery encompasses a larger area than the Eastern Shore nursery area. Grubbs and Musick (in press) estimated the amount of suitable sandbar shark nursery habitat in Chesapeake Bay to be between 524 and 2,134 $km^2$ depending on the amount of precipitation that occurred throughout the year. In contrast the area encompassed by the Eastern Shore lagoons is approximately 700 $km^2$, however a portion of this of area is comprised of islands and areas too shoal to be used as habitat by juvenile sandbar sharks.

Juvenile sandbar sharks were captured within the Eastern Shore nursery area ranging in size from 52 cm total length to over 140 cm total length. A wider size range of sandbar sharks was captured within the Eastern Shore area than within Chesapeake Bay during the summers of 2003 and 2004 (Figure 2-12). Sandbar sharks over 100 cm total length were relatively rare in Chesapeake Bay and sandbar sharks in the 100 to 130 cm size class were much more common in the Eastern Shore lagoons. This may relate again to potential differences in salinity tolerances. Within this multi-size and multi-age nursery area of the Eastern Shore we found some differences in space use between different size classes of animals. While all three size classes were distributed throughout the nursery area, smaller animals appeared to prefer areas farther from the inlet and larger animals were more common in areas closer to the inlet. As physical parameters did not explain the abundance of animals within the nursery area their distribution was likely determined by the biotic factors of prey abundance and predator avoidance. Smaller animals may move into areas farther from the inlets to avoid predation by larger sharks which face no depth or salinity barriers to prevent them from entering into the inlet areas.

In addition each inlet appeared to have its own characteristic size component present. Sand Shoal Inlet, the most southern inlet, was dominated by neonate and small juvenile sandbar sharks with large juveniles rare within this area. Great Machipongo Inlet, one of the central inlets, had the greatest abundance of sharks and all size classes were found within the area in high abundance. These two southern areas had the highest abundance of neonates indicating more pupping may occur within these areas. Quinby Inlet had only large juveniles in great abundance and this may be due to limited areas of shallow waters within the inlet to act as protective refuges from predators. Wachapreague Inlet had only small juveniles present in great

Figure 2-12. Length frequency of sandbar sharks captured in Chesapeake Bay and the Eastern Shore of Virginia by VIMS shark researchers during the summers of 2003 and 2004.


0
5
10
15
20
25
30
35
40
51-55
56-60
61-65
66-70
71-75
76-80
81-85
86-90
91-95
96-100
101-105
106-110
111-115
116-120
121-125
126-130
131-135
136-140
141-145
146-150
>150
Total Length (cm)
Eastern Shore
Chesapeake Bay

abundance. The biotic factors of where females pup combined with predator avoidance and possibly prey abundance are likely dominating how this area is used by differing size classes.

# CHAPTER 3

Investigations into the activity patterns and space use of juvenile sandbar sharks, *Carcharhinus plumbeus*, in the Eastern Shore of Virginia summer nursery area.

## Abstract

The use of nursery areas by juvenile sharks has been identified as an important information need for current and future management efforts. Previous manual tracking studies of neonate and juvenile sandbar sharks in the western North Atlantic Ocean have found these animals occupy extremely large activity spaces while remaining in their nursery areas. In order to study the space use and movement of juvenile sandbar sharks in the Eastern Shore of Virginia's coastal bays and lagoons an array of 15 passive acoustic receivers was deployed in 2003, this array was expanded to 21 receivers in 2004, and 19 receivers were deployed in 2005. During the summer of 2003, 27 sharks were implanted with transmitters. During the summer of 2004 an additional 37 sharks were implanted with transmitters and 10 sharks implanted with transmitters in 2003 returned to the array area. Shark space use was significantly correlated with distance from the inlet and time of day with sharks spending a greater amount of time in the zones farthest from the inlet and the use of the array area increasing in the night and early morning hours. Whereas shark space use was not correlated to the tidal cycle, shark movements were highly correlated to the tidal cycle with sharks rarely moving against the strong tidal currents that occur within this region. Despite being unable to determine home range size or existence due to the limited size of the acoustic array, evidence of site attachment was demonstrated using a random walk model and through the use of tag return data. The sharks returned to

the array to a greater extent than would have been expected based on random movements alone. Shark residency time within the array area decreased with increasing age likely indicating that older larger animals have larger activity spaces. Minimum estimates of annual survivorship and philopatry of juvenile sandbar sharks to the array area were estimated using known fates of sharks in subsequent summers.

**Introduction**

The use of telemetry to study shark behavior began in the mid 1960s. In a review of telemetry studies Nelson (1990) stated that previous investigations were primarily used to address diel movements and space utilization of the target species as well as to provide information on depth excursions, water and body temperatures, swimming speeds, and other correlates of behavior or physiology. It was suggested this technology is best applied to determine short and long term movements, grouping/schooling habits, small scale behaviors, and responses to stimuli such as fishing gear.

Tracking animals in the marine environment typically involves the use of acoustic rather than radio telemetry, as radio signals will not propagate in sea water. However radio tags are a critical component of satellite tracking and can play an important role in acoustic array systems. Nelson (1990) further found that at the time of his review, the predominance of tracking studies used 'ordinary manual tracking' which entails the use of a receiver and directional hydrophone to determine the position of the fish. This type of tracking allows for collection of detailed positions of the fish over a short period of time. Automated tracking systems are also used, and in general, increase the amount of time a fish can be tracked, but often the exact position of the shark can not be determined. Since the receivers are typically located in a specific location, if the shark leaves the region of the receiver or receiver array it is no longer being tracked.

Many elasmobranch telemetry studies contrast the diel movements of animals. Casterlin and Reynolds (1979) held fourteen smooth dogfish, *Mustelus canis*, in the laboratory to study diel activity patterns using artificial photoperiod conditions. The activity levels of these sharks were measured by quantifying interruptions of photocell-monitored light beams and these sharks were found to exhibit a nocturnal activity pattern. Many species of sharks tracked in their natural environment have also been found to be more active at night than during the day. The two main methods used for contrasting day and night movements are comparing the rate of movements (ROM) and the amount of space traversed or occupied during these periods. McKibben and Nelson (1986) found that gray reef sharks, *Carcharhinus amblyrhynchos*, had significantly higher rates of movement at night (mean = 3.3 km/h) than during the day (mean = 1.7 km/h). The rate of movement was calculated by measuring the distance between successive fixes and dividing by the time between these fixes. Ackerman et al. (2000) in a study on the movements of leopard sharks, *Triakis semifasciata*, also found that the movement rates were significantly greater during dark periods than fully lighted periods.

In conjunction with exhibiting higher activity at night many sharks appear to refuge or occupy a 'core' area during the daytime and to move to and from this area during the night hours. Holland et al. (1993) found a high fidelity to core areas during the day and wider ranging movements at night for juvenile scalloped hammerhead sharks, *Sphyrna lewini*, in Kaneohe Bay (Oahu, Hawaii). Klimley et al. (1993) in a study of scalloped hammerhead sharks in the southern Gulf of California (Mexico) found that these sharks remained above a seamount during the day and made nightly excursions away from and back to the seamount, with 13 out of 15 excursions away from the seamount being made during night hours. While many shark species tend to have diel activity patterns this is not always the case and other environmental parameters may be more important in determining activity rates and space use. Holts and Bedford (1993) studied the horizontal and vertical movements of three shortfin mako sharks, *Isurus oxyrinchus*, in the Southern California Bight and found no evidence of diel activity patterns.

Tidal currents likely play a role in shark movements especially in areas where currents are particularly strong. Ackerman et al. (2000) found that movements of leopard sharks in Tomales Bay, California were significantly correlated with tidal direction. Sharks moved into the inner bay during flood tide and toward the outer bay during ebb tide. It was determined that sharks were moving in the direction of the tide if they moved twice as far in the direction of the tide as they did laterally. While the effect of tidal currents on shark movements has rarely been studied, the effects of oceanic current strength and direction have been investigated in some species of large pelagic teleosts. Brill et al. (1993) found that the horizontal movements of striped marlin tracked near the Hawaiian Islands were strongly affected by currents and suggested that the speed of the animal was affected by these currents as well. However, Brill et al. (1999) found that movements of yellowfin tuna tracked near the Hawaiian Islands were little affected by oceanic currents.

Many researchers conducting tracking studies attempt to define the home range of a species or population. Burt (1943) defined home range as, 'that area traversed by the individual in its normal activities of food gathering, mating, and caring for young'. Kernohan et al. (2001) suggest that any home range definition should include a temporal aspect and the definition should be stated in terms of the area and the probability of the organism being found in the area during a specified period of time. To be said to occupy a home range an animal must be shown to return or remain within an area and not simply be traversing through the area. Hooge et al. (2001) stated that for a home range to exist an animal must exhibit site fidelity. White and Garrott (1990) define fidelity as "the tendency of an animal either to return to an area previously occupied or to remain within the same area for an extended period of time." Since many tracking experiments are logistically constrained to shorter periods of time, researchers often describe the size of the activity space of the animal during the period of tracking using home range estimators. While researchers use the same techniques to calculate both these parameters, it is important to distinguish between the two. Home range refers to a specific area, amount of space, and probability of occurring with this area. Activity space, however only refers to an amount of space used and is not associated with an actual place or locality. There are three general types of home range estimators: polygon methods, grid cell methods, and probabilistic methods. Polygon methods calculate home range by connecting the positions of the animal in such a way as to form the smallest polygon that contains each position (Kernohan et al. 2001). The minimum convex polygon method is widely used and very prevalent in the elasmobranch literature. Grid cell methods involve overlaying a grid over location data and calculating ranges based on occupied grid cells. Utilization distributions describe the relative frequency distributions for the location data over a specific time period and assess an animal's probability of occurrence at each point in space. Probabilistic models assess the utilization distribution by assuming a particular probability distribution or by attempting to characterize a variety of distributions accurately (Kernohan et al. 2001). In an evaluation of 12 home range estimators based on the criteria of sample size requirement, robustness with respect to autocorrelated data, ability to compute utilization distributions, parametric or nonparametric estimation, ability to compute multiple centers of activity, sensitivity to outliers, and comparability between estimators, Kernohan et al. (2001) found that the fixed and adaptive kernel methods performed best. Hooge (2003) also recommended the use of kernel home range methods as these methods are nonparametric, give the probability of the animal being at any x/y coordinate, and are one of the most robust methods of determining home range.

The size of activity spaces and home ranges of elasmobranchs range widely. Holland et al. (1993) calculated the activity spaces of juvenile scalloped hammerhead sharks in Kaneohe Bay (Oahu) using minimum convex polygons and grid square analysis and found the average total activity space for six animals was 1.26 $km^2$. Gruber et al. (1988) tracked nine lemon sharks for periods of time ranging from one to eight days. Activity spaces were calculated using minimum convex polygon methods and ranged from 9 to 93 $km^2$. They also found that each shark exhibited some site attachment, returning to the same area during the tracking period (site attachment was defined as diel repeatability or overlapping activity space). Morrissey and Gruber

(1993) tracked 38 juvenile lemon sharks and calculated activity spaces of these sharks ranging from 0.23 $km^2$ to 1.26 $km^2$. The area of each shark's home range was estimated using a modified minimum convex polygon method and an index of eccentricity was calculated to represent the shape of the home range. McKibben and Nelson (1986) calculated observed activity spaces of gray reef sharks using a maximum convex polygon method and found that activity spaces ranged from 0.19 $km^2$ to 53 $km^2$.

Some sharks have been found to return to areas after departing on regular occasions and move in directional paths which suggest that they are using some type of navigational cue. Klimley et al. (1993) described the movements of scalloped hammerhead sharks in the Southern Gulf of California and found that they remained above seamounts during the day and made excursions into pelagic region at night. The sharks followed particular routes to preferred feeding sites. Klimley et al. (2002) tracked six sharks of three species, shortfin mako shark, blue shark, and white shark and found that all sharks exhibited directional swimming with small differences in consecutive headings. Klimley (1993) studied the mechanisms of navigation of hammerhead sharks by tracking five sharks and trying to determine how they maintain directionality. He found evidence that the sharks were able to relocate seamounts using geomagnetic topotaxis.

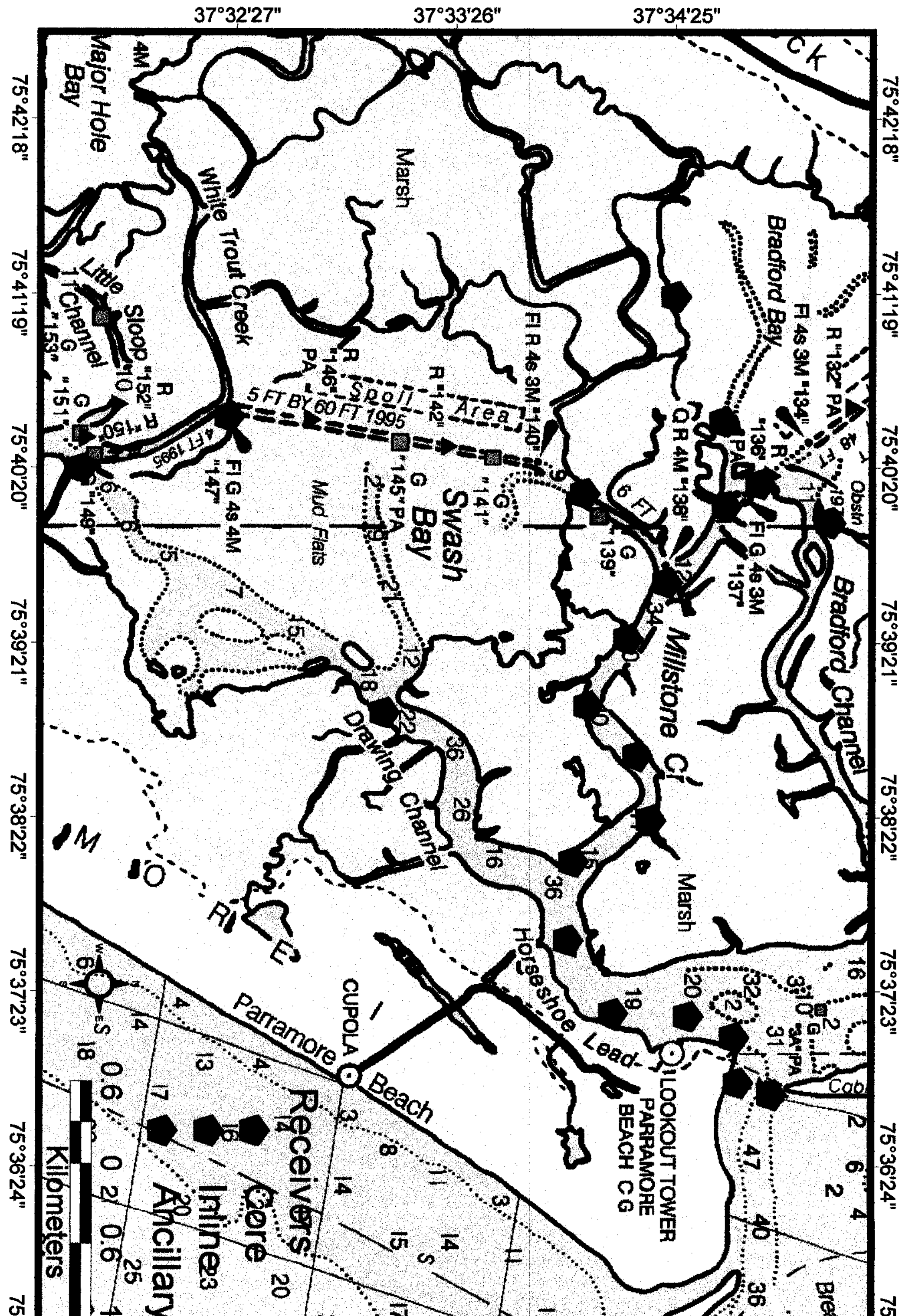
While the predominance of elasmobranch tracking research has taken place by manually tracking single individuals for relatively short periods of time, it is becoming more common to use automated listening stations to track larger numbers of individuals for longer periods of time. Radio acoustic positioning buoys are used to obtain detailed information on the movements of the animals being tracked. These automated monitors track fish and are able to obtain accurate specific locations, but these systems are quite costly and often logistically unfeasible. Automated acoustic receivers that record the presence of a fish are used to detect the presence or absence of a fish in an area (Voegeli et al. 2001). These receivers can be arranged strategically in an array to give estimates of position. Heupel and Hueter (2001) assembled an array of 15 automated acoustic receivers to passively track juvenile blacktip sharks in Terra Ceia Bay. They deployed these receivers approximately 700 m apart. They found that active tracking data was consistent with data from the automated system. Simpfendorfer et al. (2002), using the system described above by Heupel and Hueter (2001), described a method for determining shark position from this type of system. This method determines a mean position or short term center of activity for the animal by calculating a weighted mean position based on the number of occurrences at each receiver during a specified period of time. The use of passive telemetry techniques have only recently become widely used to study elasmobranch fishes but with strategic placement of receivers it is possible to gather valuable information about movement, space use, and residency time of these animals.

The purpose of this study was to examine the movements and space use of juvenile sandbar sharks within the Eastern Shore of Virginia using passive tracking techniques. The specific objectives of the project were to determine how distance from the inlet affects space utilization at different tidal cycles and times of day, if there was any periodicity in the movements of these sharks within the area, if there was evidence of site attachment or fidelity, and if age affected residency time of juvenile sandbar sharks found within the Eastern Shore of Virginia.

**Methods**

To study activity patterns of juvenile sandbar sharks within the Eastern Shore lagoonal system, an acoustic array was deployed in Millstone Creek in Wachapreague Inlet, Virginia. In 2003 fifteen receivers were positioned in an approximately 7.5 km array from the inlet through Millstone Creek to the mouth of Bradford Channel. In 2004 fifteen receivers were positioned in the same core locations as in 2003 and an additional six ancillary receivers were added to the system with the objectives of expanding array coverage and studying the use of Swash Bay by juvenile sandbar sharks (Figure 3-1). The receivers used were Vemco VR2 acoustic receivers (Vemco Ltd., 100 Osprey Drive, Shad Bay, Nova Scotia, Canada B3T 2C1). When this type of receiver detects a transmitter it records the code of the transmitter, the date, and the time allowing for the determination of when specific sharks are within range of the receiver. The array is an open 'leaky' system, sharks are able to move in and out of the system in multiple locations, with two exits at each end of the array and two major exits within the array at Drawing Channel and Seal Creek. The original fifteen core receivers of the array set up a primarily one-dimensional system which was being used to track the progress of the sharks up and down the channel of Millstone Creek. The receivers were positioned approximately two meters below the surface of the water facing downward and were anchored with 14 lb danforth anchors and attached to one or two crab pot floats. Data from the receivers were downloaded every one to two

Figure 3-1 : Acoustic array: location of receivers in 2003 and 2004 with 2004 inline and ancillary receivers denoted (NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


37°32'27"
37°33'26"
37°34'25"
75°42'18"
75°41'19"
75°40'20"
75°39'21"
75°38'22"
75°37'23"
75°36'24"
75°35'25"
Major Hole Bay
White Trout Creek
Marsh
Little Sloop Channel
Bradford Bay
Bradford Channel
Spoil Area
5 FT BY 60 FT 1995
Swash Bay
Mud Flats
Millstone Cr
Drawing Channel
Horseshoe Lead
Parramore Beach
CUPOLA
LOOKOUT TOWER PARRAMORE BEACH C G
Receivers
Core
Inlines
Ancillary
Kilometers
0.6 0 0.6 1.2

weeks and the receivers were cleared of macroalgae and any biofouling at each download.

*Transmitter attachment*

Transmitters were implanted internally to decrease the potential of transmitter loss during the two years of transmitter battery life. Transmitters used were Vemco V16 coded acoustic transmitters (Vemco Ltd., 100 Osprey Drive, Shad Bay, Nova Scotia, Canada B3T 2C1). Sharks were captured with rod and reel and brought on board the boat where the hook was removed. Each shark was measured, tagged with a convential dart tag, and placed on the surgery board where a hose was inserted into the mouth to aerate the gills. The incision site was swabbed with betadine and 1 cc of lidocaine was administered. Transmitters were implanted by making a small incision (3 to 5 cm) in the ventral body wall of the shark, where the transmitters were inserted into the body cavity. The incision was closed using 5 to 7 sutures. To determine if the implantation technique was safe, four sharks were captured during the summer of 2003 and brought to the VIMS Eastern Shore Laboratory. These sharks were implanted with transmitters, using the same techniques as those captured and implanted in the field, and held for a period of 51 days. After this time period each of these sharks was sacrificed to determine if any negative effects from the transmitter implantation could be detected both externally and internally. During the summer of 2003, 27 sharks were implanted with acoustic transmitters and during the summer of 2004, an additional 37 sharks were implanted with acoustic transmitters.

*Range Testing*

An initial range test was performed to determine the range of the acoustic receivers. To perform this range test, at the end of October 2003 after the sharks had left the array, twenty six locations approximately 100 m apart within the inner portion of the array were chosen (Figure 3-2). At each location a transmitter was moored in the water column with a float and an anchor and allowed to transmit for a ten minute period. It was then determined which of the receivers detected the transmitter signal and the distances of tag reception and non tag reception were compared. A second range test was later performed during the first two weeks of May 2005 to determine if reception from the transmitters was different throughout the day due to boat traffic or other daily events. In order to accomplish this, two transmitters were moored for a two week period near receiver #13 and receiver #15. Transmitter 3598 was positioned 100 m from receiver #13 and 390 m from receiver #15 and transmitter 3614 was positioned 150 m from receiver #13 and 300 m from receiver #15 (Figure 3-3). Chi-square tests were performed to determine if the number of receptions at each receiver during each hour were significantly different from an equivalent number throughout the day.

*Data Analysis*

Position estimates were calculated for the passively tracked sharks by taking a weighted mean of the position of the receivers that detected the shark within a thirty minute period. The location of each receiver was included in the determination of mean position the number of times it detected the shark within the thirty minute period. A track was constructed for each shark tracked using these position estimates.

Figure 3-2. Locations of transmitter moorings for the range test (NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).

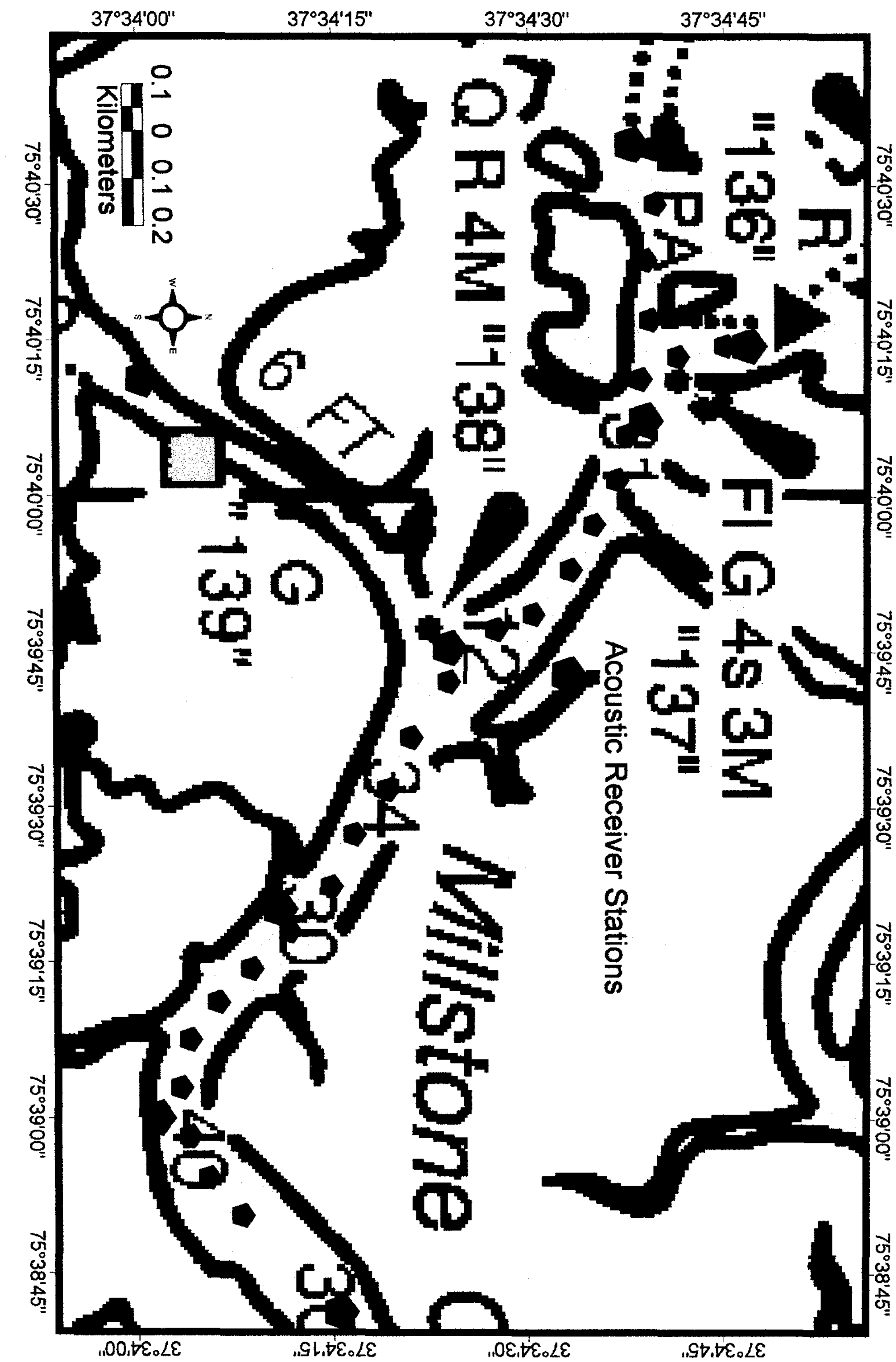
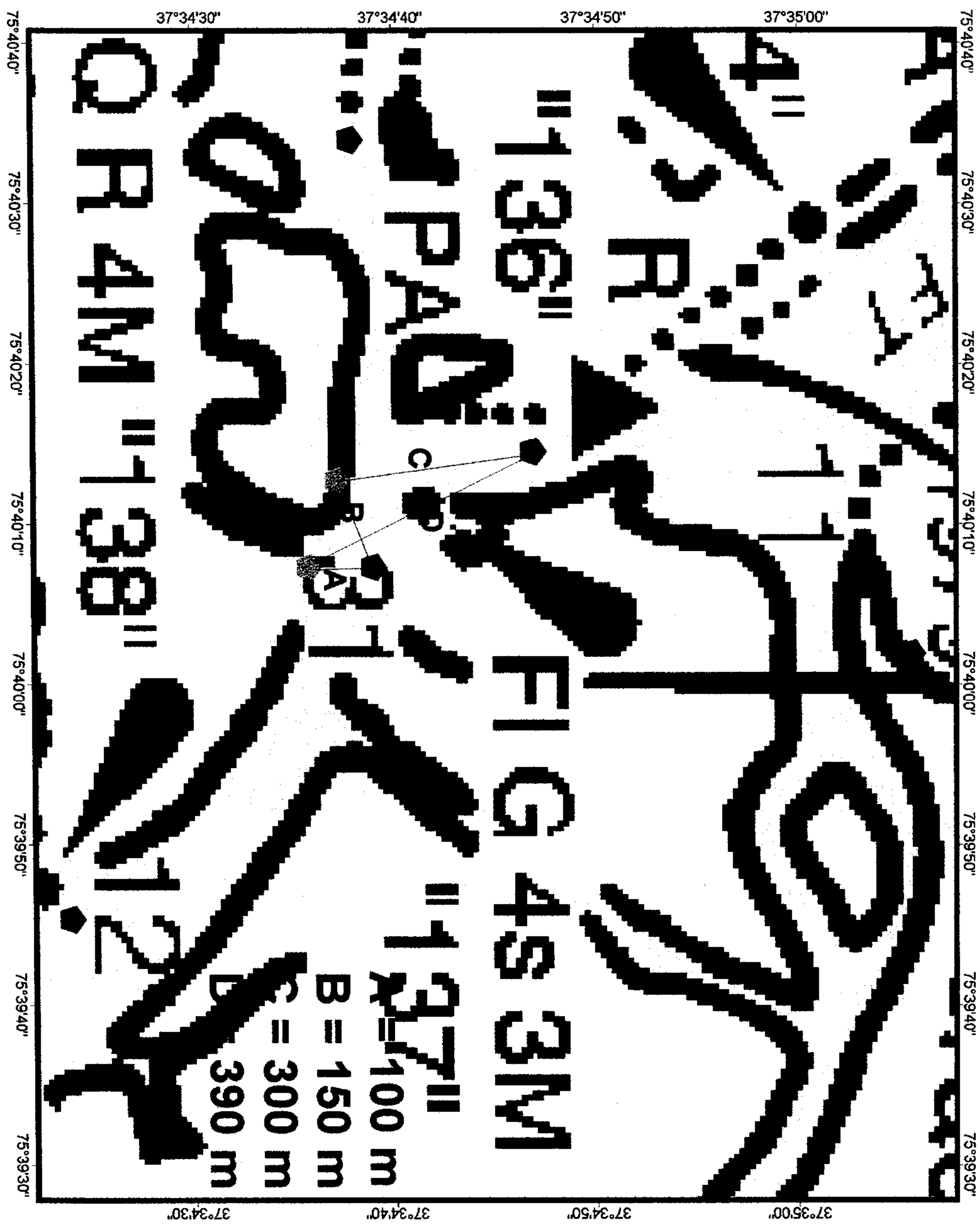

37°34'00"
37°34'15"
37°34'30"
37°34'45"
75°40'30"
75°40'15"
75°40'00"
75°39'45"
75°39'30"
75°39'15"
75°39'00"
75°38'45"
0.1 0 0.1 0.2
Kilometers
Acoustic Receiver Stations
Millstone
Fl G 4s 3M "137"
Q R 4M "138"
G "139"
"136"
6 FT

Figure 3-3. Locations of moored transmitters 3598 and 3614 and receiver numbers 13 and 15 for the hourly detection test (NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


37°34'30"
37°34'40"
37°34'50"
37°35'00"
75°40'40"
75°40'30"
75°40'20"
75°40'10"
75°40'0.0"
75°39'50"
75°39'40"
75°39'30"
A = 100 m
B = 150 m
C = 300 m
D = 390 m

The distance from the inlet to the receiver was calculated for each receiver for the core fifteen receivers and including an additional three receivers in 2004 (those in line with the core receivers). The position of the shark in terms of channel distance was determined by again taking a weighted mean of the receiver positions that detected the shark within a thirty minute period.

The core fifteen receiver stations were divided into three zones, one consisting of the five receivers closest to the inlet, one consisting of the middle five receivers, and one consisting of the five receivers farthest from the inlet. A two way ANOVA was performed to determine if there was a significant relationship between the number of detections and the zone and to determine if there was an interaction between use of each zone and month indicating a shift in the location of the sharks as the summer progressed. Since newly transmittered sharks were added to the system opportunistically throughout the summer, the number of detections was standardized as a fraction of the total detections by month for this analysis. A chi square test was performed to determine if there was a significant relationship between the number of detections for each zone and hour of the day, for each year. A two-way ANOVA was performed to determine if there was a significant relationship between the number of receptions and both tidal phase and zone and to determine if there was an interaction between tidal phase and zone. Slack tide was defined as the period between one hour before and one hour after the apex of high and low tides. The number of detections during each tidal phase was once again standardized by the amount of time spent within each tidal period.

To determine if there was periodicity in the horizontal movements of the sharks up and down the channel, the mean channel distance was used in a periodogram analysis. A periodogram analysis is a form of ANOVA which partitions the variance into the variance accounted for by N/2 periodic components where N is equal to the length of the time series. Only those average channel distance tracks from sharks that remained within the array for at least 70% of time in a 48 hour or greater period of time were used in this analysis. Due to missing values within the tracking data from periods of time when the sharks were not detected by the array the Lomb-Scargle periodogram was used (Lomb 1976, Scargle 1982). The Lomb-Scargle periodogram was designed to use on unevenly sampled data and recent developments by Press and Rybicki (1989) have allowed for the use of this technique with decreased computational power. The Lomb-Scargle periodogram analysis was completed using the computer program PAST (Hammer et al. 2001). A frequency histogram was created of the periods within each periodogram corresponding to a peak amplitude of four or larger. To further examine the relationship between the sharks' short term movements and the tidal cycle, the proportion movements in the direction of the tide, in the opposite direction of the tide, and the proportion of non-movements were calculated.

The recovery of two satellite transmitters provided the opportunity to investigate periodicity in vertical movements. Depth data taken at two minute intervals was used in a periodogram analysis to determine if there was periodicity in the depth occurrences of these two large juvenile sandbar sharks (total length = 124 and 127 cm). The periodogram analysis of this data which did not include missing values was analyzed using standard Fast Fourier Transform techniques. The computer program SAS' proc spectra analysis (Version 9.1.3 for Windows, SAS Institute Inc., Cary, NC, USA) was used to test to determine if there was periodicity in the depth of occurrence. Bartlett's Kolmogorov-Smirnov statistic was used to determine if the spectrum represented white noise.

To determine if sharks remained or returned to the array more than would be expected if they were moving randomly, a random walk analysis was performed. To perform this analysis a 12 hour time step and a 4 km distance step were chosen for these animals based on previous manual tracking data. The area of the Eastern Shore from the entrance of Magothy Bay to the south to Metompkin Inlet to the north between the Eastern Shore to the west and the Eastern Shore barrier islands to the east was divided into 53 four km distance steps. The model conservatively assumed all animals remained within the Eastern Shore and did not travel out of the inlets into the Atlantic Ocean. The model also conservatively used only major channel waterways within the Eastern Shore. A modeled random shark had an equal probability of moving from the block it was currently occupying to any adjacent block or of remaining within the block it was currently occupying. The random shark remained within the area from June 15 to September 15 and was therefore in the array for 90 days or 180 time steps. The array was contained within two blocks, Block 1 and Block 2, and all modeled sharks began their random walk in Block 1 which is the location where all the real sharks were initially captured. The model was run for 10,000 iterations or random sharks and the average percent of time a random shark remained within the array was compared to the average percent of time actual transmittered sharks spent within the array.

To determine if residency time changed with age or size, we calculated both the number of hours the sharks remained within the array and the days in residence for animals within the study of ages 1 to 5+. Only two neonate sharks were tracked so they were not included within this analysis. All animals age-5 and older were grouped in the age-5+ group to obtain an adequate sample size. A Kruskal-Wallis non parametric test was used to determine if there was a significant relationship between age and percent of time in residence.

During the course of the sampling for this project and the delineation project, conventional VIMS dart tags were applied to neonate and juvenile sandbar sharks caught within the Eastern Shore lagoons. Conventional tag returns in combination with acoustic transmitter returns and early satellite pop-up locations that occurred during the summer months were used to estimate the distances traveled by these sharks during three time periods: less than ten days between tag and recapture events, those returns that occurred within the same summer as tagging, and those returns that were reported at least one summer prior to the tagging event.

**Results**

*Transmitter attachment*

Four sharks were captured in Wachapreague Inlet using rod and reel and transported to VIMS Eastern Shore Laboratory. The sharks were then surgically implanted with acoustic transmitters using the same technique as sharks to be implanted in the field. These four sharks were held at the lab for fifty-one days, after which period of time they were sacrificed. At this time, external evidence of the implantation was very minor with a small external visible scar. No internal damage was noted from the transmitter; in each case the transmitter had migrated to the dorsal portion of the body cavity and appeared to be causing no trauma to the animal (Figure 3-4a and b).

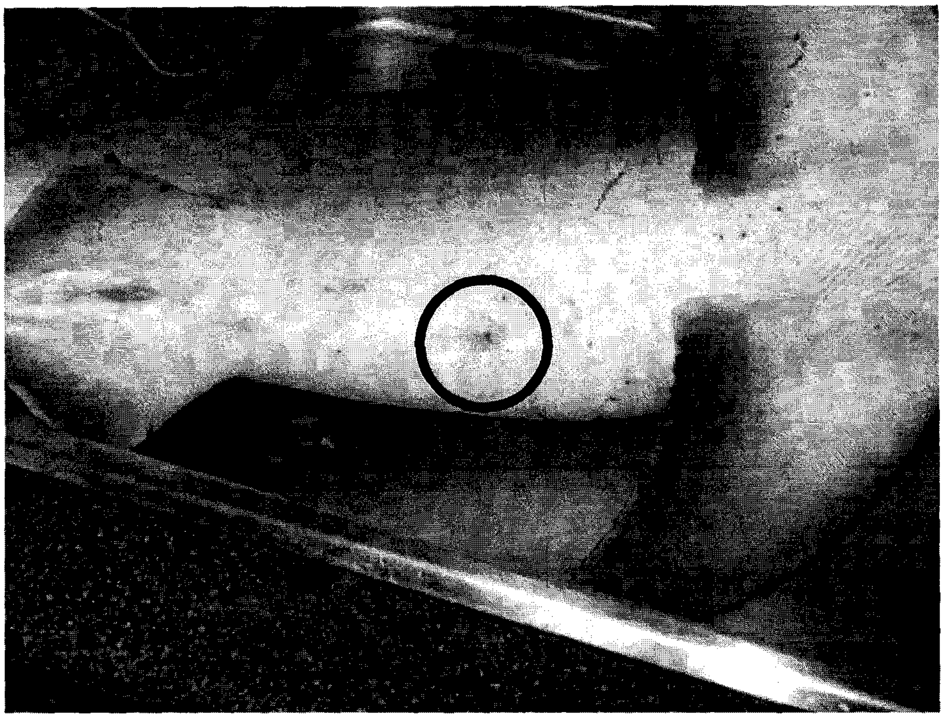
*Range testing*

Range test results revealed a consistent detection of the receiver signal to approximately 300 to 400m (Figure 3-5). At distances greater than 400 m, some signals are still detected but the frequency of detection decreases considerably at and beyond this distance. Some transmitter receptions were detected at 600 to 700 m distance, but at distances greater than 700 m no transmitter signals were detected. The small number of non-receptions that occurred at the 100 to 200 m distance were likely due to topographical features in the channel; there are many shoal areas within the inner portion of the array.

The hourly detection range test revealed contrasting results for the two transmitters moored in the water column. Transmitter 3598 which was moored 100 m from receiver #13 and 390 m from receiver #15 was only detected at receiver #13, likely due to a topographical barrier between this transmitter and receiver #15. The chi square test for the number of receptions at receiver #13 vs. hour of the day was insignificant ($p = 0.64$) and there was little difference in the number of receptions throughout the day (Figure 3-6a). Transmitter #3614 was moored 150 m away from receiver #13 and 300 m away from receiver #15 and was detected by both receivers,

Figure 3-4. Shark held at the laboratory 51 days after implantation. a. external view and b. internal view.

a.



b.

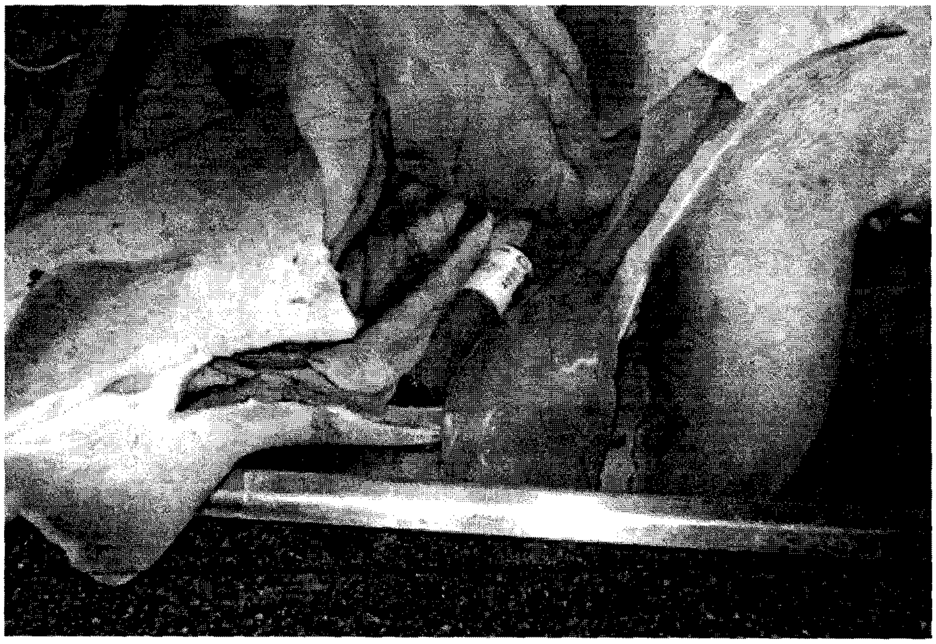



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Figure 3-5. Range test #1 results, percent detection and non detection at 100 m distance intervals from transmitter to receiver.

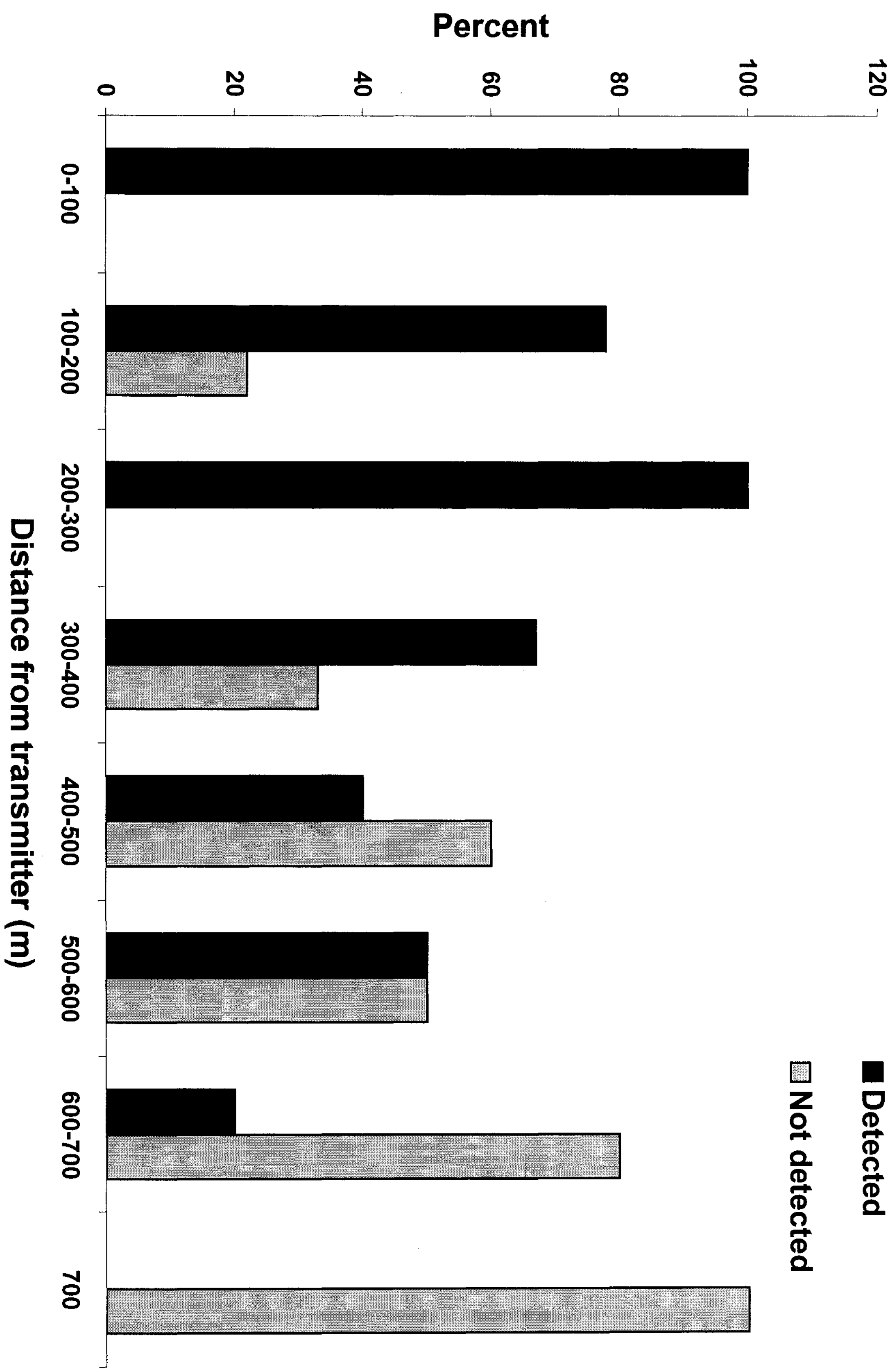
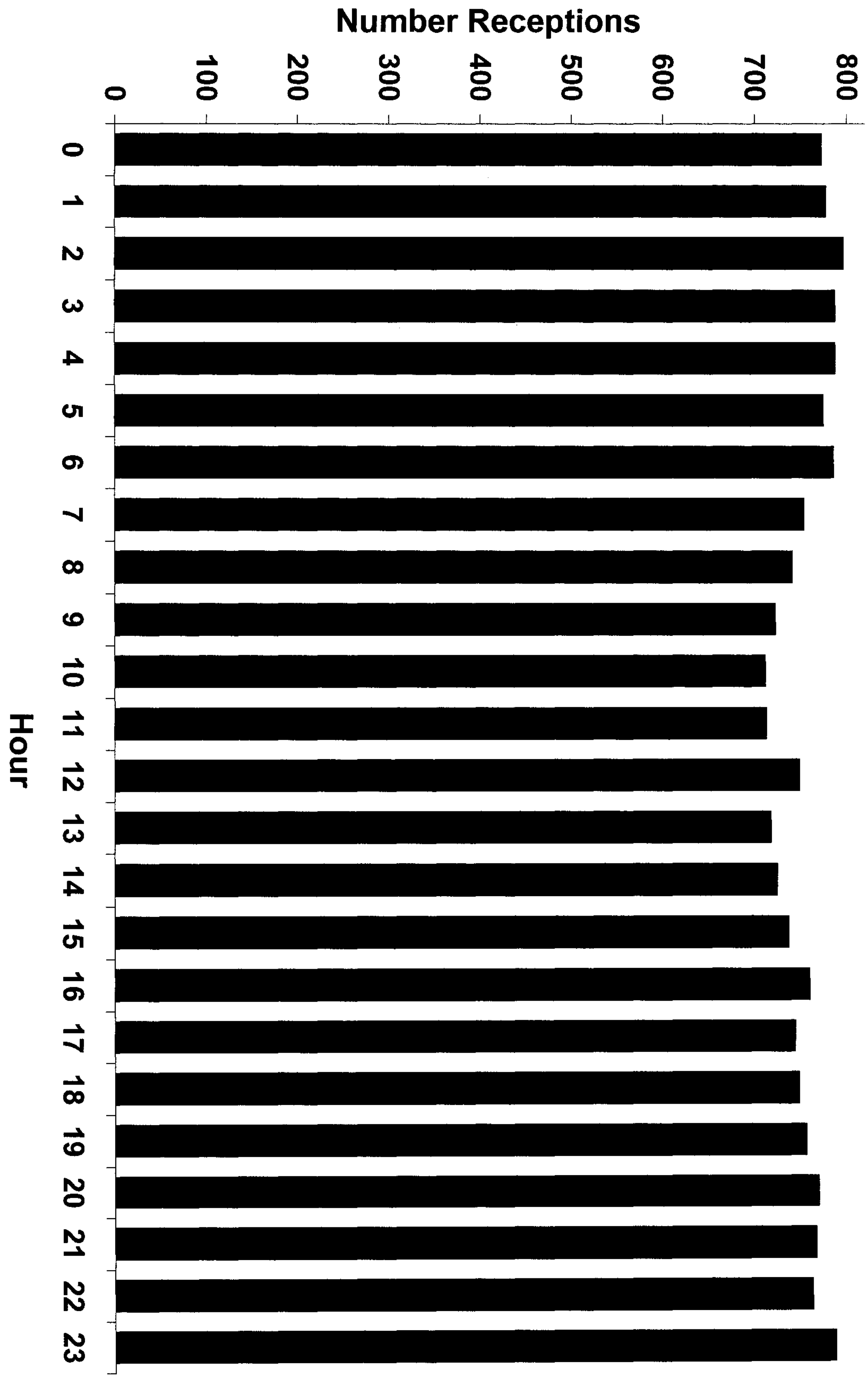

Percent
0
20
40
60
80
100
120
0-100
100-200
200-300
300-400
400-500
500-600
600-700
700
Distance from transmitter (m)
Detected
Not detected

Figure 3-6. Daily detection test, number of receptions by hour of the day for a) transmitter 3598 and b) transmitter 3614.


Number Receptions
0
100
200
300
400
500
600
700
800
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
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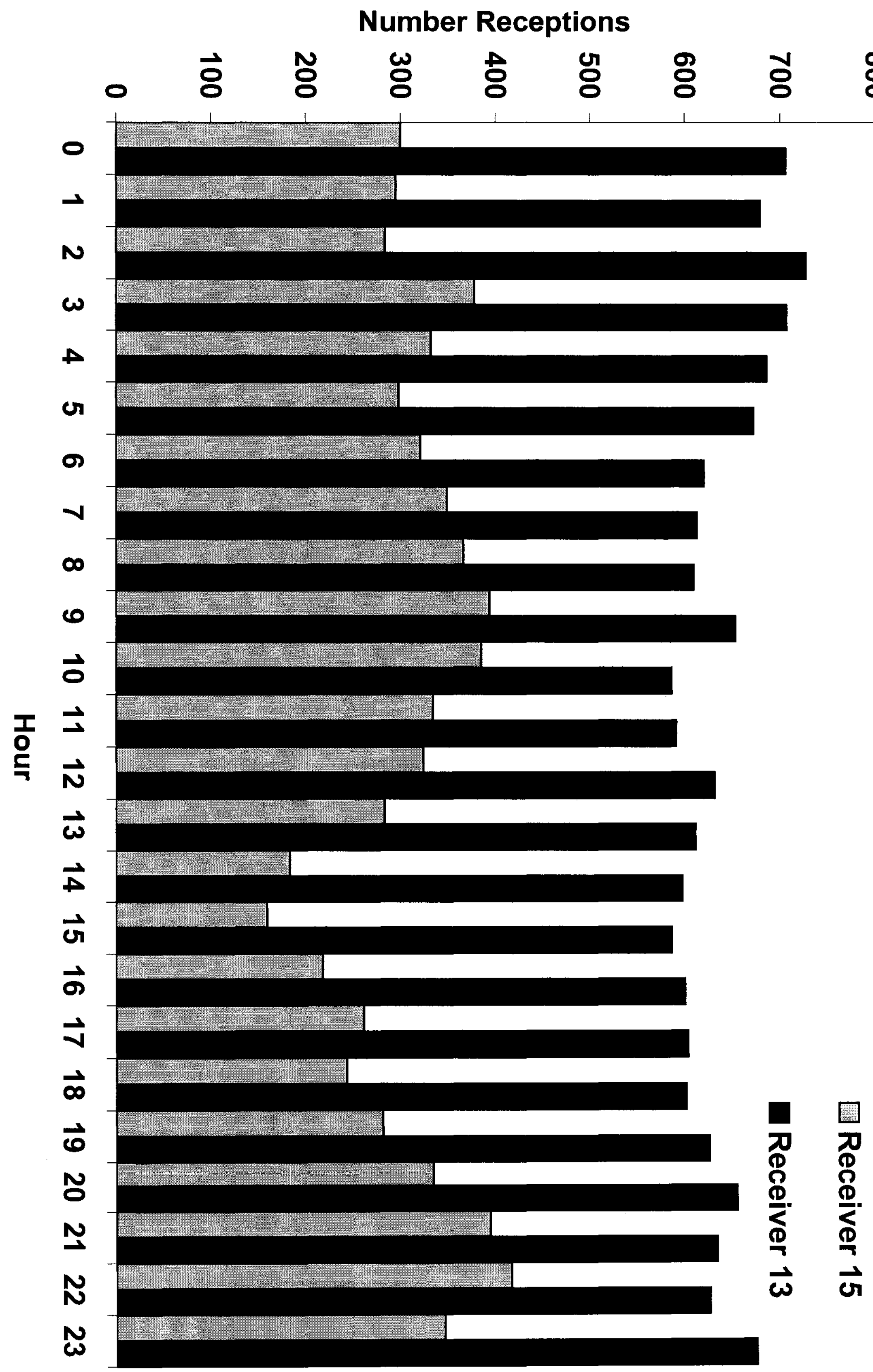
17
18
19
20
21
22
23



Number Receptions
0
100
200
300
400
500
600
700
800
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Receiver 15
Receiver 13

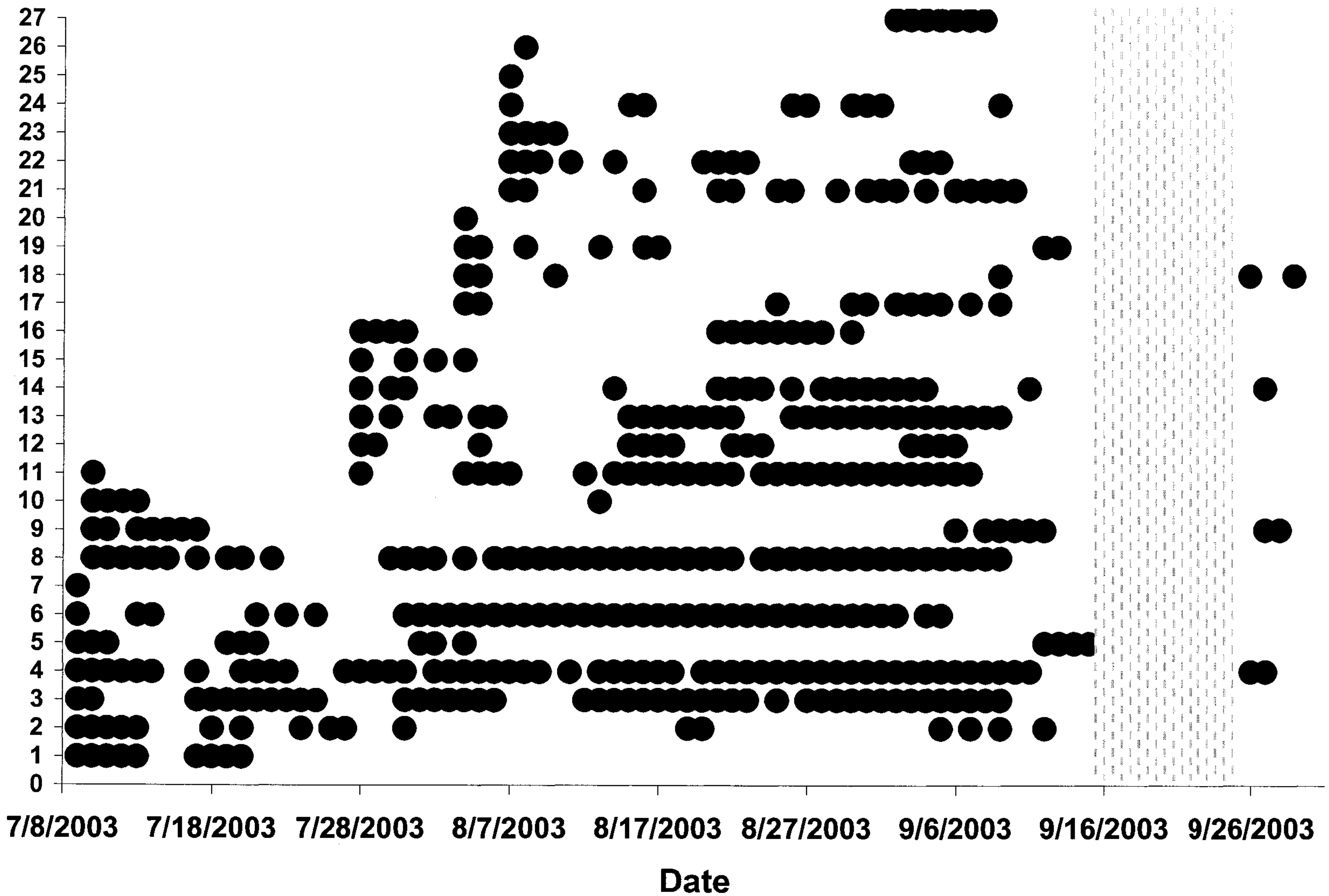
however it was detected at receiver #15 about half as frequently (Figure 3-6b). The chi square tests for the number of receptions at receiver #13 and receiver #15 were both significantly different than expected ($p < 0.001$ and $p < 0.001$). Both of these receivers show a drop in the frequency of receptions during the day hours. However, this drop is much more pronounced in receiver #15 suggesting that as the transmitter travels further from the receiver, boat traffic and other potential disrupters may have a greater effect on transmitter reception.

*General results*

During 2003, 27 juvenile sandbar sharks were tracked for intermittent periods of time ranging from 2.5 hours to 80 days. The total length of sharks tracked ranged from 78 to 128 cm, with a mean TL of 95.2 cm. The proportion of days in residence for these sharks ranged from 1.5 to 79 % (Figure 3-7). A day in residence is defined as any day the shark was present within the array for any length of time. During 2004, 37 sharks were outfitted with transmitters (33 with new transmitters, 4 transmitters that were recovered from sharks caught and killed by commercial fishermen and reused). The total lengths of sharks tracked ranged from 58 to 106 cm TL with a mean TL of 80.5 cm. The proportion of days in residence for these sharks ranged from 1.1 to 100% (Figure 3-8).

While positional tracks were created for each shark during each summer it occurred in the array, such tracks can be deceptive and may more accurately reflect the position of the acoustic array rather than elucidate movement patterns of the sharks being tracked. Figure 3-9 shows a positional track of shark #654 in 2004. While the shark used virtually all of the study area, its use of space was concentrated in the area

Figure 3-7. Days in residence for juvenile sandbar sharks tracked in 2003 (Dashed lines indicate days when the array was removed during September 15 –25th).


27
26
25
24
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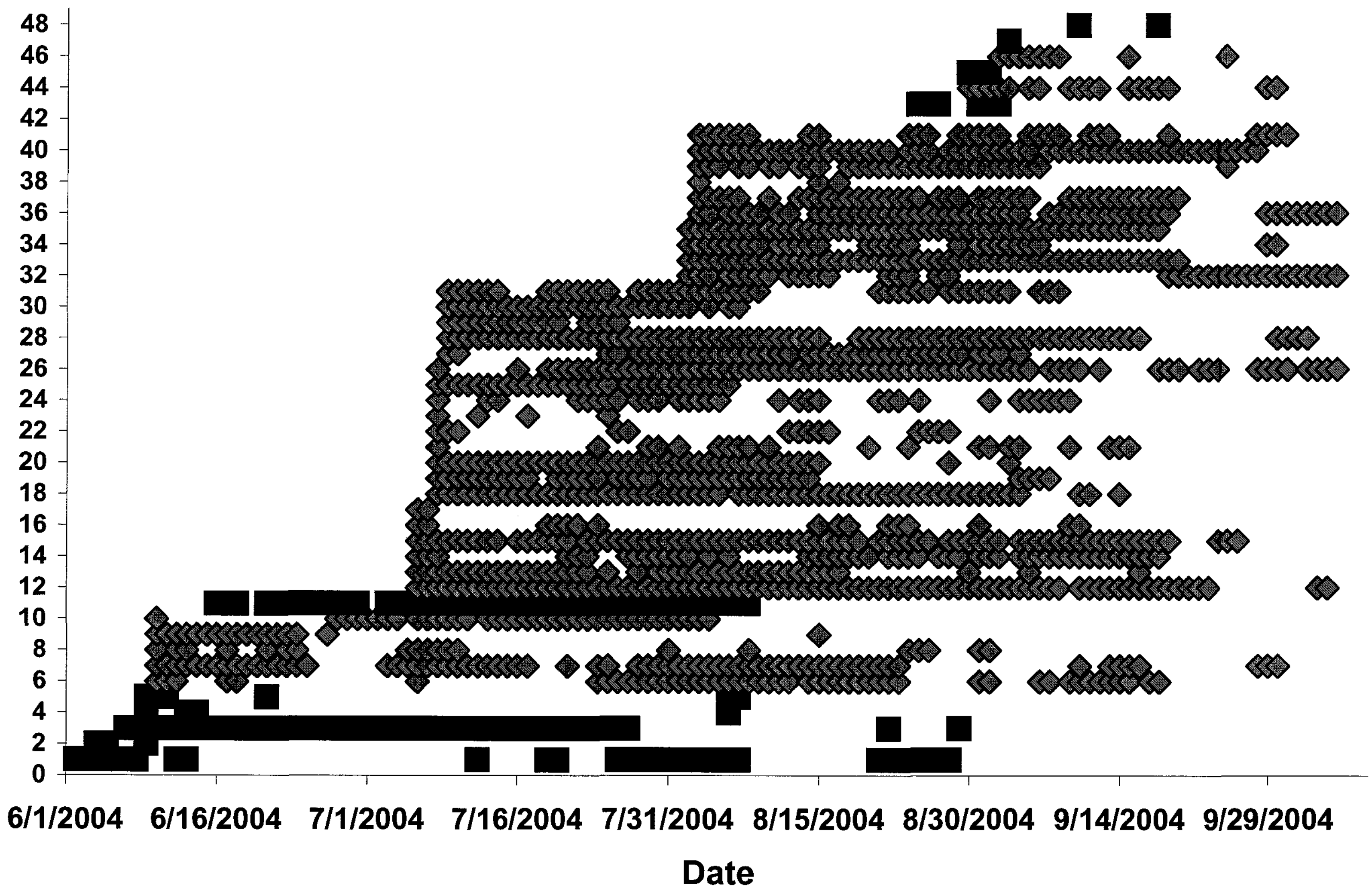
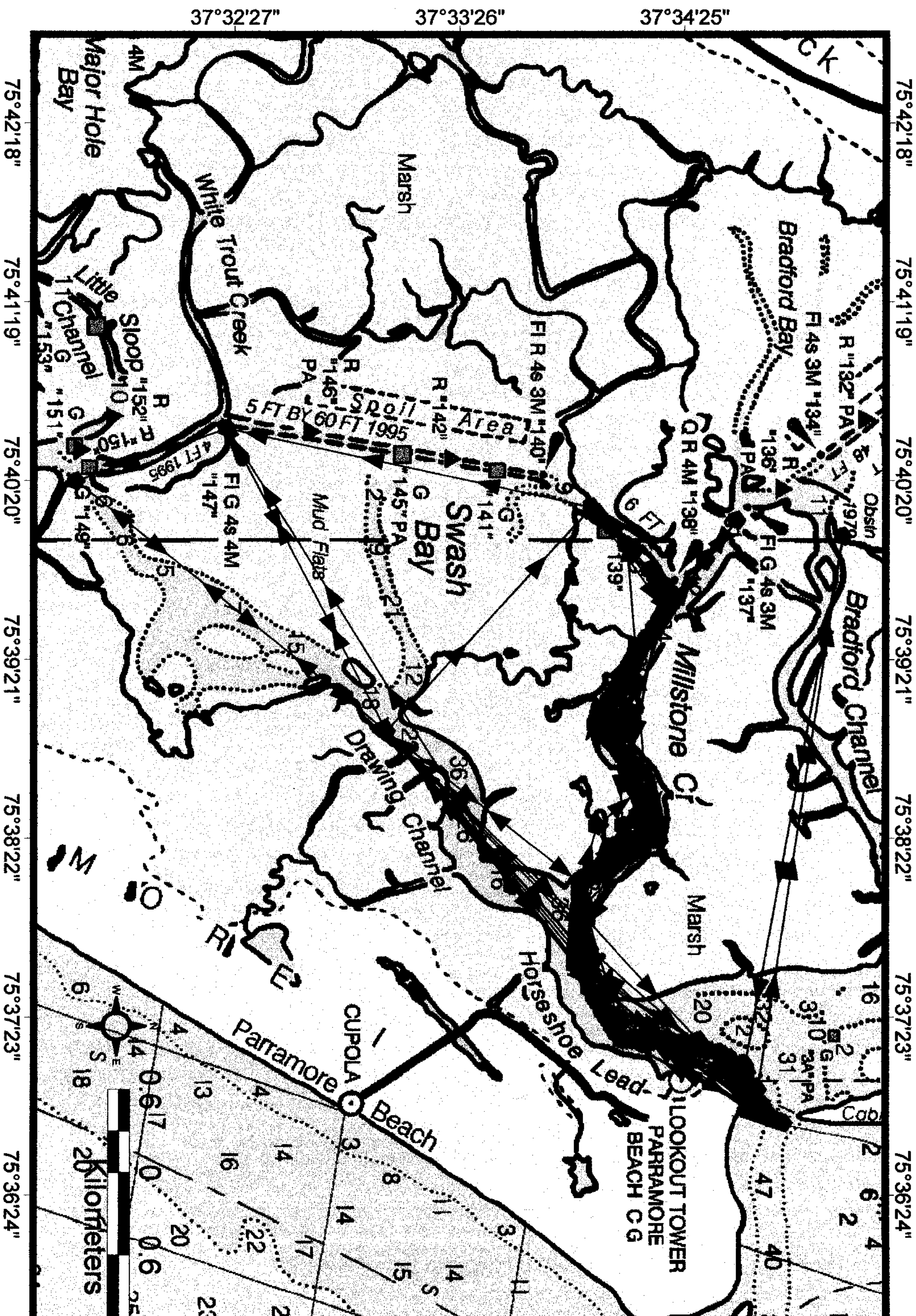
19
18
17
16
15
14
13
12
11
10
9
8
7
6
5
4
3
2
1
0
7/8/2003
7/18/2003
7/28/2003
8/7/2003
8/17/2003
8/27/2003
9/6/2003
9/16/2003
9/26/2003
Date

Figure 3-8. Days in residence for juvenile sandbar sharks tracked in 2004 both newly transmittered sharks (diamonds) and sharks transmittered in 2003 (squares) that returned to the array area.



48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
0
6/1/2004
6/16/2004
7/1/2004
7/16/2004
7/31/2004
8/15/2004
8/30/2004
9/14/2004
9/29/2004
Date

Figure 3-9. Track of Shark # 654, with positions determined using weighted average of reception locations (NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).


37°32'27"
37°33'26"
37°34'25"
75°42'18"
75°41'19"
75°40'20"
75°39'21"
75°38'22"
75°37'23"
75°36'24"
75°35'25"
Major Hole Bay
Little Sloop Channel
White Trout Creek
Marsh
Swash Bay
Mud Flats
Spoil Area
5 FT BY 60 FT 1995
Bradford Bay
Bradford Channel
Millstone Cr
Drawing Channel
Horseshoe Lead
Parramore Beach
CUPOLA
LOOKOUT TOWER PARRAMORE BEACH C G
Breakers
Kilometers
0 0.6 1.2

between receivers 8 to 12 with nearly 60% of its receptions occurring at these receivers.

*Space Use*

The environmental space use results indicated that the space use of juvenile sandbar sharks was concentrated away from the inlet, was related to hour of the day and was unrelated to tidal stage. Juvenile sandbar sharks spent significantly more time in zones two and three and less time near the inlet during both the summer of 2003 and the summer of 2004 as indicated by the significant relationship between zone and the percentage of hits. The interaction between zone and month was insignificant in both years despite the use of the inlet area increasing later in the summer and despite a drop off in the use of zone three late in the summer during 2004 (Figures 3-10 and 3-11). During 2003 the majority of hits occurred in zone three throughout the summer, whereas during 2004 zone two and three had a comparable number of hits throughout the summer. The amount of time spent in each zone by hour was significantly different for each zone and each year (Figure 3-12). In 2003 and 2004 there was increased use of the inner area (zone three) of the nursery area during the night time hours, particularly in 2003. In 2003 there was also an increase in the use of the middle zone in the night time and morning hours. In 2003 there was also a noted decrease in the use of the outer most area of the channel (zone one) during the middle of the day (11 am to 6 pm). In both 2003 and 2004 the number of receptions was not significantly correlated to tide stage and there was no significant interaction of tide stage with zone. Tide was therefore not influencing the location of animals within the array area (Figure 3-13).

Figure 3-10. A map of the three receiver groupings/zones used for environmental comparisons (NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).

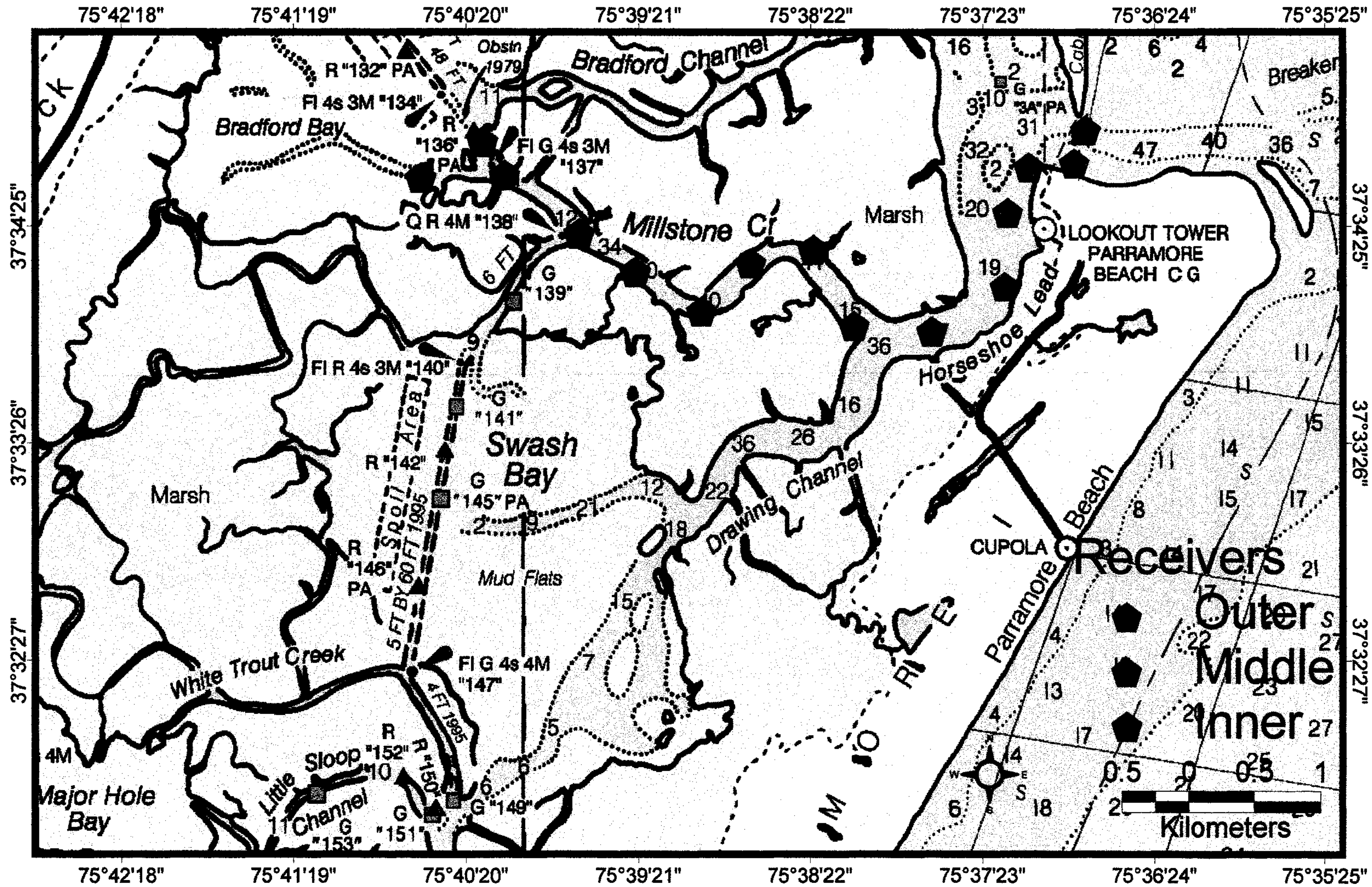
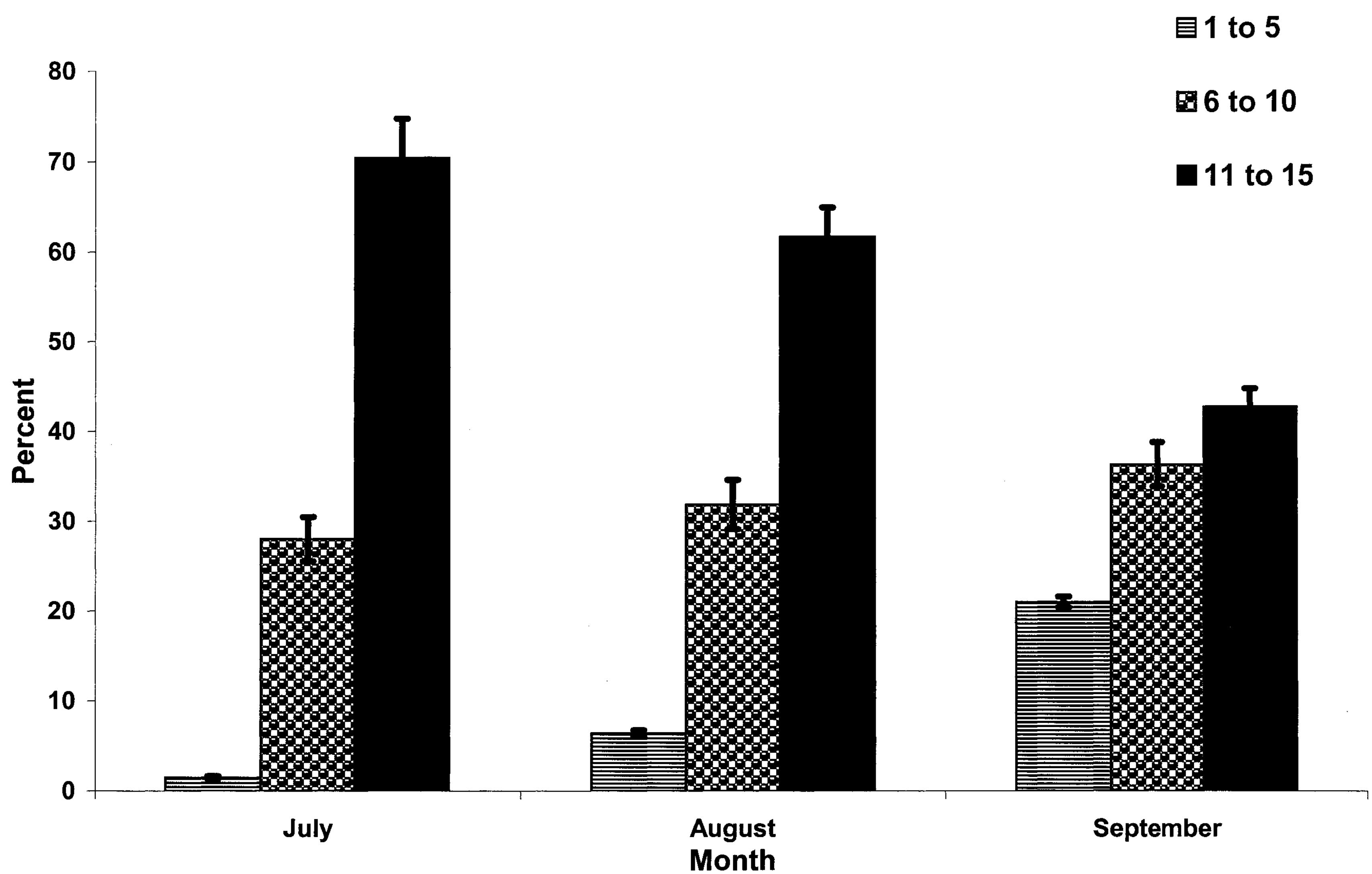

75°42'18"
75°41'19"
75°40'20"
75°39'21"
75°38'22"
75°37'23"
75°36'24"
75°35'25"
37°34'25"
37°33'26"
37°32'27"
Bradford Channel
Bradford Bay
Obstn 1979
R "132" PA
Fl 4s 3M "134"
R "136" PA
Fl G 4s 3M "137"
Q R 4M "138"
G "139"
Millstone Cr
Marsh
LOOKOUT TOWER
PARRAMORE BEACH C G
Breaker
Horseshoe Lead
Fl R 4s 3M "140"
G "141"
Swash Bay
R "142"
G "145" PA
Spoil Area
5 FT BY 60 FT 1995
R "146" PA
Mud Flats
Drawing Channel
CUPOLA
Parramore Beach
Receivers
Outer
Middle
Inner
White Trout Creek
Fl G 4s 4M "147"
4 FT 1995
R "152"
R "150"
G "149"
G "151"
G "153"
Little Sloop Channel
Major Hole Bay
0.5
0
0.5
1
Kilometers

Figure 3-11. The percent of transmitter receptions by zone and month for a. 2003 and b. 2004 (error bars are standard error of the mean).


1 to 5
6 to 10
11 to 15
Percent
80
70
60
50
40
30
20
10
0
July
August
September
Month

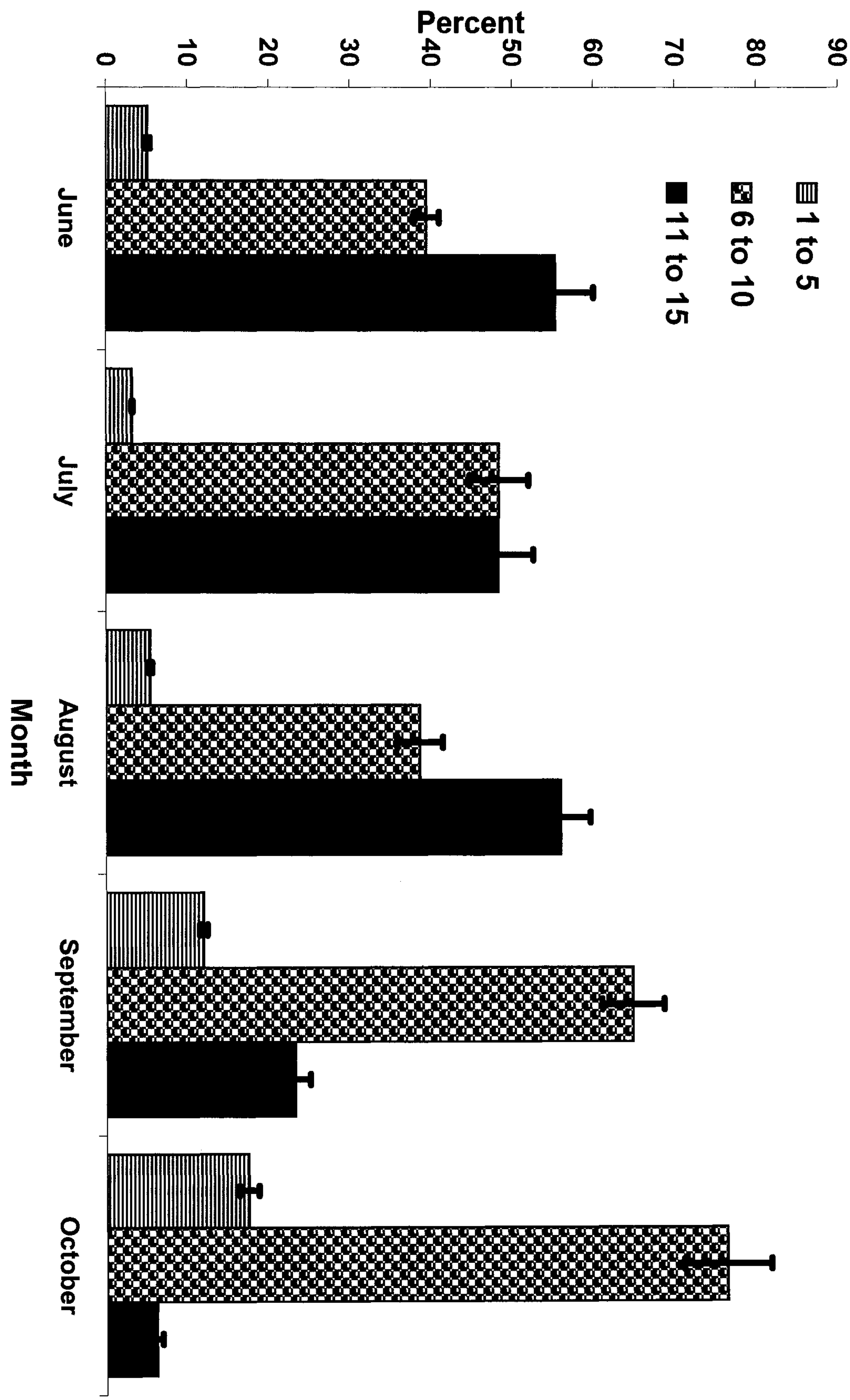
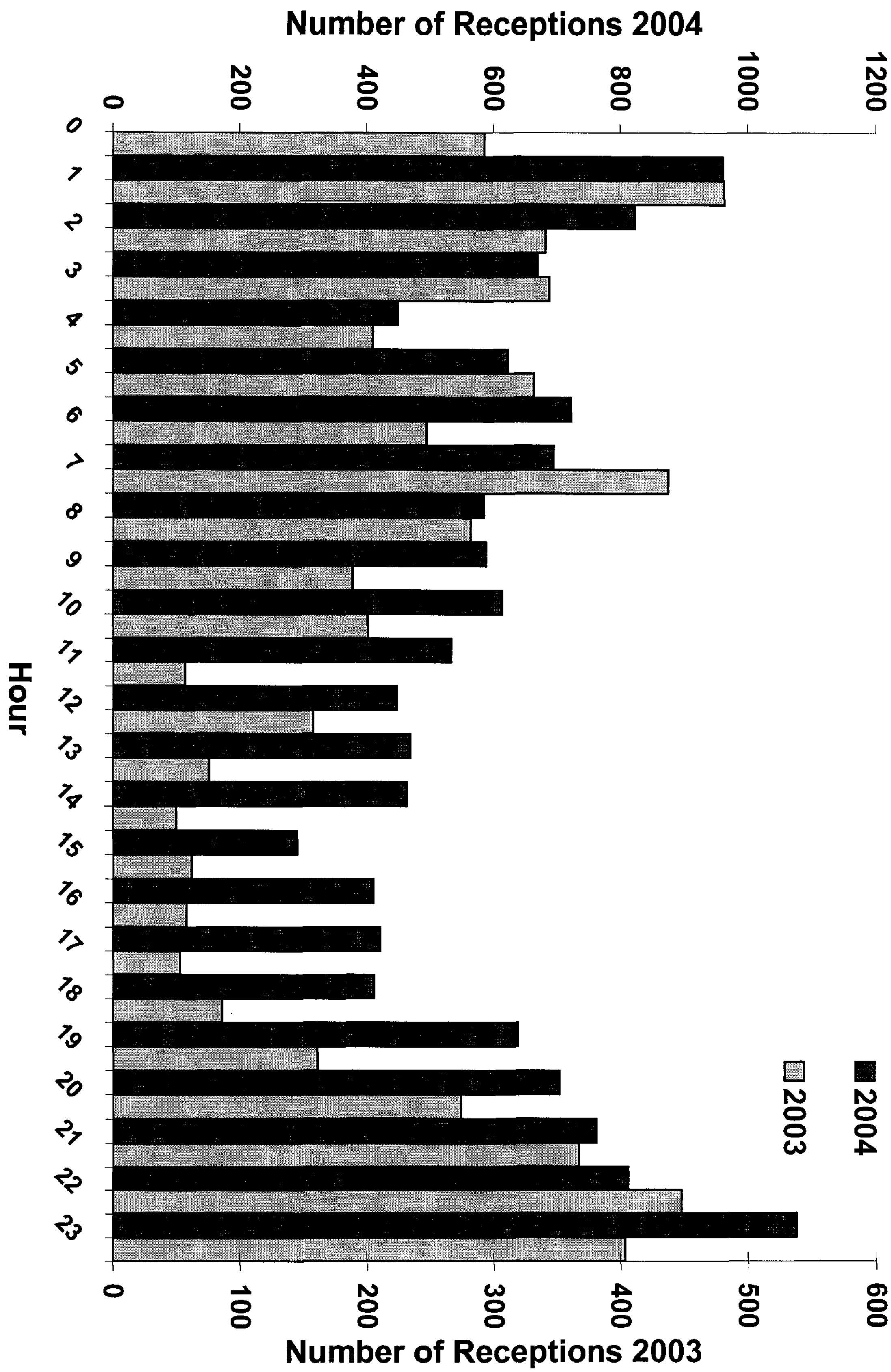
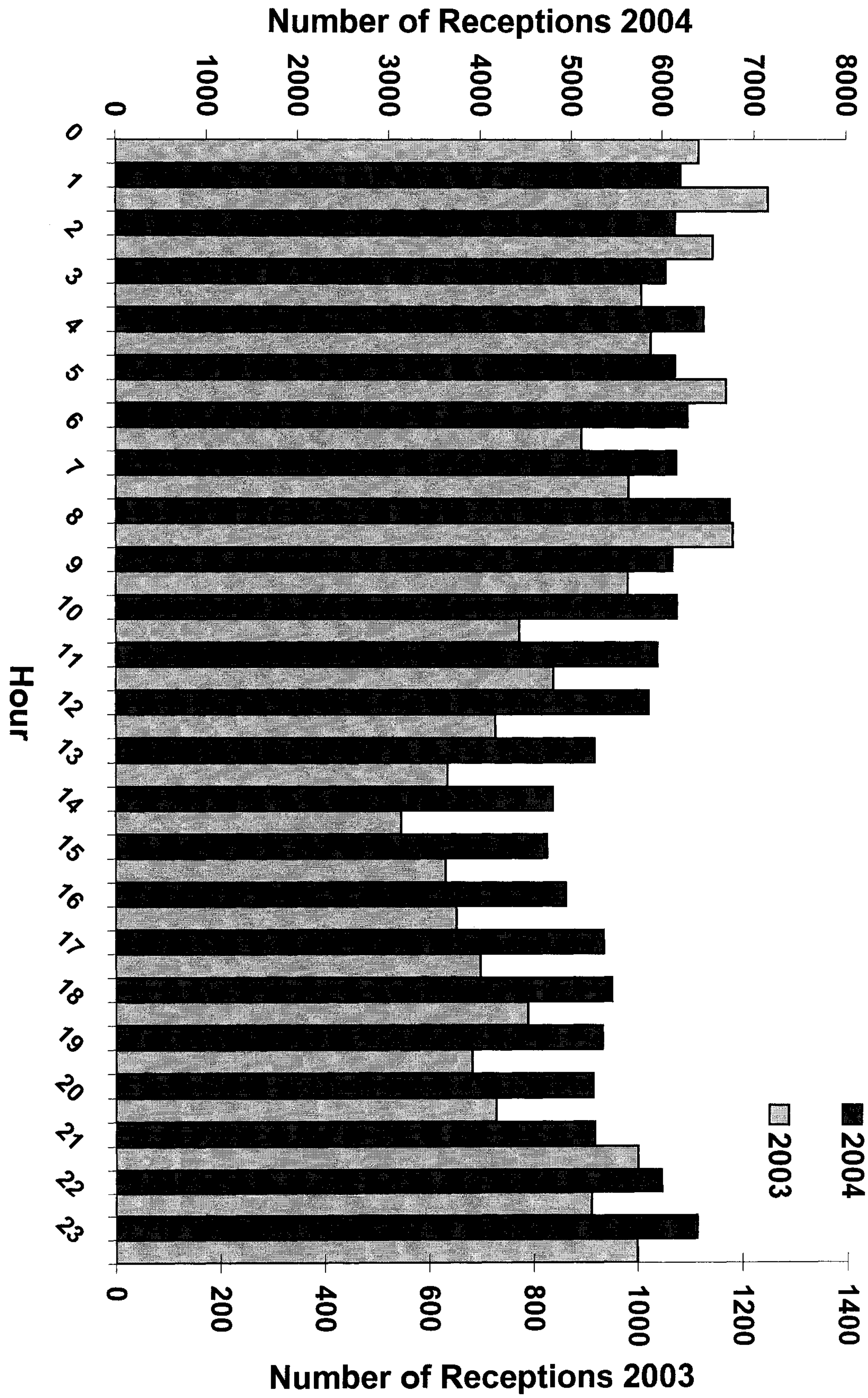

Percent
0
10
20
30
40
50
60
70
80
90
1 to 5
6 to 10
11 to 15
June
July
August
September
October
Month

Figure 3-12. The number of transmitter receptions by hour in 2003 and 2004 for a. zone 1, b. zone 2, and c. zone 3.


Number of Receptions 2004
0
200
400
600
800
1000
1200
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
2004
2003
0
100
200
300
400
500
600
Number of Receptions 2003



Number of Receptions 2004
0
1000
2000
3000
4000
5000
6000
7000
8000
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
2004
2003
0
200
400
600
800
1000
1200
1400
Number of Receptions 2003

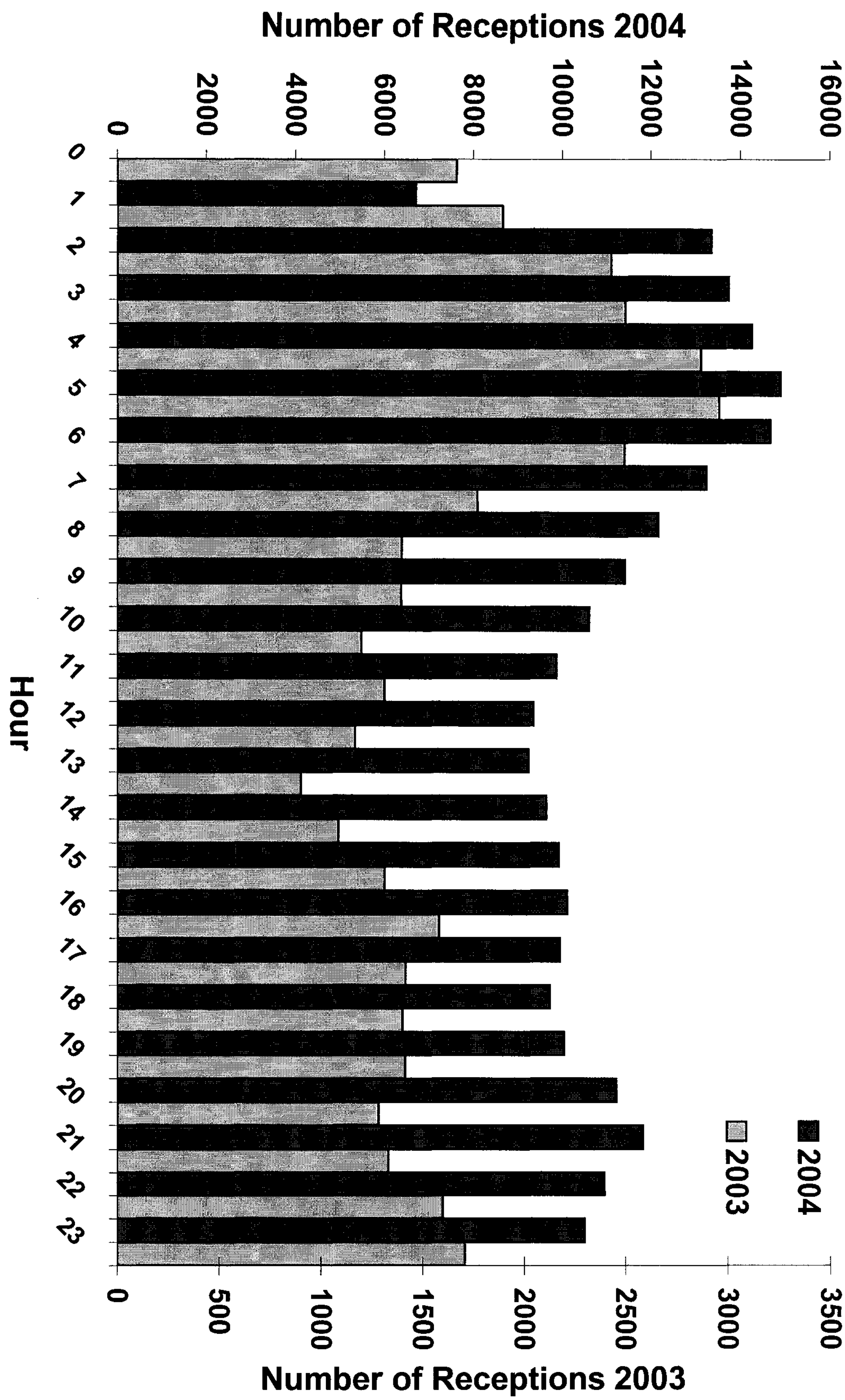
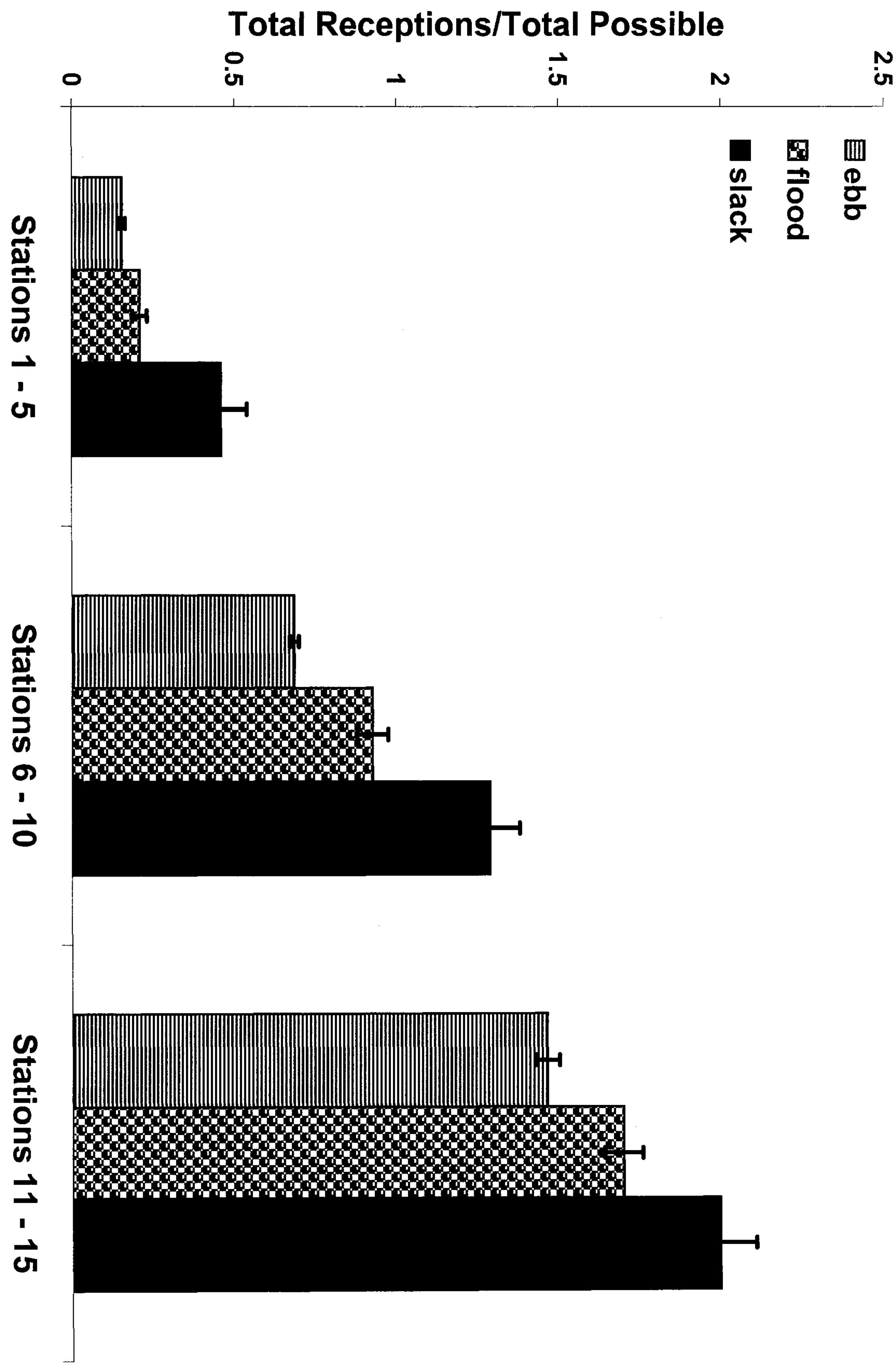
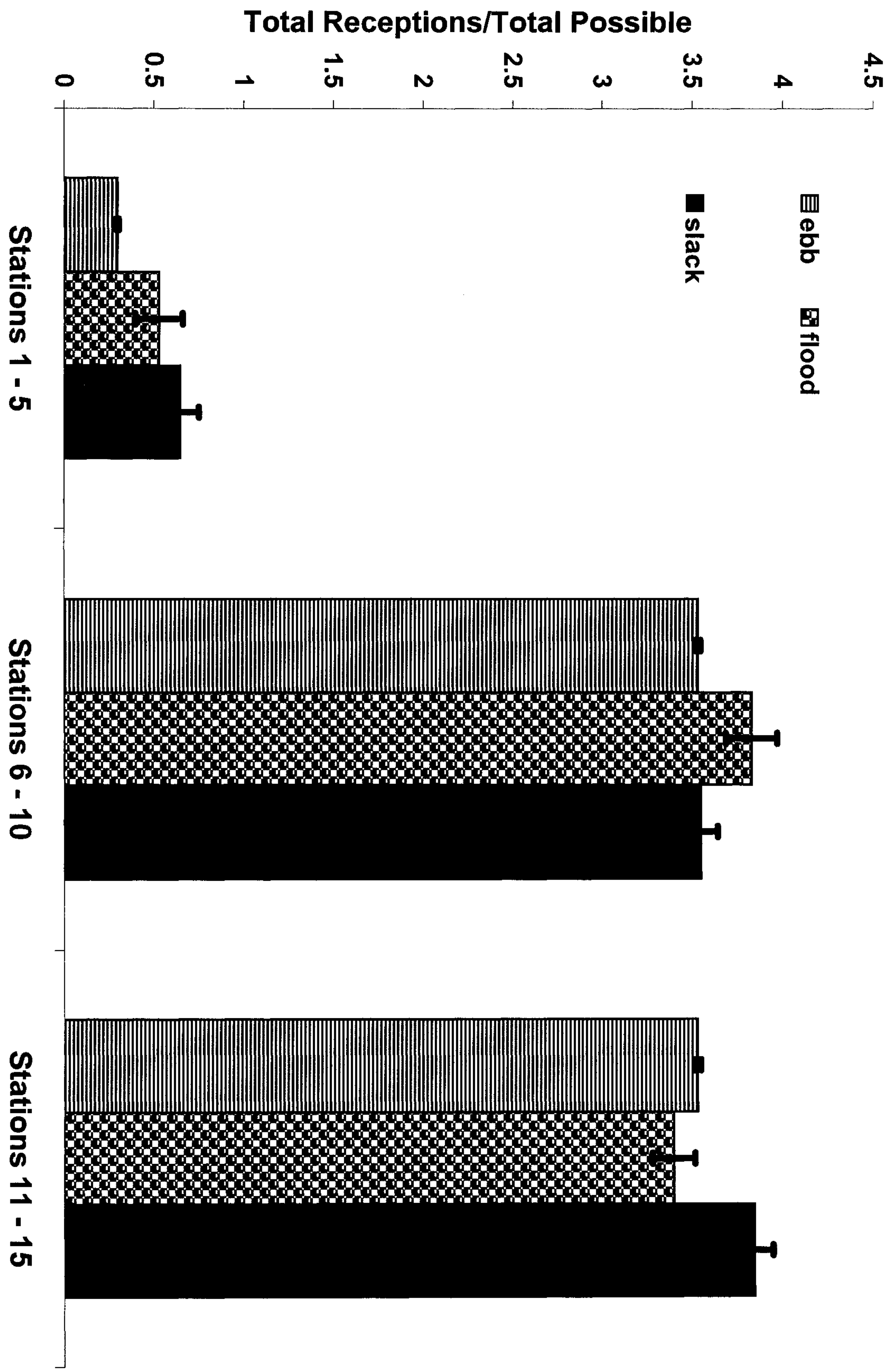

Number of Receptions 2004
0
2000
4000
6000
8000
10000
12000
14000
16000
Hour
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
2004
2003
0
500
1000
1500
2000
2500
3000
3500
Number of Receptions 2003

Figure 3-13. The proportion of transmitter receptions by zone and tide stage for a. 2003 and b. 2004.


Total Receptions/Total Possible
0
0.5
1
1.5
2
2.5
ebb
flood
slack
Stations 1 - 5
Stations 6 - 10
Stations 11 - 15


Total Receptions/Total Possible
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
ebb
flood
slack
Stations 1 - 5
Stations 6 - 10
Stations 11 - 15

*Periodicity in movement*

Periodicity in small scale horizontal movements of the sharks was studied using periodogram analysis of the sharks' half hourly channel distance. Thirty-eight tracks from multiple sharks were deemed usable for the analysis fitting the criteria mentioned above. There was strong evidence of a tidal periodicity of the shark movements up and down the channel. There was a tidal phase periodicity in the majority of the shark tracks (77%) and the 12 hour peak is the dominant peak found within the periodograms of the tracks (Figure 3-14). Many of the sharks were clearly moving in the direction of the tide when they were moving (Figure 3-15). In addition, when the percentage of up and down channel movements with and against the tide was determined, it was found that 59.9% of movements were with the tide, 8.3% of movements were against the tide, and the sharks remained at the same channel distance 31.9% of the time (Figure 3-16).

Periodicity in small scale vertical movements of the sharks was studied using periodogram analysis of the depth data from the two recovered satellite transmitters. For both depth series the null hypothesis that the series was white noise was rejected (test statistic =0.79, $p < 0.0001$ and test statistic = 0.55, $p < 0.0001$). Both series have two large peaks at 12 and 24 hour periods (Figure 3-17). The 24 hour peak corresponds to a diel cycle present within the data. The presence of an additional peak at 6 hours and 12 hours may indicate that the 24 hour peak is nonsinusoidal and harmonics of this peak are present within the periodogram. However, the 12 hour peak is the dominant peak present in the data indicating a tidal phase influence in the depth utilization of these sharks. Both sharks exhibited a significant decrease in the

Figure 3-14. Histogram of periodogram peak frequencies, all frequencies with a corresponding amplitude greater than 4 are included.

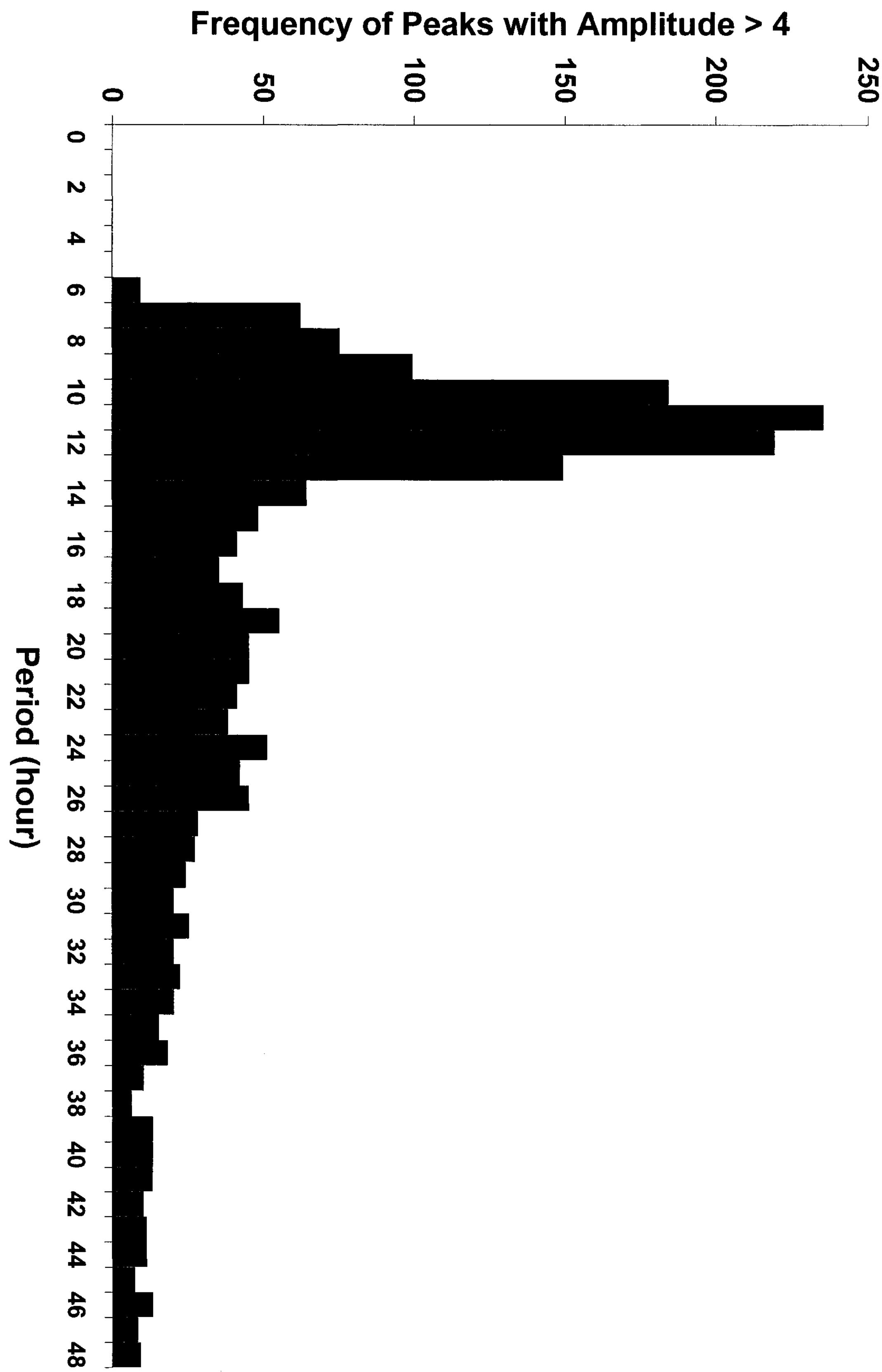

Frequency of Peaks with Amplitude > 4
0
50
100
150
200
250
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48
Period (hour)

Figure 3-15. The average channel distance for shark 654 and shark 666 and tide height during July 12-17, 2004.

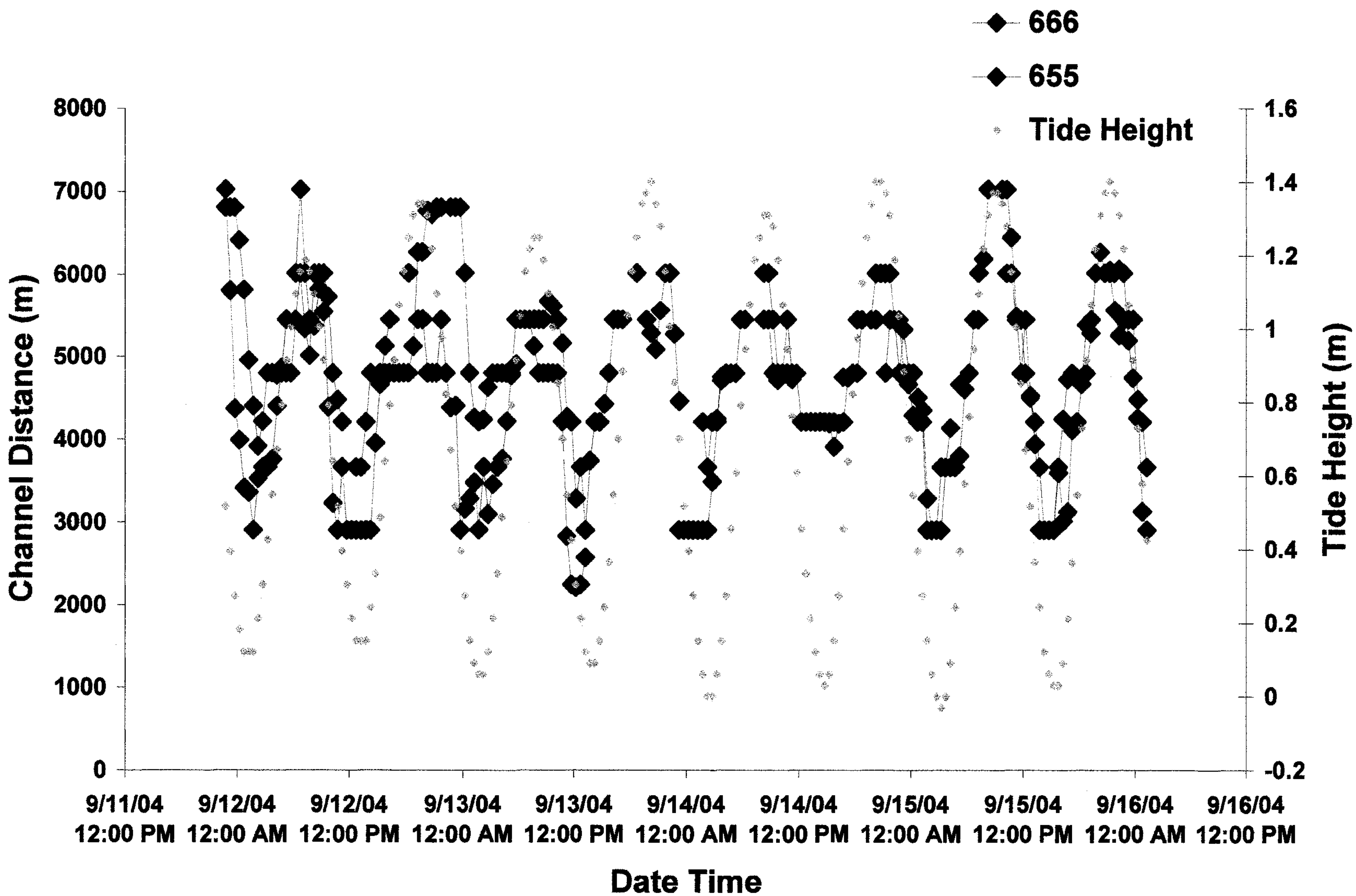

666
655
Tide Height
Channel Distance (m)
Tide Height (m)
Date Time
8000
7000
6000
5000
4000
3000
2000
1000
0
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
9/11/04 12:00 PM
9/12/04 12:00 AM
9/12/04 12:00 PM
9/13/04 12:00 AM
9/13/04 12:00 PM
9/14/04 12:00 AM
9/14/04 12:00 PM
9/15/04 12:00 AM
9/15/04 12:00 PM
9/16/04 12:00 AM
9/16/04 12:00 PM

Figure 3-16. Average proportion of juvenile sandbar shark movements with tide, against tide, and with no movement (error bars are standard error of the mean).

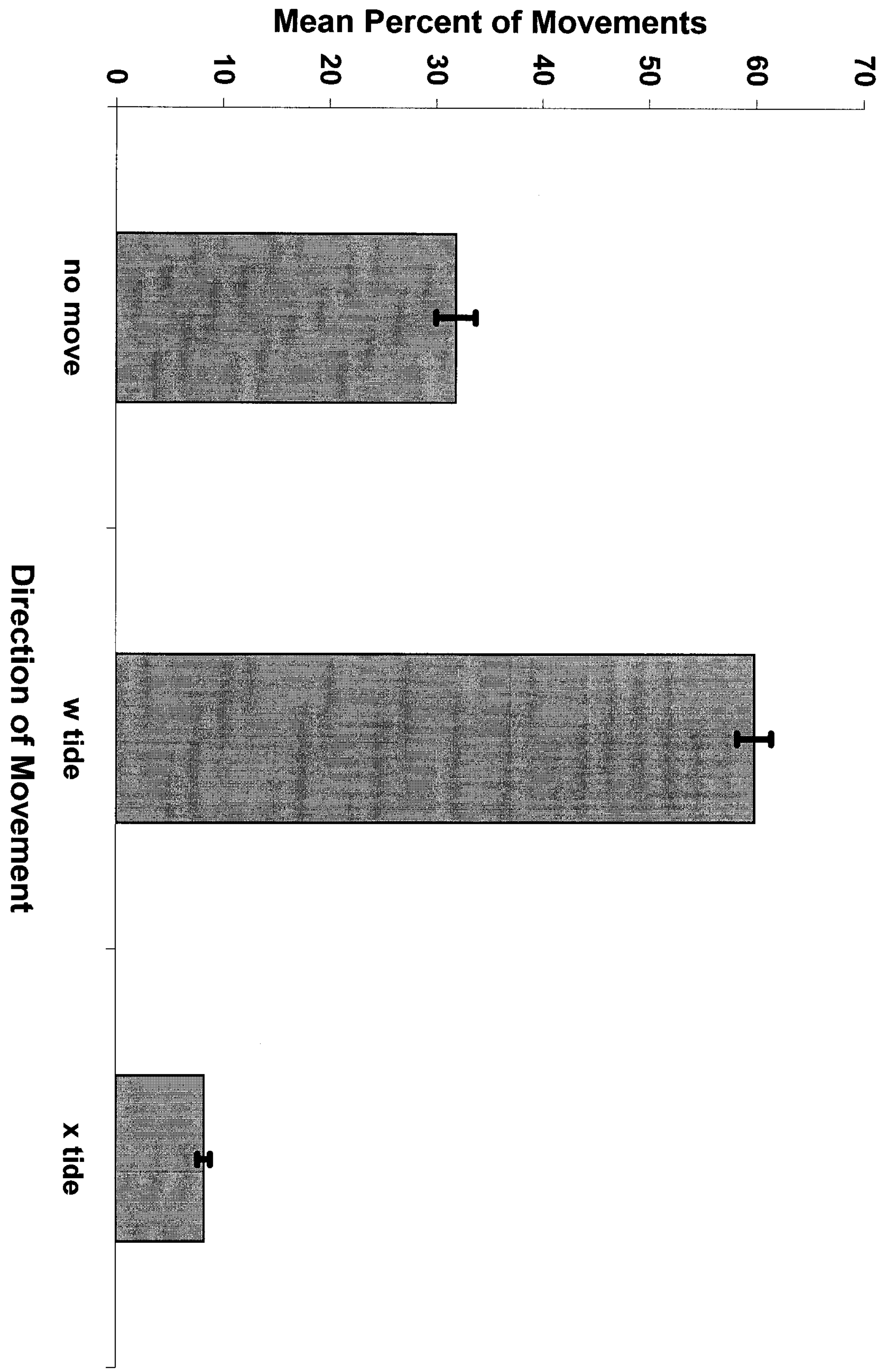
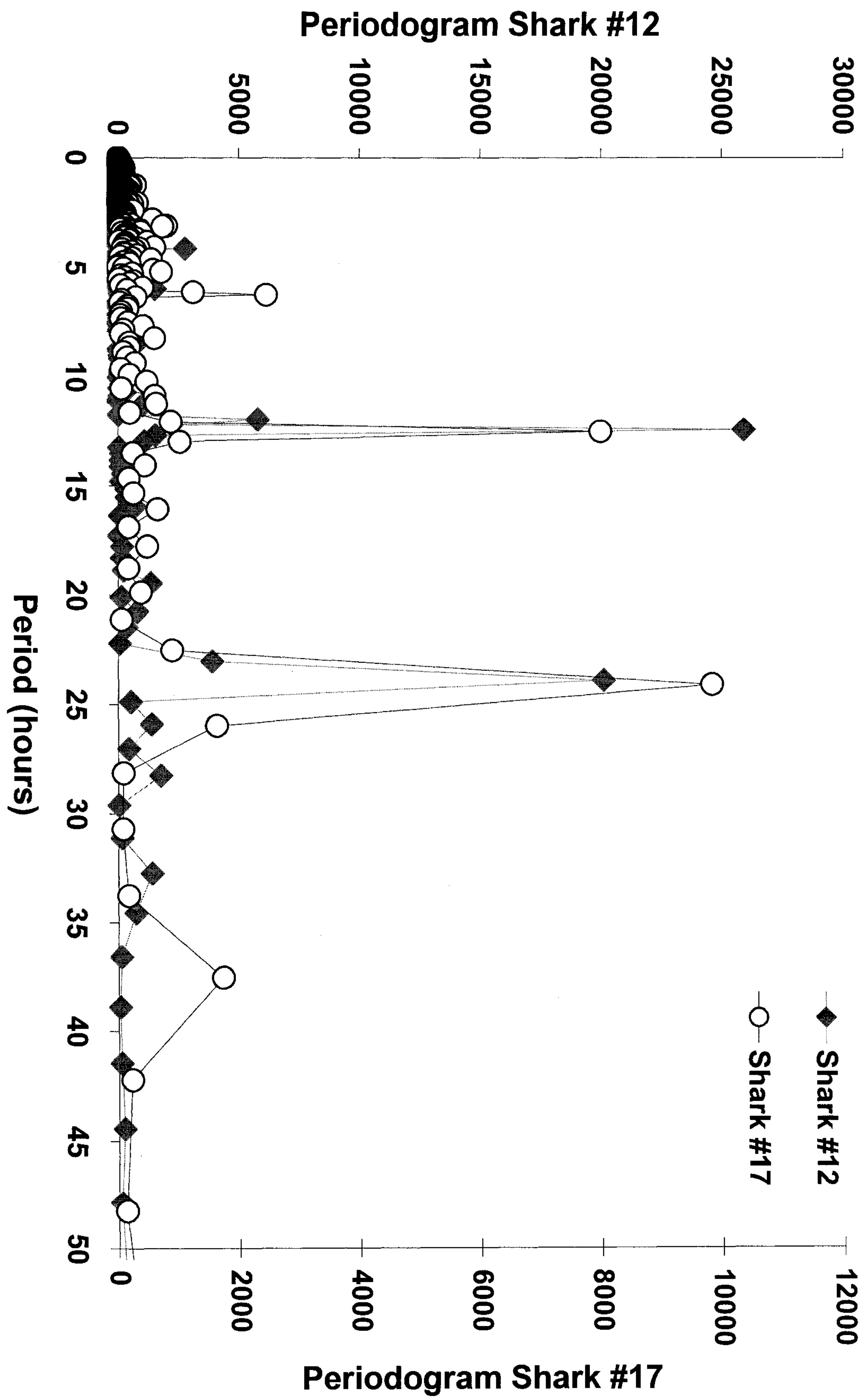

Mean Percent of Movements
0
10
20
30
40
50
60
70
no move
w tide
x tide
Direction of Movement

Figure 3-17. Periodogram heights for the periodogram of shark #12 and shark #17 mean hourly depths.

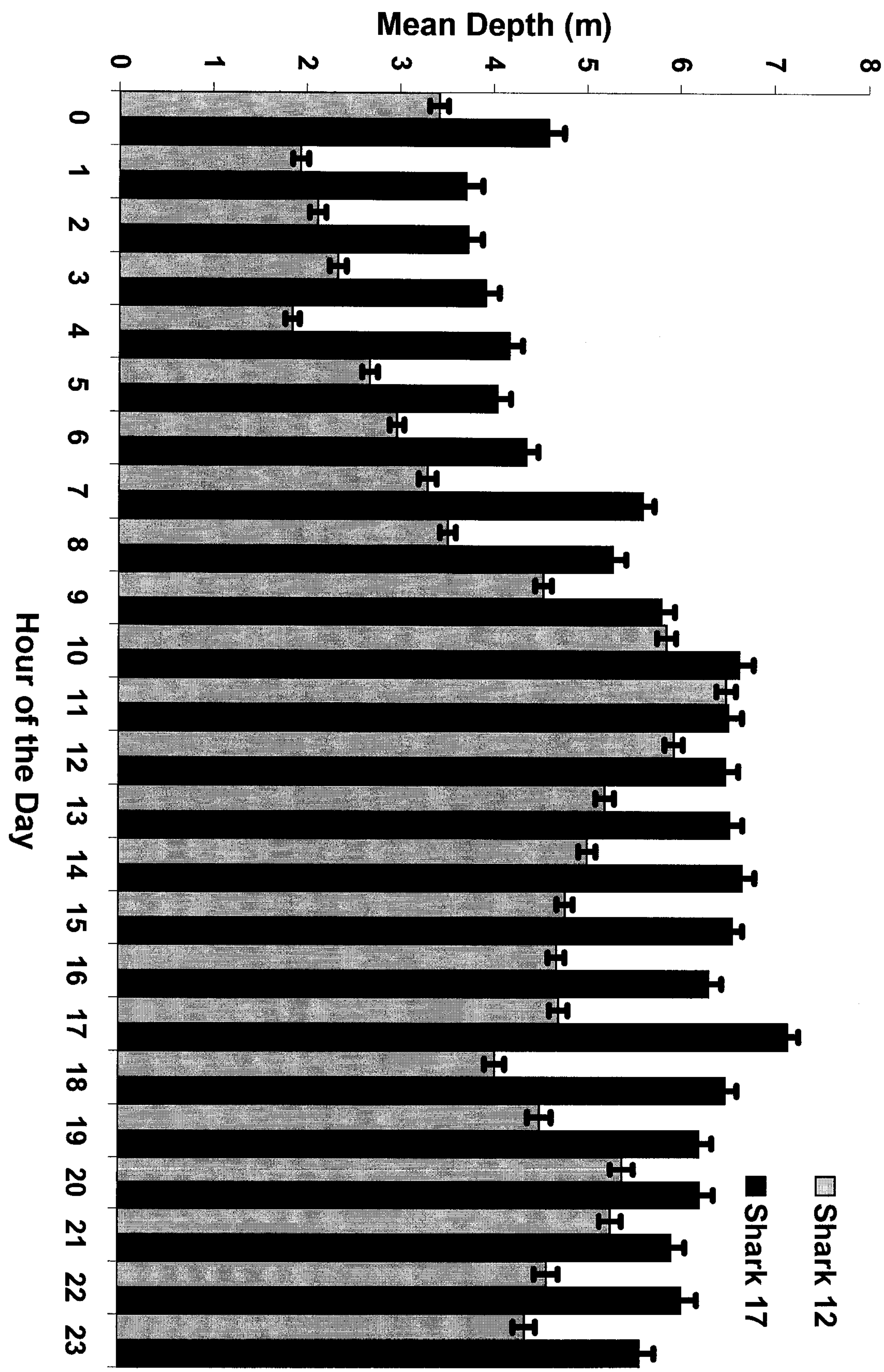

Periodogram Shark #12
0
5000
10000
15000
20000
25000
30000
Period (hours)
0
5
10
15
20
25
30
35
40
45
50
Shark #12
Shark #17
0
2000
4000
6000
8000
10000
12000
Periodogram Shark #17

mean depth of occurrence in the night and early morning hours of the day (Figure 3-18). When tidal height at Great Machipongo Inlet and the depth of the sharks was plotted, the two sharks exhibited different patterns, shark #12 appeared to go deeper in the water column during high tide, whereas shark #17 appeared to go into deeper waters during low tide (Figure 3-19 a and b). Since the depth data are highly variable and inconsistent patterns are exhibited with the tidal phase for these two sharks, more data will be needed to determine if depth occurrence is correlated with the tidal cycle and the significance of the 12 hour peak in the periodogram analysis.

*Site attachment*

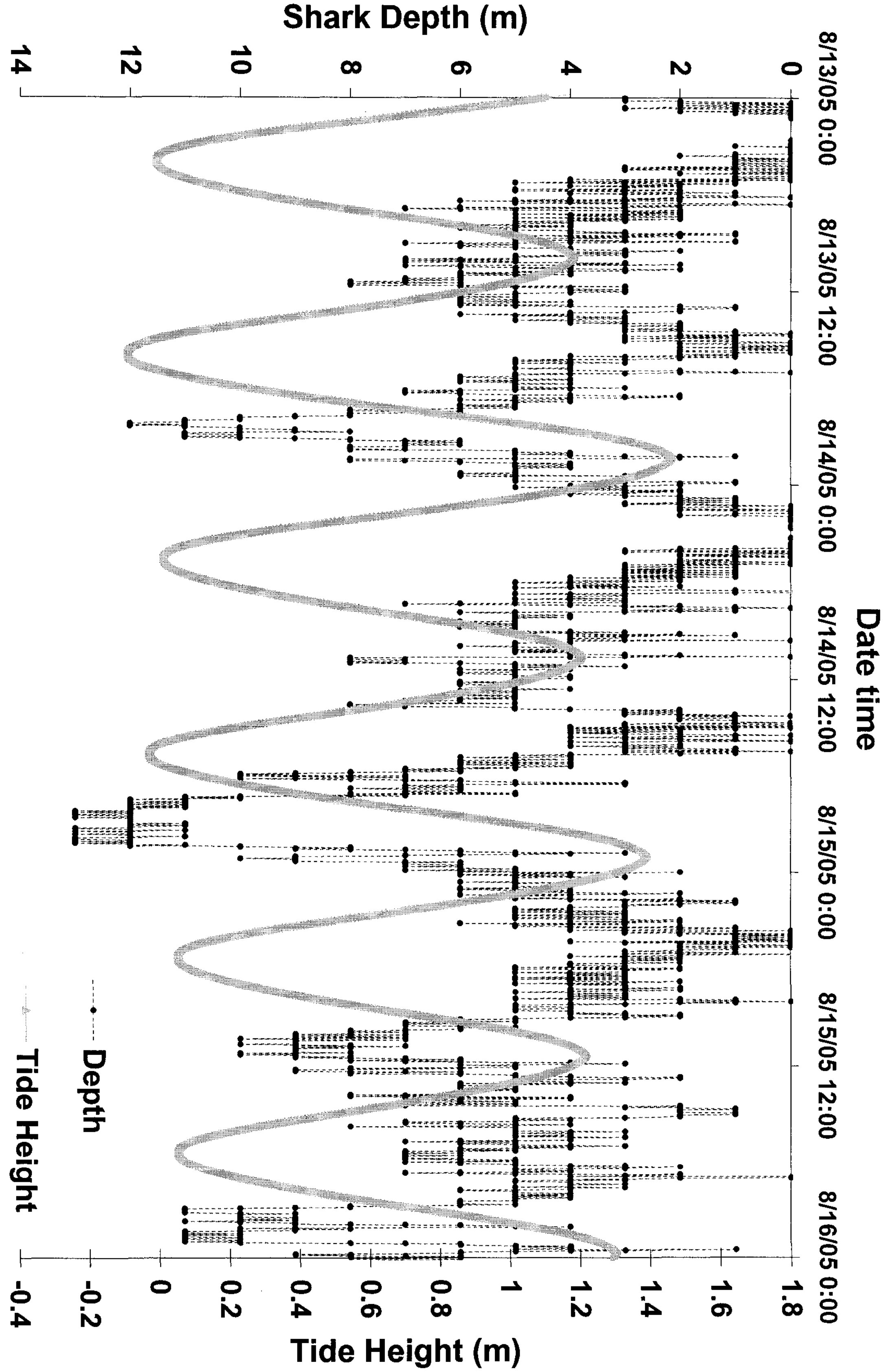
To determine if sharks remained within the array area more than expected than if they were moving randomly, the average amount of time a random shark would remain within the array was calculated using a conservative random walk analysis. Our random model had fifty-three steps ranging from Magothy Bay to the south to Metompkin Inlet to the North (Figure 3-20). On average, a random shark would remain within the array 6.5% of the time, in 2003 the average amount of time the actual sharks remained within the array was 22.5% of the half days, and in 2004 the average amount of time the actual sharks remained within the array was 41.2% of the half days. Actual sharks within the study ranged in behavior from leaving the array almost immediately to staying with the array and appearing on each half day. But the random shark models never spent more than 35% of their half days within the array indicating that if shark movements within the area were entirely random the sharks would eventually leave the array and move too far away to return (Figure 3-21). This

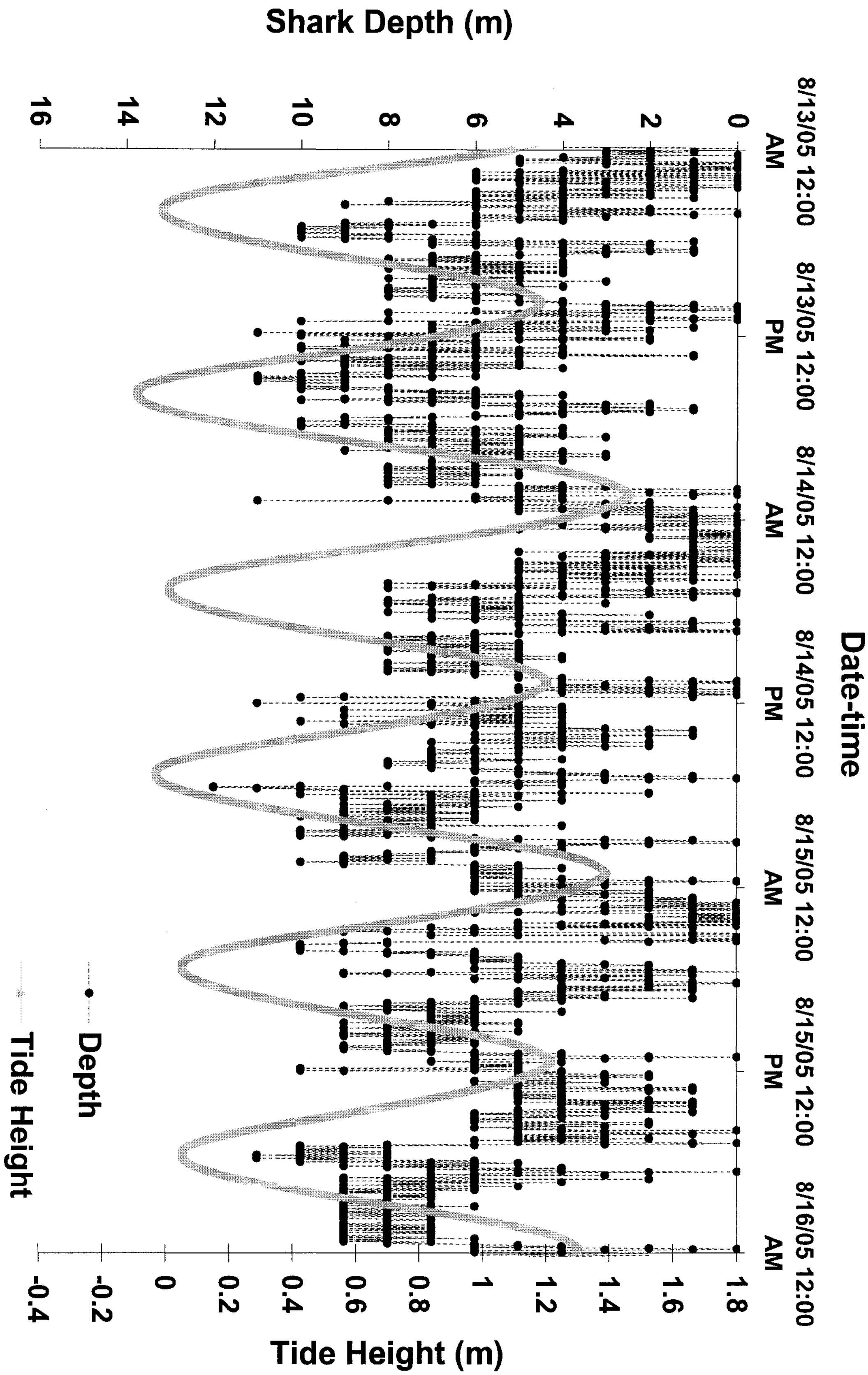
Figure 3-18. Mean depth plotted against hour of the day (error bars are standard error of the mean).



Mean Depth (m)
0
1
2
3
4
5
6
7
8
Hour of the Day
0
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
Shark 12
Shark 17

Figure 3-19. Mean hourly depth plotted against Great Machipongo Inlet tidal cycle for a) shark #12 and b) shark #17.


Shark Depth (m)
0
2
4
6
8
10
12
14
Date time
8/13/05 0:00
8/13/05 12:00
8/14/05 0:00
8/14/05 12:00
8/15/05 0:00
8/15/05 12:00
8/16/05 0:00
Tide Height (m)
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
Depth
Tide Height



Shark Depth (m)
Date-time
Tide Height (m)
Depth
Tide Height
8/13/05 12:00 AM
8/13/05 12:00 PM
8/14/05 12:00 AM
8/14/05 12:00 PM
8/15/05 12:00 AM
8/15/05 12:00 PM
8/16/05 12:00 AM

Figure 3-20. Map of the area covered by the random walk model (NOAA, Chesapeake Bay Entrance #12221, 1:80,000 and NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000).

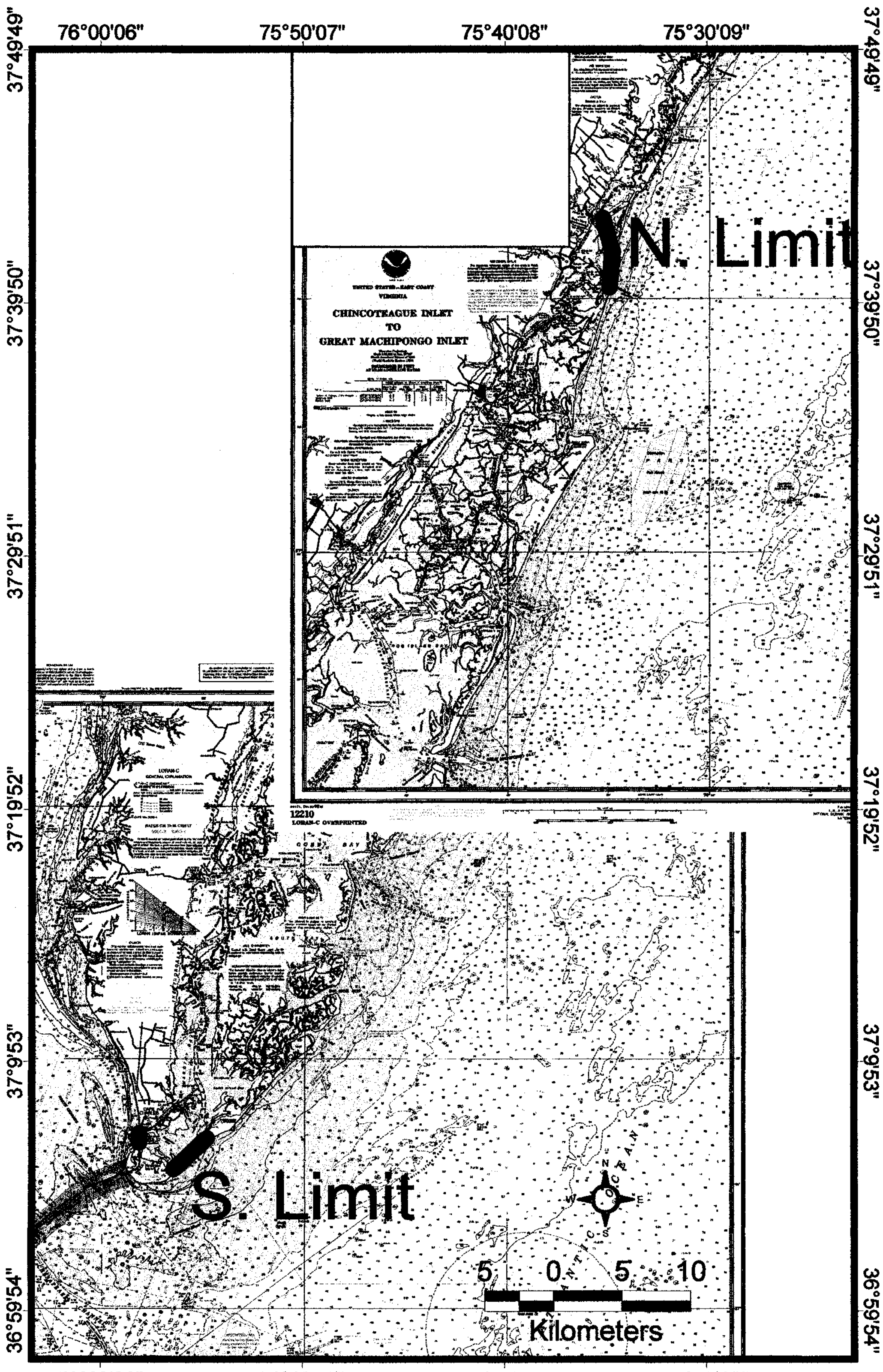
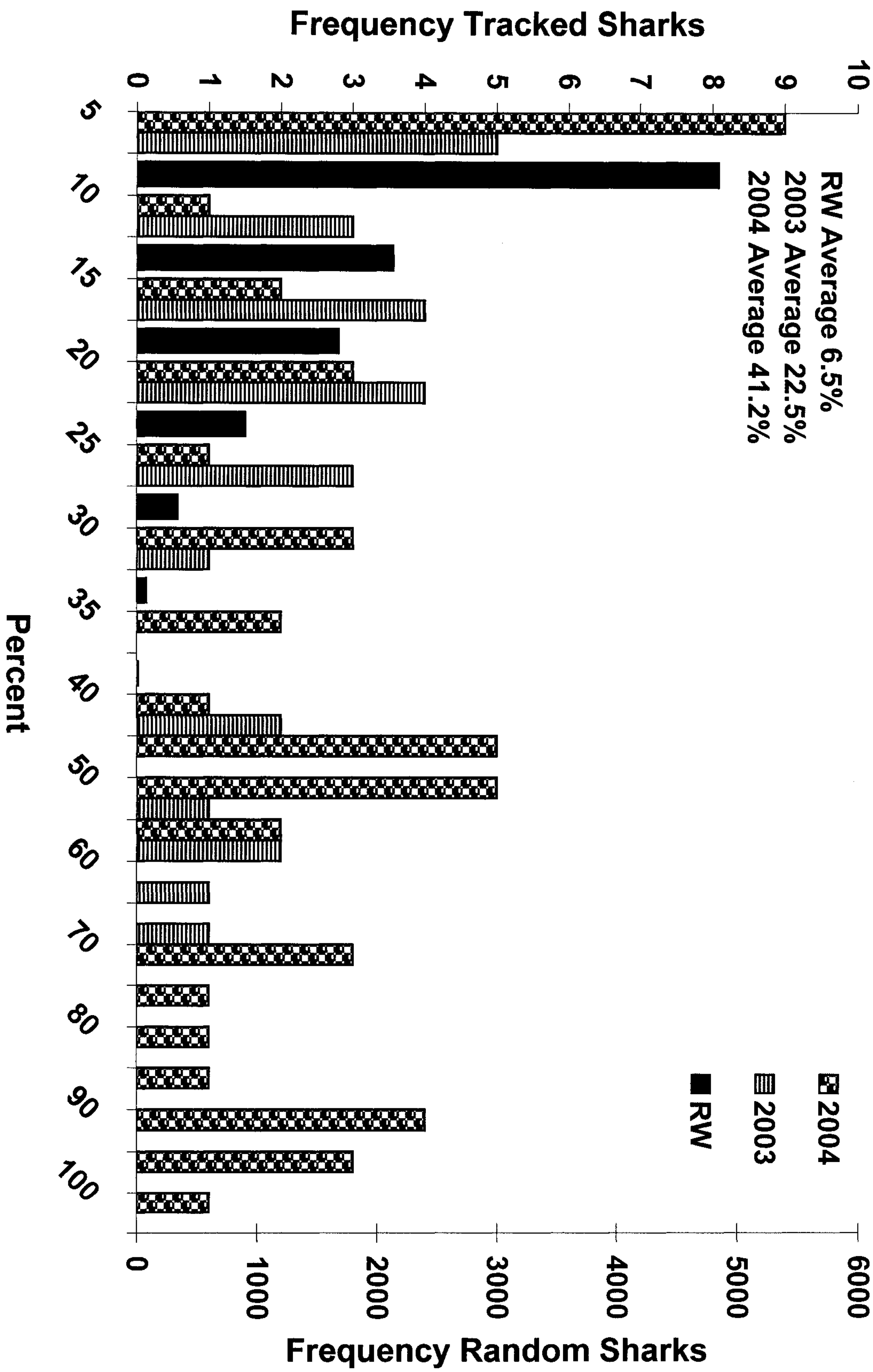

76°00'06"
75°50'07"
75°40'08"
75°30'09"
37°49'49"
37°39'50"
37°29'51"
37°19'52"
37°9'53"
36°59'54"
N. Limit
S. Limit
CHINCOTEAGUE INLET
TO
GREAT MACHIPONGO INLET
12210
5
0
5
10
Kilometers

Figure 3-21. Histogram of the percent residency of random walk model sharks and actual sharks tracked in 2003 and 2004.



Frequency Tracked Sharks
RW Average 6.5%
2003 Average 22.5%
2004 Average 41.2%
2004
2003
RW
Percent
5
10
15
20
25
30
35
40
50
60
70
80
90
100
0
1
2
3
4
5
6
7
8
9
10
0
1000
2000
3000
4000
5000
6000
Frequency Random Sharks

was an indication that a portion of the sharks did return and spent more time within the array than they would have if they were moving randomly.

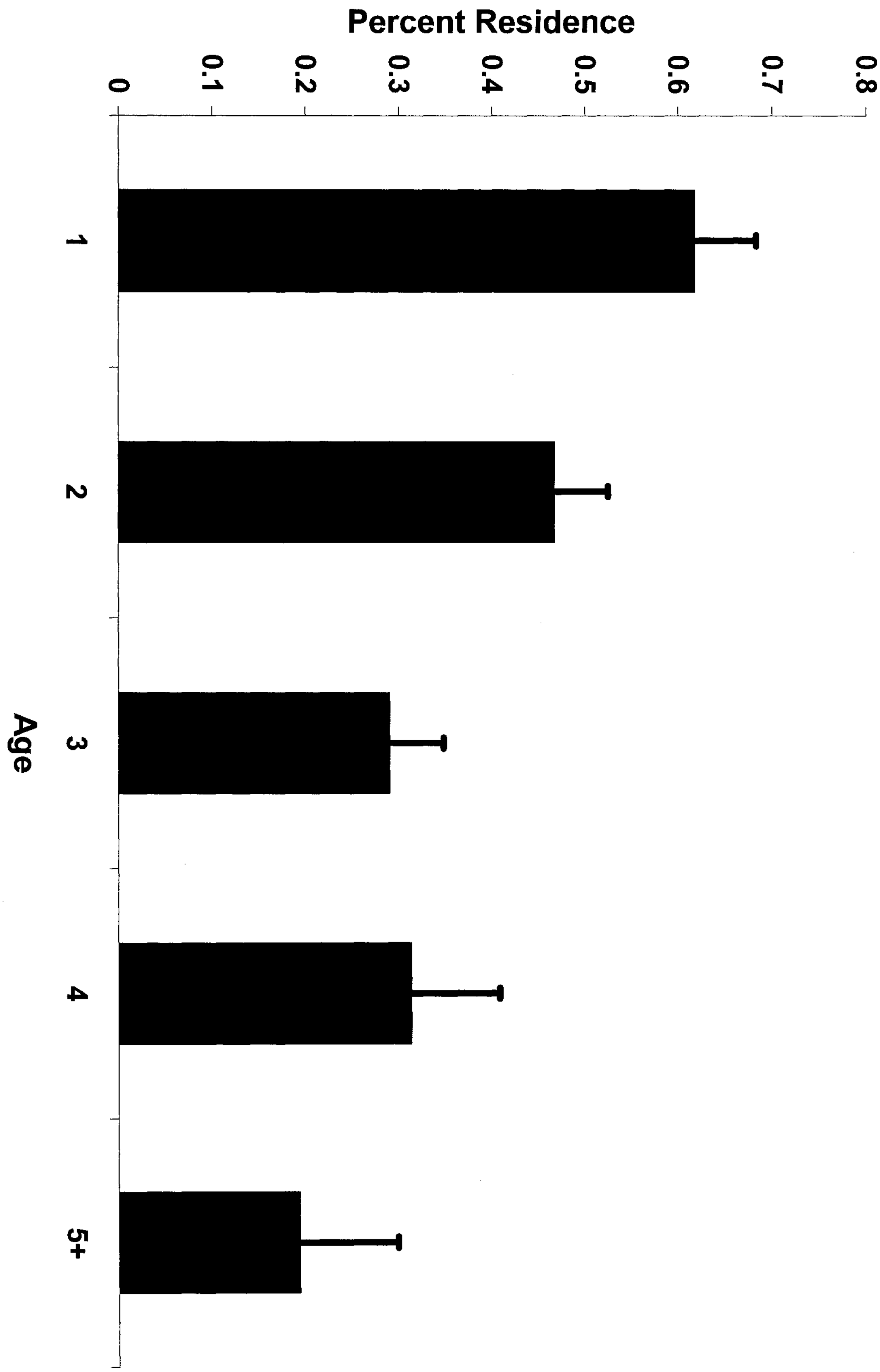
*Age Effects*

There was a significant relationship between age and the amount of time spent within the array with younger animals exhibiting a larger residency time both in terms of days (Kruskal Wallis test H = 13.74 DF = 4 P = 0.008) and hours (Kruskal Wallis H = 11.97 DF = 4 P = 0.018) in residence (Figure 3-22). This likely indicates smaller animals were moving less, and had smaller more localized activity spaces and potentially smaller home ranges.

*Distances traveled*

During the course of the sampling for this project and the delineation project, 1,082 conventional VIMS dart tags were applied to neonate and juvenile sandbar sharks caught within the Eastern Shore lagoons. Additional tags were applied by the VIMS shark longlining program, and by other VIMS researchers. During the summers of 2003 to 2005, 27 conventional VIMS tag returns were reported, six acoustic transmitters were returned, and seven satellite transmitters popped-up during the summer months (Figure 3-23). Six returns occurred after less than ten days at liberty, a few of the sharks traveled considerable distances before being recaptured while others remained very close to the same location. The distances traveled for these short returns ranged from 2.8 to 40.7 km, with a mean of 17.0 km (SE = 5.6). Twenty-two returns were reported within the same summer that the sharks were tagged. The distances traveled within the same summer ranged from 2.2 to 101.3 km with a mean of 31.9 km (SE = 8.72, N=28). Twelve returns were reported during

Figure 3-22. a. Average daily residence time by age and b. average hourly residency time by age for sharks tracked in 2003 and 2004.


Percent Residence
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
1
2
3
4
5+
Age

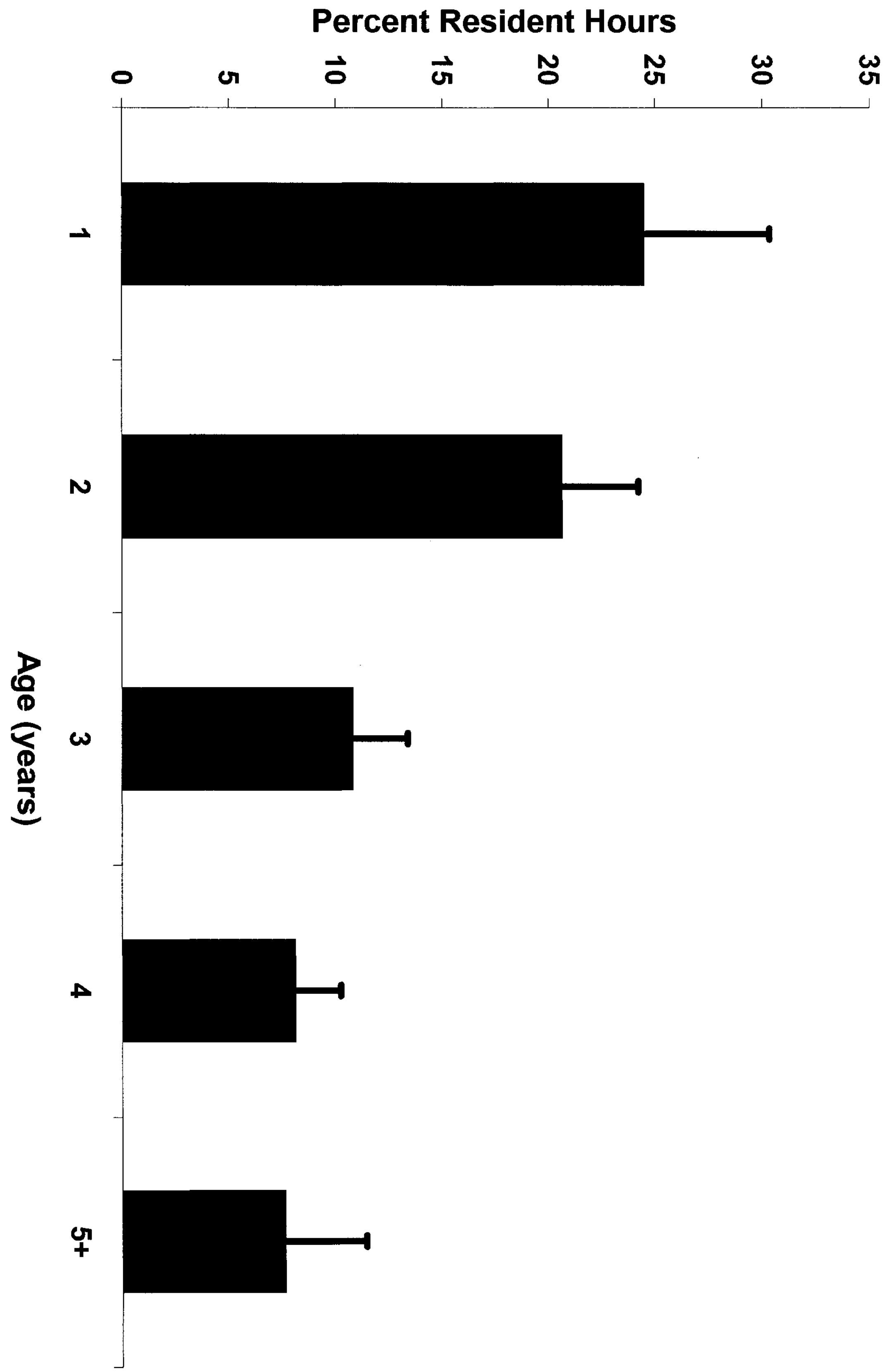
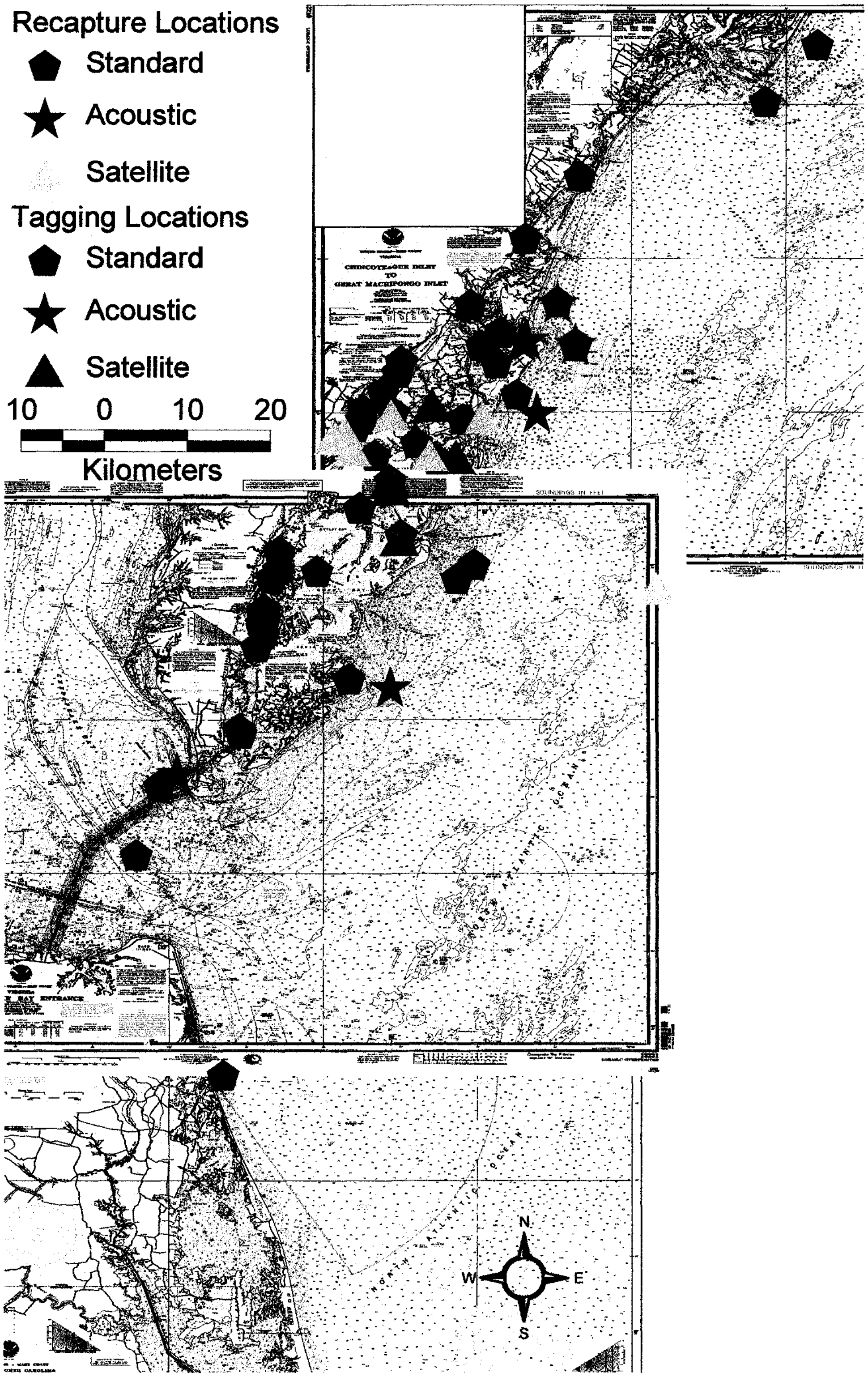

Percent Resident Hours
0
5
10
15
20
25
30
35
1
2
3
4
5+
Age (years)

Figure 3-23. Tag recaptures by tag type during the summers of 2003 to 2005 (NOAA, Chesapeake Bay Entrance #12221, 1:80,000, NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000, and NOAA, Cape Henry to Currituck Beach Light #12207, 1:80,000).



Recapture Locations
Standard
Acoustic
Satellite
Tagging Locations
Standard
Acoustic
Satellite
10 0 10 20
Kilometers
N
W
E
S

subsequent summers after tagging. The distance from tag location to recapture location between summers ranged from 9.1 to 420.4 km with a mean distance of 70.2 km (SE = 32.9). One of these sharks was captured in North Carolina over 400 km from the tagging location, the other eleven returns all occurred within 80 km of the recapture site (Figure 3-24).

*Mortality and philopatry*

Some knowledge of fate of the juvenile sandbar sharks transmittered in 2003 was obtained during the following two summers. During 2004, 37.1% (10) of the sharks transmittered in 2003 returned to the array, six returned before June 15, 2004 and four returned after August 15$^{th}$, 2004. Also during 2004, 18.5% (five) of the sharks transmittered in 2003 were detected at receivers located in Delaware Bay, one of these sharks was also one detected in the Eastern Shore in 2004, four were only detected in Delaware Bay (D. Fox and H. Brundage personal communication) (Table 3-1). During the summer of 2004, 14.8% (four) of these sharks were known to have been killed by commercial fishermen. Therefore at least 67% (18) of the sharks transmittered in 2003 were known to have survived to the beginning of the summer of 2004. During 2005 the battery life of the transmitters deployed in 2003 should have been about at an end; however, two of these sharks were detected in Delaware Bay that summer.

Some knowledge of the fates of the juvenile sandbar sharks transmittered in 2004 was obtained during the summers of 2004 and 2005. Late in the summer of 2004, three of these sharks experienced mortality (8.1%), two were captured and killed by commercial fishermen and one was inadvertently caught and killed by VIMS

Figure 3-24. Tag recaptures by time at liberty during the summers of 2003 to 2005 (NOAA, Chesapeake Bay Entrance #12221, 1:80,000, NOAA, Chincoteague Inlet to Great Machipongo Inlet #12210, 1:80,000, and NOAA, Cape Henry to Currituck Beach Light #12207, 1:80,000).

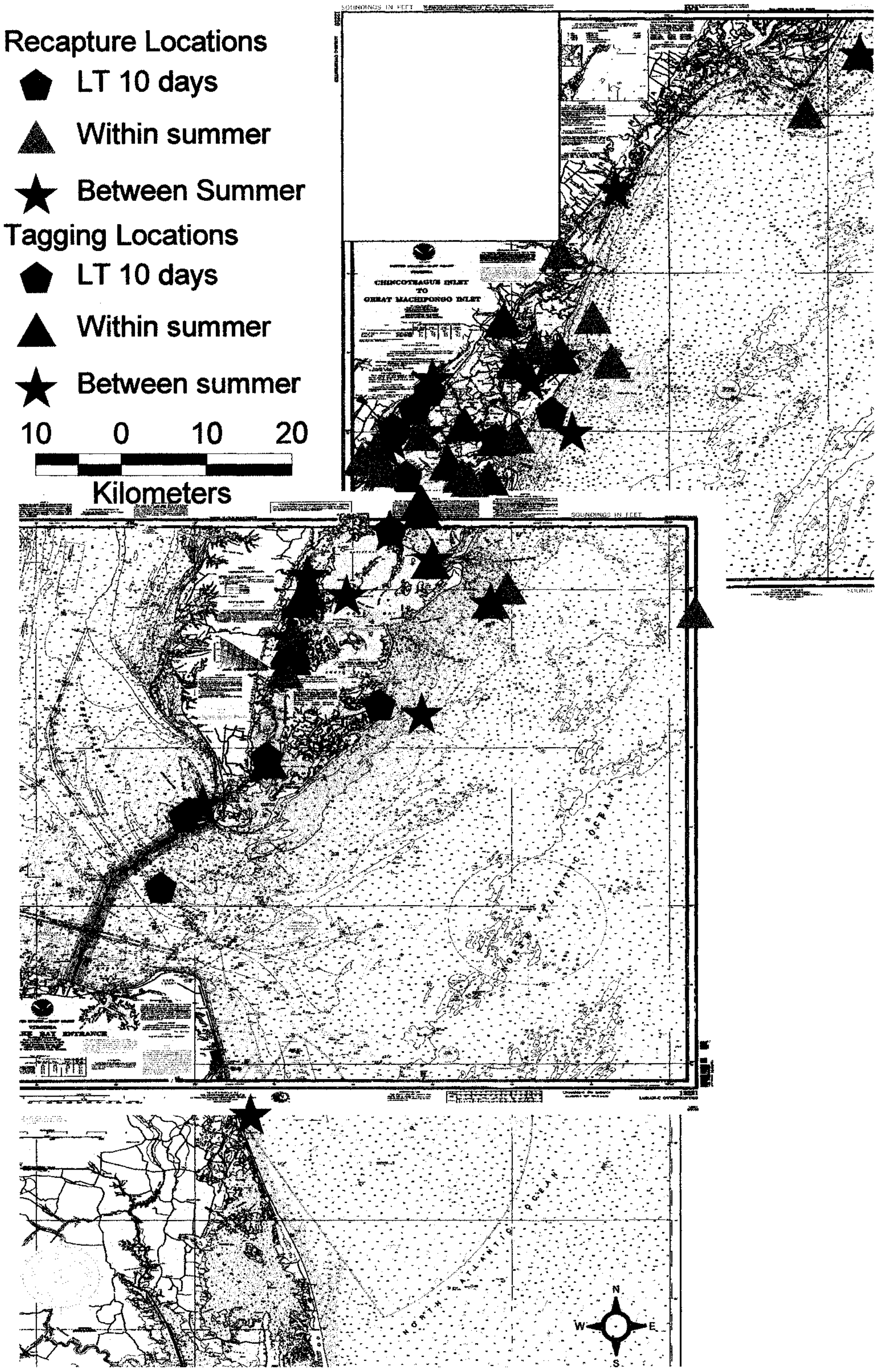

Recapture Locations
LT 10 days
Within summer
Between Summer
Tagging Locations
LT 10 days
Within summer
Between summer
10 0 10 20
Kilometers
CHINCOTEAGUE INLET TO GREAT MACHIPONGO INLET
NORTH ATLANTIC OCEAN
N
W
E
S

Table 3-1. Known locations and mortalities of sandbar sharks transmittered in 2003, during 2004 and 2005 (ES = Eastern Shore, DB = Delaware Bay, F = fishing mortality).

| # | Date | Sex | PCL | TL | 2004 | 2005 |
|---|---|---|---|---|---|---|
| 3612 | 8/7/2003 | M | 57 | 78 | | |
| 3610 | 7/10/2003 | M | 52 | 79 | ES | DB |
| 3606 | 8/7/2003 | F | 59 | 80 | | |
| 3613 | 8/4/2003 | F | 59 | 81 | ES | |
| 3603 | 8/7/2003 | F | 60 | 82 | ES | |
| 3608 | 8/4/2003 | M | 60 | 82 | DB | |
| 3591 | 8/7/2003 | F | 64 | 83 | | |
| 3600 | 8/4/2003 | F | 63 | 86 | ES | |
| 3594 | 8/7/2003 | M | 66 | 88 | DB | |
| 3589 | 8/4/2003 | M | 67 | 91 | DB | |
| 3592 | 7/9/2003 | M | 68 | 94 | | |
| 3588 | 7/10/2003 | M | 69 | 95 | | |
| 3604 | 7/9/2003 | F | 69 | 95 | ES | |
| 3586 | 7/9/2003 | F | 71 | 96 | F | |
| 3597 | 9/2/2003 | F | 71 | 96 | ES | |
| 3595 | 7/10/2003 | M | 72 | 97 | F | |
| 3605 | 7/28/2003 | M | 70 | 97 | F | |
| 3585 | 7/28/2003 | F | 73 | 99 | | |
| 3601 | 7/9/2003 | F | 72 | 99 | F | |
| 3611 | 7/28/2003 | M | 76 | 103 | ES,DB | |
| 3596 | 7/9/2003 | F | 76 | 105 | ES | |
| 3593 | 7/9/2003 | M | 76 | 106 | | |
| 3609 | 7/9/2003 | M | 77 | 106 | ES | |
| 3602 | 7/28/2003 | F | 79 | 107 | DB | DB |
| 3587 | 7/28/2003 | M | 79 | 108 | | |

Summary – 27 sharks implanted with transmitters in 2003:

67% (18) were located the following summer (2004), 33% unknown location

14.8% (4) were killed by the commercial fishery during 2004

37.1% (10) returned to Chesapeake Bay

18.5% (5) were detected in Delaware Bay

researchers. During the summer of 2005 67.6% (23 of 34 possible living) of the sharks transmittered in 2004 returned to the array on the Eastern Shore. One of these sharks also traveled to Delaware Bay (Table 3-2).

**Discussion**

The first objective of this project was to examine the effect of environmental parameters on space use. In order to do this we examined the amount of time sharks spent in areas at varying distances from the inlet. Distance from the inlet was positively correlated with increasing temperature, and decreasing dissolved oxygen, salinity, and depth (Chapter 2). These abiotic factors likely influence the number of predators present and prey available to neonate and juvenile sandbar sharks within this area. Sandbar sharks tracked in our study spent less time in the area closest to the inlet and this varied little throughout the summer months. There was a slight shift in the latest months of the summer, presumably due to animals preparing to depart the summer nursery and migrate to their overwintering grounds. Heupel et al. (2004) found that neonate blacktip sharks in Terra Ceia Bay underwent a population level expansion of home range during the month of July. Our study found no evidence of a shift or expansion of activity within the time period of their summer nursery occupation. The sharks while in each area of the array were detected less frequently during the middle of the day. This may, at least partially, be due to increased interference with acoustic signals due to boat noise which appeared to affect the reception of transmitter signals at distances from the receiver greater than 150 m. Arendt et al. (2001) reported higher rates of detection of tautog, *Tautoga onitis*, in the

Table 3-2. Known locations and mortalities of sandbar sharks transmittered in 2004, during 2004 and 2005 (ES = Eastern Shore, DB = Delaware Bay, ** denotes sharks experiencing mortality in 2004).

| # | Date | Sex | PCL | TL | 2005 |
|---|---|---|---|---|---|
| 658 | 8/3/2004 | M | 43 | 58 | |
| 670 | 8/2/2004 | M | 44 | 60 | |
| 656 | 8/3/2004 | M | 51 | 69 | |
| 3601 | 9/2/2004 | F | 54 | 72 | |
| 651 | 7/9/2004 | M | 53 | 73 | ES |
| 3598** | 6/10/2004 | M | 53 | 73 | |
| 664 | 7/8/2004 | F | 55 | 74 | |
| 3601** | 6/10/2004 | F | 54 | 74 | |
| 676 | 7/9/2004 | M | 56 | 75 | ES |
| 659 | 7/6/2004 | M | 55 | 75 | |
| 661 | 8/3/2004 | M | 56 | 76 | ES |
| 669 | 7/6/2004 | F | 56 | 76 | ES |
| 673 | 7/8/2004 | F | 56 | 77 | ES |
| 665 | 7/8/2004 | F | 58 | 78 | ES |
| 667 | 8/3/2004 | F | 57 | 78 | ES |
| 677 | 7/8/2004 | M | 57 | 78 | |
| 650 | 8/2/2004 | F | 59 | 80 | ES |
| 653 | 7/9/2004 | M | 62 | 80 | ES |
| 655 | 8/3/2004 | M | 59 | 80 | ES |
| 662 | 7/9/2004 | M | 58 | 80 | ES |
| 671 | 7/6/2004 | M | 58 | 80 | ES |
| 3595 | 6/10/2004 | M | 59 | 81 | ES |
| 3599 | 6/10/2004 | F | 59 | 81 | ES |
| 668 | 8/2/2004 | M | 60 | 82 | ES |
| 678 | 8/3/2004 | M | 61 | 82 | ES |
| 672 | 7/8/2004 | M | 60 | 82 | |
| 654 | 7/8/2004 | M | 61 | 84 | ES |
| 675 | 7/8/2004 | F | 65 | 85 | |
| 660 | 7/6/2004 | F | 59 | 86 | ES |
| 666 | 7/6/2004 | F | 63 | 86 | ES |
| 3586 | 8/30/2004 | M | 63 | 86 | |
| 674 | 8/2/2004 | F | 64 | 87 | ES |
| 3614** | 6/10/2004 | F | 69 | 92 | |
| 663 | 7/8/2004 | F | 68 | 93 | ES |
| 652 | 7/9/2004 | M | 72 | 97 | ES |
| 657 | 7/8/2004 | M | 71 | 97 | ES,DB |
| 679 | 7/6/2004 | M | 77 | 106 | |

Summary
67.6% (23) sharks survived to year 2005 and returned to the eastern shore
8.1% (3) sharks were killed during the summer of 2004

lower Chesapeake Bay during daylight hours. They propose this is due to the diurnal nature of tautog with increased activity during the day and inactivity in or near structure during the night hours. Our study found no significant correlation between space use and the daily tidal cycle. Other studies have found short-term movements of sandbar sharks related to environmental parameters but few of these studies have examined the effect of these parameters on long-term space use.

The second major objective of this project was to determine if environmental parameters affected movement patterns. Unlike the first objective listed above, here we sought to determine if small scale movements were affected by the time of day or the tidal cycle. The only strong periodicity found in the horizontal channel movements of the sharks corresponded to the daily tidal phase cycle. The sharks tended to move in the same direction as the tide if they were moving or to remain within the same location in the channel. This was somewhat counterintuitive given that tide did not appear to affect where the sharks occurred in the nursery area. Due to the strength of the tidal currents within this area it is likely energetically costly to move against the tidal currents. Manual tracking studies of juvenile sandbar sharks in temperate Atlantic estuaries also found movements to be correlated with the tidal cycle and not correlated to the diurnal cycle. Medved and Marshall (1983) tracked 23 sandbar sharks in Chincoteague inlet, 20 with tethered floats and three with acoustic transmitters. It was found that the pattern of movement was predominantly in the direction of the tidal currents. There was no evidence that time of day, monthly tidal cycle, sex, or size affected movement patterns. Wetherbee et al. (2001) tracked twenty-five juvenile sandbar sharks in Delaware Bay for periods ranging from 2.5

hours to 75 hours. It was also found that there was evidence that the movements of the sharks they tracked were highly correlated with tidal currents and that the repeatability of movements was associated with this physical parameter. Grubbs (2001) tracked ten sandbar sharks for periods of time ranging from 10 to 50 hours in Chesapeake Bay and found that swimming direction was correlated with mean tidal direction.

In contrast to horizontal movements, vertical movements of juvenile sandbar sharks within the Eastern Shore of Virginia nursery appear to exhibit a diurnal periodicity. Sharks occupied a shallower mean depth of occurrence during the night to early morning hours and occupied a deeper mean depth of occurrence during the day to early night periods. However it should be noted that these animals occurred in very shallow coastal waters and this behavior may reflect increased activity and use of the entire water column during the night hours more than a shift into shallower waters during this period. Many shark species have been shown to be more active at night than during the day (McKibben and Nelson 1986, Ackerman et al. 2000, Nelson and Johnson 1970). Sims et al. (2001) found that male small spotted catsharks exhibited a similar pattern being more active during the day and occupying a mean depth of 12 to 24 m and being less activity at night and occupying a mean depth of less than 4 m. Grubbs (2001) also found that juvenile sandbar sharks manually tracked in Chesapeake Bay also had a significantly deeper mean swimming depth during the daytime hours (12.8 m) than during the nighttime hours (8.5 m). The two sharks in this study occupied depths ranging from 1.8 to 7.1 m and were likely remaining in deeper waters and exhibiting less activity in the daylight hours.

Previous manual tracking studies of sandbar sharks in the western North Atlantic have found that these animals have extremely large activity spaces. Wetherbee et al. (2001) estimated activity space using minimum convex polygons and grid-square analysis. The activity space and movement patterns differed depending on the location of capture. On the Delaware side of Delaware Bay the average activity space was 45 +\- 52 $km^2$ and on the New Jersey side of Delaware Bay the average activity space was 108 +\- 125 $km^2$. Grubbs (2001) estimated activity spaces using minimum convex polygons and kernel activity spaces. It was estimated that mean activity space was 110 $km^2$. The large activity spaces of these sharks combined with the logistical difficulties of tracking make determining if these animals occupy a home range problematic.

Our data suggests that these animals did exhibit some site attachment to certain areas within their summer nurseries. However our data further suggests that these animals were highly active and while they appeared to exhibit some site fidelity, we found no evidence that they occupied a consistent and regular home range, particularly at larger juvenile sizes. A larger array or greater period of time (probably at least weeks) manually tracking these animals may elucidate a more consistent pattern of space occupation. Rechisky and Wetherbee (2003) found that sandbar sharks manually tracked in Delaware Bay also had movement patterns ranging from nomadic to home-ranging. It was suggested that these sharks exhibit site attachment to some extent but are capable of making longer excursions across Delaware Bay. This is in contrast to shark species that have been shown to exhibit small home ranges and strong site fidelity to home ranges or core areas like juvenile lemon sharks in the

Bahamas and juvenile scalloped hammerheads in Hawaii (Morrissey and Gruber 1993, Holland et al. 1993).

The last objective of the study was to determine if age affects residency time. We found that younger animals tended to remain within the constricted array area for a greater period on both the hour and day time scale. This indicates young animals may either have an increased attachment to certain areas within the nursery and or that these animals are occupying a smaller amount of space than the larger older juveniles. Morrissey and Gruber (1993) similarly found lemon shark activity space was positively correlated to shark size. Ackerman et al. (2000) also found that longer leopard sharks had greater movement rates. This is in contrast to results of the manual tracking study conducted by Rechisky and Wetherbee (2003) which found no correlations between the length of the shark and activity space in sandbar sharks tracked in Delaware Bay. Some shark species may exhibit the opposite pattern of decreasing activity space with increasing shark size. Goldman and Anderson (1999) suggested that larger white sharks, *Carcharadon carcharias*, have smaller activity spaces.

Many shark species have been shown to exhibit homing or philopatry. Gerking (1982) defines homing as 'a choice that a fish makes between returning to a place formerly occupied instead of going to equally probable places.' Philopatry is more generally defined as the tendency to return to or stay in a home area, natal site, or another adopted locality (Mayr 1963). The tendency of sharks to exhibit this behavior may make them vulnerable to localized depletion due to fishing pressure. If a population of sharks is decimated in a specific area it will take longer for this area to repopulate as this process will be dependent on animals straying from other locations (Hueter et al. 2005). Species known to exhibit philopatric behavior to some extent include the small spotted catshark, *Scyliorhinus canicula*, the lemon shark, *Negaprion brevirostris*, the sandbar shark, the blacknose shark, *Carcharhinus acronotus*, and the blacktip shark, *Carcharhinus limbatus* (Sims et al. 2001, Sundstrom et al. 2001, Grubbs et al. in press, Hueter et al. 2003). Edren and Gruber (2005) found that 81% of 32 lemon sharks in the Bahamas displaced four to 16 km from their observed home range returned to the area they were observed in before displacement, indicating these animals had the ability to home to a specific area. Our study found sharks to be philopatric to the very small area covered by the acoustic array with 33% of sharks transmittered in 2003 returning the subsequent summer and 67% of sharks transmittered in 2004 returning the subsequent summer. Considering the array covered only a portion of the Eastern Shore lagoons philopatry to this nursery area was probably higher than we have reported and philopatry to Virginia waters would presumably be higher than that. Clearly the scale of interest (lagoon, bay, state waters, etc.) will affect the proportion of animals that are determined to exhibit philopatry.

The use of passive telemetry techniques may allow researches to estimate mortality and or survivorship based on the known fates of fish. Mortality is a difficult parameter to estimate and is essential for modeling fish populations. Manire and Gruber (1993) estimated young of the year mortality for neonate lemon sharks in an enclosed lagoon in the Bahamas by intensive sampling and found that annual mortality was between 41 to 64%. Heupel and Simpfendorfer (2002) estimated the mortality of neonate blacktip sharks within the Terra Ceia Bay nursery area. Natural mortality and removals of the sharks were determined by the movement pattern of the shark/transmitter. It was estimated that mortality was 61 to 92% during the six months the sharks remained within the nursery area. We predominantly tracked larger individuals and did not identify any animals experiencing mortality throughout the tracking period. However we did learn about the fates of a significant number of our sharks in subsequent years. It was determined that at least 67% of the sharks that were tracked during the summers of 2003 and 2004 survived until the following summer. This must be considered a minimum estimate of survivorship as some sharks likely survived the winter to stray into other nursery areas or coastal areas and were not detected by our array. As a minimum estimate of survivorship this value may not be particularly useful but it does put one boundary on survivorship and does point to the fact that with future collaboration, reasonable estimates of mortality and philopatry could be achieved.

# CONCLUSIONS

The results from this project stress the importance of two areas of the habitat of the western North Atlantic population of sandbar sharks, the juvenile overwintering area that occurs off the central coast of North Carolina, and the Eastern Shore of Virginia summer nursery area. All aspects of this study were initiated from the Eastern Shore of Virginia coastal bays and lagoons and this area potentially represents a location in which studies of long term site fidelity, natal homing, mortality and other important population parameters could be initiated. In addition, this is a unique location with a wide range of ages of juvenile sandbar sharks present that provides the opportunity to study how different age and size classes use this nursery area.

*North Carolina overwintering area*

The movements of large juvenile sandbar sharks tagged with satellite transmitters support the size and scope of the closed area off of North Carolina enacted in the winter months by Amendment 1 to the NMFS Fishery Management Plan for Tunas, Swordfish, and Sharks. The fishery independent data from this project support the conclusions drawn from tagging studies about the high concentration of juvenile sandbar sharks found within close proximity of the outer banks of North Carolina from Cape Hatteras to Cape Lookout. It appears that the juveniles of this population have a more constricted distribution in the winter months, which may make this population vulnerable to overfishing during this time period. It further appears that this closed area does encompass the areas off the coast of North Carolina with the highest abundance of neonate and juvenile sandbar sharks. The closed area encompasses six of the seven transmitter pop-off locations for this species and all but one of the winter juvenile sandbar shark tag returns reported in Grubbs et al (in press).

*Eastern Shore summer nursery*

The Eastern Shore of Virginia's coastal bays and lagoons function as important pupping, primary, and secondary nursery grounds for the western North Atlantic population of sandbar sharks. Pupping has been shown to occur in relatively high abundance in Great Machipongo Inlet in particular. The presence of neonates throughout the study site indicates that pupping likely occurs throughout this area, but is particularly concentrated in the southern inlets, Great Machipongo and Sand Shoal Inlet. In addition, the presence of neonates indicates that the area is a primary nursery ground for these animals likely throughout the summer until the fall migration of these animals to their overwintering area. The area appears to act as a secondary nursery for juveniles for several year classes, with a large size range of juveniles present within the nursery area. Both Chesapeake and Delaware Bays have been identified as Habitat Areas of Particular Concern for this species by the 2003 Amendment 1 to the FMP. This area has a comparable abundance of neonate and juvenile sharks, is vulnerable to coastal degradation and habitat loss, and should be included in future management measures as a HAPC.

Acoustic data indicates that neonate and juvenile sandbar sharks experience some fidelity to the Eastern Shore of Virginia bays and lagoons, with animals both tending to remain within the area more than would be expected based on random movements alone and to return to the area in the following summers. During 2005, 67% of the animals tracked in 2004 returned to the array indicating relatively high site fidelity. It is impossible to determine how many of the remaining 33% of the animals experienced mortality and how many spent the summer in a different location, but likely both of these events occurred to some degree. In 2004, only 33% of the animals transmittered in 2003 returned to the array. An additional 13.5% were caught and killed by commercial fishermen and 14.8% were detected in more northern localities. A larger percentage of animals tracked in 2003 were not detected within the array. More animals appear to have traveled northward in subsequent years and more were known to have been killed by commercial fishermen. The animals tracked in 2003 had a mean total length 20 cm larger than 2004 and this larger size may explain why fewer animals returned to the array during 2004. It appears the larger animals were more likely to move into Delaware Bay and be recorded on receivers placed in Delaware by other researchers and these animals likely spent more time offshore increasing their vulnerability to commercial fisheries.

Both the acoustic data and the longline catch data indicate there were differences in the use of the nursery area as animals age and increase in size. The largest size classes of these animals were most abundant in middle or outer regions of the study area. The largest size classes also were resident within the acoustic array for the shortest periods of time. These animals appear to have extremely large activity spaces and it appears as size increases activity size also increases. The increase of abundance of small juveniles farthest from the inlets may be a predator avoidance tactic. There is no obvious physiological barrier to prevent larger predatory sharks from entering this nursery area. This study emphasizes the need to consider that separate size classes of the same population of animals may exhibit different behavior patterns with respect to movement and habitat use.

Additional studies of sandbar sharks within this area may be able to elucidate patterns on site fidelity, mortality, and other important parameters for future management efforts.

Appendix 1: Distance from the inlet, set depth, water quality measurements, and tidal flow direction and phase for longline sampling sets during the summers of 2003 and 2004 (St. = start, E. = end, S = surface and B = bottom).

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20030602 | 2.8 | 37 37.008 | 75 36.493 | 4.3 | 5.5 | 15.2 | 14.9 | 29.8 | 29.9 | 7.35 | 7.23 | High | Flood |
| 20030602 | 6.1 | 37 37.135 | 75 40.406 | 2.4 | 2.6 | 17.4 | 17.0 | 26.8 | 27.8 | 6.43 | 6.65 | High | Ebb |
| 20030602 | 2.4 | 37 33.231 | 75 33.448 | 5.1 | 8.5 | 18.4 | 18.0 | 28.6 | 28.7 | 7.04 | 6.81 | Low | Ebb |
| 20030602 | 2.0 | 37 34.852 | 75 39.139 | 5.6 | 8.0 | 18.3 | 18.5 | 28.6 | 28.6 | 7.06 | 7.11 | Low | Flood |
| 20030603 | 1.3 | 37 27.230 | 75 40.894 | 9.7 | 13.7 | 16.7 | 16.2 | 29.7 | 29.8 | 6.94 | 7.00 | High | Ebb |
| 20030603 | 4.1 | 37 28.259 | 75 44.340 | 5.6 | 8.2 | 17.4 | 17.2 | 29.4 | 29.4 | 6.74 | 6.68 | High | Flood |
| 20030603 | 1.6 | 37 29.618 | 75 41.111 | 5.7 | 6.7 | 17.9 | 17.6 | 29.5 | 29.6 | 6.54 | 6.57 | Low | Ebb |
| 20030603 | 3.7 | 37 30.971 | 75 43.087 | 3.5 | 6.5 | 18.5 | 18.4 | 29.2 | 29.5 | 6.44 | 6.62 | Low | Flood |
| 20030604 | 4.4 | 37 25.589 | 75 45.737 | 7.4 | 8.3 | 18.3 | 17.6 | 29.0 | 29.4 | 6.60 | 6.52 | High | Flood |
| 20030604 | 6.0 | 37 27.149 | 75 46.610 | 7.4 | 11.2 | 18.5 | 18.3 | 28.9 | 29.0 | 6.34 | 6.32 | High | Ebb |
| 20030604 | 12.0 | 37 31.318 | 75 46.229 | 4.2 | 7.1 | 19.8 | 19.6 | 24.4 | 24.8 | 5.80 | 5.63 | Low | Ebb |
| 20030604 | 9.6 | 37 29.429 | 75 47.547 | 6.9 | 8.4 | 19.7 | 19.6 | 25.6 | 25.7 | 5.67 | 5.61 | Low | Flood |
| 20030605 | 1.4 | 37 21.713 | 75 45.095 | 9.2 | 10.8 | 15.0 | 14.8 | 30.6 | 30.6 | 7.18 | 7.12 | High | Ebb |
| 20030605 | 4.5 | 37 23.771 | 75 47.735 | 5.9 | 6.2 | 19.6 | 18.9 | 29.0 | 29.2 | 6.53 | 6.52 | High | Flood |
| 20030605 | 9.1 | 37 21.379 | 75 52.869 | 1.6 | 3.2 | 19.9 | 19.7 | 29.2 | 29.1 | 5.82 | 4.82 | Low | Flood |
| 20030605 | 7.4 | 37 19.209 | 75 53.381 | 4.9 | 10.2 | 19.9 | 19.7 | 29.2 | 29.3 | 5.88 | 5.86 | Low | Ebb |
| 20030611 | 2.4 | 37 17.823 | 75 50.963 | 14.2 | 15.1 | 20.3 | 21.0 | 30.0 | 30.0 | 6.67 | 6.66 | High | Flood |
| 20030611 | 6.5 | 37 15.871 | 75 53.859 | 7.5 | 8.7 | 21.7 | 21.6 | 29.6 | 29.6 | 5.86 | 5.87 | High | Ebb |
| 20030611 | 3.2 | 37 08.833 | 75 55.242 | 5.0 | 6.1 | 23.0 | 22.8 | 28.9 | 29.1 | 5.90 | 5.62 | Low | Ebb |
| 20030611 | 7.7 | 37 13.057 | 75 55.489 | 3.0 | 5.1 | 23.1 | 23.1 | 29.2 | 29.2 | 5.38 | 5.37 | Low | Flood |
| 20030627 | 2.8 | 37 37.043 | 75 38.693 | 6.9 | 9.0 | 29.3 | 28.4 | 29.7 | 29.7 | 6.41 | 5.54 | Low | Flood |
| 20030627 | 6.1 | 37 37.043 | 75 40.456 | 2.4 | 2.7 | 30.5 | 30.3 | 27.2 | 27.5 | 7.68 | 7.25 | Low | Ebb |
| 20030701 | 4.4 | 37 25.014 | 75 45.656 | 7.9 | 8.8 | 28.2 | 27.7 | 30.4 | 30.3 | 5.59 | 5.20 | low | Ebb |
| 20030701 | 9.6 | 37 29.055 | 75 47.991 | 8.0 | 8.9 | 27.9 | 27.9 | 30.0 | 30.0 | 4.86 | 4.84 | High | Ebb |
| 20030701 | 12.0 | 37 30.950 | 75 46.585 | 5.5 | 7.5 | 28.3 | 28.3 | 27.7 | 28.1 | 4.30 | 4.25 | High | Flood |
| 20030701 | 6.0 | 37 26.727 | 75 46.327 | 6.0 | 9.4 | 28.7 | 28.6 | 28.7 | 28.6 | 6.34 | 6.38 | low | Flood |
| 20030702 | 1.4 | 37 21.729 | 75 45.122 | 9.8 | 11.9 | 26.4 | 26.2 | 30.1 | 30.2 | 5.54 | 5.54 | low | Ebb |
| 20030702 | 4.5 | 37 23.768 | 75 48.244 | 4.3 | 5.7 | 26.7 | 26.7 | 31.0 | 31.0 | 4.39 | 4.42 | low | Flood |
| 20030702 | 7.4 | 37 19.7 | 75 53.378 | 6.6 | 6.9 | 27.0 | 27.0 | 30.6 | 30.6 | 4.77 | 4.73 | High | Flood |
| 20030702 | 9.1 | 37 20.870 | 75 52.939 | 3.4 | 6.0 | 27.1 | 27.1 | 30.6 | 30.7 | 4.45 | 4.45 | High | Ebb |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20030703 | 3.2 | 37 08.892 | 75 55.249 | 5.7 | 6.1 | 24.9 | 24.8 | 28.7 | 29.0 | 5.31 | 5.20 | High | Ebb |
| 20030703 | 7.7 | 37 13.638 | 75 55.354 | 3.7 | 6.6 | 25.1 | 25.0 | 30.7 | 30.6 | 5.12 | 5.05 | High | Flood |
| 20030703 | 6.5 | 37 16.305 | 75 53.861 | 8.6 | 8.9 | 26.2 | 25.8 | 30.6 | 30.6 | 5.51 | 5.22 | low | Ebb |
| 20030703 | 2.4 | 37 17.845 | 75 50.808 | 9.6 | 10.5 | 26.4 | 26.4 | 30.5 | 30.5 | 5.15 | 5.15 | low | Flood |
| 20030708 | 1.6 | 37 29.460 | 75 41.138 | 6.0 | 6.2 | 20.8 | 20.3 | 29.8 | 29.7 | 7.17 | 7.05 | High | Flood |
| 20030708 | 3.7 | 37 30.534 | 75 43.090 | 6.1 | 8.0 | 21.7 | 21.7 | 29.9 | 29.8 | 5.82 | 5.78 | High | Ebb |
| 20030708 | 1.3 | 37 27.052 | 75 41.436 | 6.9 | 11.6 | 27.1 | 27.1 | 30.3 | 30.3 | 4.43 | 4.46 | Low | Flood |
| 20030708 | 4.1 | 37 27.815 | 75 43.952 | 7.8 | 8.2 | 27.8 | 27.8 | 30.3 | 30.3 | 5.12 | 5.04 | Low | Ebb |
| 20030709 | 2.0 | 37 35.216 | 75 38.437 | 6.8 | 7.2 | 19.6 | 19.2 | 29.5 | 29.5 | 5.79 | 5.69 | High | Ebb |
| 20030709 | 2.4 | 37 33.163 | 75 38.898 | 6.8 | 9.4 | 20.2 | 20.0 | 29.6 | 29.6 | 6.61 | 6.40 | High | Flood |
| 20030729 | 1.3 | 37 27.034 | 75 41.380 | 6.4 | 6.5 | 16.1 | 13.8 | 32.7 | 32.6 | 5.87 | 5.98 | High | Ebb |
| 20030729 | 1.6 | 37 29.144 | 75 40.713 | 6.4 | 7.1 | 23.7 | 20.8 | 32.3 | 32.4 | 6.46 | 6.72 | Low | Ebb |
| 20030729 | 4.1 | 37 27.929 | 75 44.077 | 4.9 | 9.1 | 23.0 | 23.0 | 32.1 | 32.1 | 6.31 | 6.16 | High | Flood |
| 20030729 | 3.7 | 37 30.458 | 75 42.986 | 3.5 | 10.8 | 24.6 | 24.6 | 32.3 | 32.3 | 6.74 | 6.63 | Low | Flood |
| 20030730 | 2.4 | 37 17.904 | 75 50.157 | 6.6 | 9.6 | 20.1 | 18.8 | 31.7 | 31.9 | 5.12 | 5.20 | High | Ebb |
| 20030730 | 6.5 | 37 15.536 | 75 53.848 | 8.2 | 8.6 | 22.4 | 22.4 | 31.5 | 31.5 | 6.21 | 5.97 | High | Flood |
| 20030731 | 2.8 | 37 36.604 | 75 38.672 | 5.6 | 7.9 | 19.6 | 19.5 | 31.5 | 31.5 | 5.19 | 5.19 | High | Ebb |
| 20030731 | 6.1 | 37 37.156 | 75 40.445 | 2.2 | 3.4 | 22.3 | 22.3 | 29.7 | 29.8 | 4.78 | 4.81 | High | Flood |
| 20030731 | 2.4 | 37 33.467 | 75 38.467 | 7.4 | 8.0 | 23.0 | 22.8 | 31.1 | 31.2 | 6.29 | 6.11 | Low | Ebb |
| 20030731 | 2.0 | 37 34.888 | 75 39.044 | 6.0 | 7.9 | 23.4 | 23.1 | 31.4 | 31.4 | 4.69 | 4.74 | Low | Flood |
| 20030805 | 4.4 | 37 25.587 | 75 45.747 | 6.9 | 6.7 | 24.1 | 22.7 | 30.4 | 30.8 | 6.75 | 5.86 | High | Flood |
| 20030805 | 6.0 | 37 26.983 | 75 46.560 | 7.0 | 8.7 | 26.0 | 24.3 | 29.7 | 30.1 | 4.61 | 4.57 | High | Ebb |
| 20030805 | 12.0 | 37 31.393 | 75 46.157 | 7.0 | 4.4 | 27.8 | 27.8 | 27.4 | 27.4 | 4.88 | 4.84 | Low | Ebb |
| 20030805 | 9.6 | 37 29.556 | 75 47.557 | 6.4 | 8.3 | 27.9 | 28.0 | 26.6 | 26.8 | 4.39 | 4.54 | Low | Flood |
| 20030806 | 1.4 | 37 21.956 | 75 45.441 | 12.4 | 7.7 | 16.4 | 15.8 | 32.4 | 32.1 | 6.84 | 6.23 | High | Flood |
| 20030806 | 4.5 | 37 23.781 | 75 47.656 | 6.3 | 6.6 | 24.8 | 22.7 | 30.0 | 30.8 | 5.20 | 4.90 | High | Flood |
| 20030806 | 9.1 | 37 21.385 | 75 52.882 | 4.2 | 4.1 | 24.9 | 25.2 | 29.5 | 29.8 | 4.63 | 4.77 | Low | Flood |
| 20030806 | 7.4 | 37 19.685 | 75 53.367 | 9.3 | 6.4 | 25.4 | 25.4 | 30.1 | 30.2 | 5.55 | 5.51 | Low | Ebb |
| 20030808 | 7.7 | 37 13.547 | 75 55.372 | 5.1 | 4.6 | 25.3 | 25.3 | 29.6 | 29.7 | 4.95 | 4.90 | Low | Ebb |
| 20030808 | 3.2 | 37 09.270 | 75 55.423 | 6.8 | 4.6 | 25.9 | 25.6 | 29.7 | 29.7 | 4.21 | 4.24 | Low | Flood |
| 20030825 | 1.4 | 37 21.720 | 75 45.014 | 11.6 | 10.2 | 23.9 | 23.1 | 31.1 | 31.5 | 5.56 | 5.61 | Low | Ebb |
| 20030825 | 7.4 | 37 19.797 | 75 53.378 | 5.4 | 11.4 | 24.4 | 24.4 | 31.6 | 31.6 | 4.63 | 4.61 | High | Flood |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20030825 | 4.5 | 37 23.79 | 75 47.64 | 4.8 | 4.2 | 24.8 | 24.7 | 30.1 | 30.2 | 4.95 | 4.90 | Low | Flood |
| 20030825 | 9.1 | 37 20.891 | 75 52.919 | 4.7 | 2.8 | 24.8 | 24.8 | 31.4 | 31.4 | 4.71 | 4.71 | High | Ebb |
| 20030828 | 3.2 | 37 08.847 | 75 55.235 | 5.8 | 6.8 | 26.6 | 25.6 | 30.3 | 31.1 | 4.77 | 4.86 | High | Ebb |
| 20030828 | 2.4 | 37 17.842 | 75 50.877 | 10.9 | 11.7 | 27.3 | 26.3 | 31.8 | 31.9 | 4.98 | 4.79 | Low | Flood |
| 20030828 | 7.7 | 37 13.496 | 75 55.416 | 5.4 | 5.6 | 26.4 | 26.4 | 31.7 | 31.7 | 4.13 | 4.10 | High | Flood |
| 20030828 | 6.5 | 37 16.270 | 75 53.860 | 9.0 | 8.0 | 26.8 | 26.5 | 31.9 | 31.9 | 4.55 | 4.48 | Low | Ebb |
| 20030829 | 2.4 | 37 33.455 | 75 38.281 | 8.6 | 8.4 | 22.4 | 22.3 | 31.7 | 31.8 | 5.59 | 5.64 | High | Flood |
| 20030829 | 2.0 | 37 35.229 | 75 38.493 | 7.0 | 7.8 | 22.5 | 22.4 | 31.7 | 31.7 | 5.96 | 5.99 | High | Ebb |
| 20030829 | 2.8 | 37 36.984 | 75 38.689 | 7.8 | 6.3 | 27.6 | 27.4 | 31.6 | 31.6 | 4.62 | 4.65 | Low | Ebb |
| 20030829 | 6.1 | 37 37.644 | 75 40.690 | 2.8 | 1.4 | 30.4 | 30.4 | 29.5 | 29.5 | 3.39 | 3.38 | Low | Flood |
| 20030903 | 4.4 | 37 25.496 | 75 45.709 | 9.1 | 8.4 | 26.2 | 26.2 | 31.3 | 31.4 | 4.68 | 4.69 | Low | Ebb |
| 20030903 | 6.0 | 37 27.030 | 75 46.540 | 6.7 | 8.7 | 26.7 | 26.6 | 30.9 | 31.0 | 4.28 | 4.31 | Low | Flood |
| 20030903 | 9.6 | 37 29.468 | 75 47.541 | 8.8 | 10.3 | 27.1 | 27.0 | 30.9 | 30.9 | 4.43 | 4.33 | High | Flood |
| 20030903 | 12.0 | 37 31.415 | 75 46.190 | 5.8 | 5.9 | 28.0 | 28.0 | 29.6 | 29.5 | 4.11 | 4.10 | High | Flood |
| 20030904 | 1.6 | 37 29.607 | 75 41.096 | 7.3 | 11.7 | 24.5 | 22.0 | 31.5 | 31.6 | 5.70 | 5.96 | High | Flood |
| 20030904 | 3.7 | 37 30.965 | 75 43.099 | 3.8 | 8.4 | 24.7 | 24.8 | 31.5 | 31.5 | 5.26 | 5.26 | High | Ebb |
| 20030904 | 1.3 | 37 27.242 | 75 40.896 | 9.6 | 13.4 | 25.5 | 25.5 | 31.3 | 31.4 | 4.37 | 4.36 | Low | Flood |
| 20030904 | 4.1 | 37 27.242 | 75 44.063 | 6.1 | 4.0 | 25.8 | 25.7 | 31.3 | 31.4 | 4.42 | 4.50 | Low | Ebb |
| 20030929 | 2.8 | 37 36.665 | 75 38.672 | 8.4 | 8.1 | 22.6 | 22.6 | 31.3 | 31.3 | 5.35 | 5.32 | High | Ebb |
| 20030929 | 6.1 | 37 37.644 | 75 40.437 | 2.3 | 1.7 | 23.0 | 23.0 | 30.1 | 30.1 | 4.12 | 3.51 | High | Flood |
| 20030929 | 2.0 | 37 34.890 | 75 39.044 | 7.9 | 5.6 | 23.1 | 23.2 | 31.2 | 31.2 | 5.57 | 5.60 | Low | Flood |
| 20030929 | 2.4 | 37 33.443 | 75 38.364 | 11.0 | 7.5 | 23.4 | 23.5 | 31.0 | 31.0 | 5.38 | 5.50 | Low | Ebb |
| 20030930 | 4.4 | 37 25.026 | 75 45.684 | 7.7 | 5.8 | 21.5 | 21.5 | 30.9 | 30.9 | 5.79 | 5.48 | High | Flood |
| 20030930 | 6.0 | 37 26.395 | 75 46.045 | 9.1 | 8.7 | 21.5 | 21.5 | 30.9 | 30.9 | 5.63 | 5.61 | High | Ebb |
| 20030930 | 12.0 | 37 31.003 | 75 46.593 | 7.0 | 4.7 | 22.9 | 22.9 | 27.1 | 27.2 | 4.25 | 4.23 | Low | Ebb |
| 20030930 | 9.6 | 37 29.093 | 75 47.930 | 8.1 | 7.2 | 23.1 | 23.2 | 28.2 | 28.2 | 4.35 | 4.34 | Low | Flood |
| 20031001 | 3.7 | 37 30.952 | 75 43.163 | 2.0 | 6.1 | 20.2 | 20.2 | 31.2 | 31.2 | 5.74 | 5.62 | Low | Flood |
| 20031001 | 1.6 | 37 29.423 | 75 40.882 | 10.2 | 6.7 | 20.4 | 20.4 | 31.4 | 31.4 | 5.52 | 5.39 | Low | Flood |
| 20031001 | 4.1 | 37 27.846 | 75 43.898 | 5.9 | 7.5 | 20.9 | 20.9 | 31.4 | 31.4 | 5.77 | 5.73 | High | Ebb |
| 20031001 | 1.3 | 37 27.195 | 75 40.92 | 5.9 | 10.5 | 21.3 | 21.3 | 31.1 | 31.2 | 6.18 | 6.01 | High | Flood |
| 20031002 | 9.1 | 37 20.862 | 75 52.930 | 3.7 | 1.8 | 19.3 | 19.3 | 30.9 | 30.9 | 5.56 | 5.56 | Low | Flood |
| 20031002 | 4.5 | 37 23.766 | 75 47.704 | 5.9 | 2.7 | 20.1 | 20.0 | 30.8 | 30.7 | 6.44 | 6.47 | High | Flood |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20031002 | 7.4 | 37 19.241 | 75 53.323 | 8.3 | 5.2 | 20.4 | 20.2 | 30.8 | 30.9 | 5.82 | 6.11 | Low | Ebb |
| 20031002 | 1.4 | 37 21.975 | 75 45.515 | 7.5 | 6.4 | 20.5 | 20.5 | 30.7 | 30.7 | 6.56 | 6.75 | High | Flood |
| 20031020 | 4.4 | 37 24.461 | 75 45.650 | 8.4 | 7.5 | 16.3 | 16.2 | 31.2 | 31.2 | 5.82 | 5.85 | Low | Flood |
| 20031020 | 6.0 | 37 26.987 | 75 46.580 | 5.2 | 5.6 | 16.4 | 16.3 | 31.1 | 31.1 | 5.63 | 5.63 | Low | Flood |
| 20031020 | 9.6 | 37 29.449 | 75 47.538 | 7.2 | 6.3 | 17.2 | 16.8 | 31.1 | 31.1 | 6.24 | 6.00 | High | Flood |
| 20031020 | 12.0 | 37 30.995 | 75 46.631 | 5.1 | 6.6 | 17.6 | 17.6 | 30.2 | 30.2 | 5.54 | 5.52 | High | Ebb |
| 20031021 | 6.1 | 37 37.645 | 75 40.686 | 5.0 | 1.0 | 15.8 | 15.8 | 29.3 | 29.2 | 5.64 | 5.64 | High | Flood |
| 20031021 | 2.8 | 37 37.011 | 75 38.697 | 7.7 | 6.5 | 16.3 | 16.3 | 31.3 | 31.5 | 5.90 | 5.96 | High | Ebb |
| 20031021 | 2.0 | 37 35.185 | 75 38.584 | 5.6 | 6.6 | 17.0 | 17.0 | 31.5 | 31.5 | 5.80 | 5.75 | Low | Ebb |
| 20031021 | 2.4 | 37 33.444 | 75 38.346 | 10.0 | 7.3 | 17.4 | 17.3 | 31.4 | 31.5 | 5.85 | 5.82 | Low | Ebb |
| 20031022 | 4.1 | 37 27.826 | 75 43.886 | 6.2 | 6.6 | 16.8 | 16.8 | 31.3 | 31.4 | 5.56 | 5.52 | Low | Flood |
| 20031022 | 1.3 | 37 27.186 | ??? | 10.5 | 10.5 | 16.9 | 16.9 | 31.3 | 31.3 | 5.29 | 5.29 | Low | Ebb |
| 20031022 | 3.7 | 37 30.473 | 75 43.038 | 8.7 | 2.5 | 17.3 | 17.3 | 31.2 | 31.2 | 5.77 | 5.75 | High | Ebb |
| 20031022 | 1.6 | 37 29.25 | 75 40.672 | 6.8 | 7.4 | 17.8 | 17.7 | 30.7 | 30.9 | 5.66 | 5.65 | High | Ebb |
| 20031028 | 4.5 | 37 23.760 | 75 47.707 | 6.0 | 4.7 | 15.9 | 15.9 | 30.8 | 30.8 | 5.97 | 5.97 | High | Ebb |
| 20031028 | 1.4 | 37 21.966 | 75 45.483 | 11.4 | 5.4 | 16.0 | 16.0 | 30.8 | 30.8 | 5.99 | 5.97 | High | Flood |
| 20040504 | 2.8 | 37 36.596 | 75 38.656 | 7.8 | 5.1 | 13.6 | 13.1 | 32.2 | 32.3 | 4.48 | 4.59 | High | Flood |
| 20040504 | 6.1 | 37 37.135 | 75 40.419 | 2.2 | 4.1 | 15.5 | 15.5 | 31.0 | 31.1 | 3.59 | 3.60 | High | Ebb |
| 20040504 | 2.0 | 37 35.208 | 75 38.510 | 7.3 | 6.8 | 15.6 | 15.6 | 31.9 | 31.9 | 4.53 | 4.53 | Low | Ebb |
| 20040504 | 2.4 | 37 33.238 | 75 38.834 | 6.3 | 5.7 | 15.7 | 15.7 | 32.0 | 32.0 | 4.51 | 4.49 | Low | Flood |
| 20040505 | 7.4 | 37 19.685 | 75 53.367 | 5.2 | 6.3 | 15.1 | 15.1 | 31.5 | 31.4 | 4.77 | 4.25 | High | Flood |
| 20040505 | 9.1 | 37 20.862 | 75 52.930 | 4.2 | 3.0 | 15.2 | 15.3 | 31.4 | 31.4 | 4.23 | 4.21 | High | Ebb |
| 20040506 | 1.3 | 37 26.995 | 75 41.530 | 9.9 | 8.4 | 13.6 | 13.0 | 32.2 | 32.2 | 4.64 | 4.68 | High | Ebb |
| 20040506 | 4.1 | 37 27.891 | 75 44.041 | 3.6 | 8.8 | 14.9 | 14.9 | 32.2 | 32.1 | 4.42 | 4.39 | High | Flood |
| 20040506 | 1.6 | 37 29.064 | 75 40.647 | 6.0 | 10.9 | 16.3 | 14.9 | 32.3 | 32.2 | 4.72 | 4.74 | Low | Ebb |
| 20040506 | 3.7 | 37 30.912 | 75 43.098 | 4.0 | 6.2 | 17.0 | 16.6 | 32.1 | 32.1 | 4.38 | 4.44 | Low | Flood |
| 20040511 | 4.4 | 37 25.570 | 75 45.734 | 7.7 | 6.0 | 19.8 | 19.5 | 31.9 | 31.9 | 8.97 | 8.85 | High | Flood |
| 20040511 | 6.0 | 37 27.188 | 75 46.676 | 8.8 | 6.8 | 20.3 | 20.1 | 31.9 | 31.9 | 8.43 | 8.36 | High | Ebb |
| 20040511 | 9.6 | 37 29.482 | 75 47.548 | 8.1 | 7.9 | 22.1 | 22.1 | 29.0 | 29.0 | 7.38 | 7.35 | Low | Flood |
| 20040511 | 12.0 | 37 31.366 | 75 46.187 | 6.8 | 4.1 | 22.5 | 22.5 | 27.6 | 27.7 | 7.50 | 7.47 | Low | Ebb |
| 20040512 | 2.4 | 37 17.894 | 75 50.257 | 7.0 | 8.1 | 20.2 | 20.1 | 31.8 | 31.8 | 8.79 | 8.61 | High | Flood |
| 20040512 | 6.5 | 37 16.208 | 75 53.840 | 5.9 | 5.8 | 21.7 | 21.3 | 31.8 | 31.8 | 7.88 | 7.67 | High | Flood |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20040512 | 7.7 | 37 13.637 | 75 55.272 | 4.9 | 5.3 | 22.0 | 22.0 | 31.9 | 31.9 | 7.31 | 7.30 | Low | Ebb |
| 20040512 | 3.2 | 37 9.336 | 75 55.448 | 5.0 | 3.7 | 22.3 | 22.2 | 31.5 | 31.5 | 7.34 | 7.32 | Low | Flood |
| 20040603 | 7.7 | 37 13.020 | 75 55.551 | 4.5 | 5.7 | 23.0 | 23.0 | 31.9 | 32.0 | 5.61 | 5.52 | High | Ebb |
| 20040603 | 2.4 | 37 17.880 | 75 50.182 | 11.2 | 9.8 | 24.0 | 23.1 | 32.1 | 32.1 | 6.36 | 6.16 | Low | Flood |
| 20040603 | 3.2 | 37 9.370 | 75 55.474 | 5.7 | 7.5 | 23.0 | 23.2 | 29.8 | 30.6 | 6.41 | 6.18 | High | Flood |
| 20040603 | 6.5 | 37 15.612 | 75 53.884 | 6.5 | 8.0 | 24.0 | 23.3 | 32.1 | 32.1 | 6.00 | 5.77 | Low | Ebb |
| 20040604 | 4.4 | 37 34.380 | 75 39.688 | 6.6 | 6.3 | 23.9 | 23.9 | 32.2 | 32.3 | 5.61 | 5.53 | Low | Ebb |
| 20040604 | 6.0 | 37 29.978 | 75 45.498 | 5.7 | 4.6 | 24.1 | 23.9 | 32.1 | 32.2 | 5.33 | 5.42 | Low | Flood |
| 20040604 | 9.6 | 37 29.085 | 75 47.903 | 7.7 | 9.1 | 24.1 | 24.1 | 32.1 | 32.2 | 5.31 | 5.16 | High | Ebb |
| 20040604 | 12.0 | 37 31.130 | 75 46.198 | 4.9 | 5.7 | 24.7 | 24.7 | 31.5 | 31.5 | 4.90 | 4.81 | High | Flood |
| 20040607 | 1.4 | 37 21.978 | 75 45.498 | 11.1 | 11.0 | 21.3 | 21.3 | 31.0 | 31.1 | 6.63 | 6.63 | High | Flood |
| 20040607 | 4.5 | 37 23.787 | 75 47.655 | 6.1 | 4.9 | 22.2 | 22.1 | 31.2 | 31.2 | 6.33 | 6.24 | High | Ebb |
| 20040607 | 9.1 | 37 20.823 | 75 52.940 | 2.5 | 4.4 | 24.8 | 23.0 | 31.3 | 31.3 | 7.43 | 6.52 | Low | Ebb |
| 20040607 | 7.4 | 37 19.250 | 75 53.359 | 3.9 | 8.7 | 24.1 | 23.1 | 31.4 | 31.4 | 6.11 | 6.08 | Low | Ebb |
| 20040608 | 2.4 | 37 33.436 | 75 38.343 | 5.7 | 6.5 | 21.6 | 20.9 | 30.8 | 30.7 | 6.16 | 6.36 | High | Ebb |
| 20040608 | 2.0 | 37 35.199 | 75 38.548 | 6.2 | 6.0 | 22.2 | 21.8 | 30.8 | 30.9 | 5.91 | 5.85 | High | Flood |
| 20040608 | 2.8 | 37 37.068 | 75 38.729 | 4.7 | 6.4 | 22.7 | 22.7 | 31.0 | 31.1 | 4.94 | 4.86 | Low | Flood |
| 20040608 | 6.1 | 37 37.164 | 75 40.454 | 4.1 | 1.1 | 23.4 | 23.4 | 30.1 | 30.2 | 4.76 | 4.74 | Low | Ebb |
| 20040609 | 1.6 | 37 29.538 | 75 40.992 | 7.3 | 8.1 | 22.8 | 21.0 | 30.9 | 30.8 | 6.54 | 6.92 | High | Flood |
| 20040609 | 1.3 | 37 27.026 | 75 41.439 | 8.2 | 5.0 | 23.6 | 23.6 | 31.2 | 31.2 | 5.63 | 5.54 | Low | Flood |
| 20040609 | 3.7 | 37 30.485 | 75 43.044 | 7.9 | 2.8 | 23.8 | 23.8 | 31.1 | 31.2 | 6.27 | 6.23 | High | Ebb |
| 20040609 | 4.1 | 37 27.764 | 75 43.933 | 6.3 | 7.2 | 24.1 | 24.1 | 31.2 | 31.3 | 5.95 | 5.90 | Low | Ebb |
| 20040628 | 2.8 | 37 36.546 | 75 38.660 | 7.7 | 6.2 | 22.7 | 22.7 | 31.2 | 31.2 | 6.28 | 6.21 | High | Ebb |
| 20040628 | 6.1 | 37 37.649 | 75 40.689 | 5.6 | 4.2 | 24.2 | 24.2 | 30.3 | 30.3 | 4.99 | 4.91 | High | Flood |
| 20040629 | 2.4 | 37 17.892 | 75 50.928 | 7.9 | 7.7 | 24.2 | 23.8 | 31.0 | 30.9 | 6.97 | 7.22 | High | Ebb |
| 20040629 | 7.7 | 37 13.038 | 75 55.531 | | | 24.4 | 24.4 | 31.5 | 31.5 | 4.88 | 4.83 | Low | Ebb |
| 20040629 | 6.5 | 37 16.123 | 75 55.839 | 6.2 | 6.5 | 24.4 | 24.4 | 31.3 | 31.3 | 5.61 | 5.45 | High | Flood |
| 20040629 | 3.2 | 37 09.330 | 75 55.432 | 4.5 | 6.1 | 24.2 | 24.8 | 31.5 | 31.4 | 5.38 | 5.30 | Low | Flood |
| 20040630 | 1.4 | 37 21.925 | 75 45.431 | 9.0 | 9.5 | 24.1 | 24.0 | 31.1 | 31.0 | 6.20 | 6.16 | Low | Ebb |
| 20040630 | 7.4 | 37 19.790 | 75 52.922 | | | 24.1 | 24.3 | 30.9 | 31.1 | 5.21 | 5.32 | High | Flood |
| 20040630 | 9.1 | 37 20.937 | 75 52.922 | 4.5 | 2.3 | 24.1 | 24.3 | 30.5 | 31.0 | 5.61 | 5.49 | High | Ebb |
| 20040630 | 4.5 | 37 23.759 | 75 48.223 | 4.5 | 4.8 | 24.8 | 24.7 | 30.0 | 30.3 | 5.57 | 5.62 | Low | Flood |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20040701 | 1.3 | 37 27.204 | 75 40.939 | 9.0 | 9.5 | 22.3 | 22.0 | 31.2 | 31.2 | 6.65 | 6.69 | High | Ebb |
| 20040701 | 4.1 | 37 27.858 | 75 44.026 | 7.6 | 4.5 | 24.1 | 24.1 | 31.1 | 31.1 | 5.86 | 5.86 | High | Flood |
| 20040701 | 1.6 | 37 29.124 | 75 40.664 | 5.5 | 5.5 | 25.4 | 25.0 | 30.8 | 30.8 | 5.84 | 5.46 | Low | Ebb |
| 20040701 | 3.7 | 37 30.983 | 75 43.075 | 3.4 | 6.6 | 25.4 | 25.4 | 30.9 | 30.9 | 5.77 | 5.74 | Low | Flood |
| 20040706 | 2.0 | 37 35.209 | 75 38.533 | 5.9 | 7.0 | 28.0 | 27.3 | 31.6 | 31.5 | 5.95 | 5.76 | Low | Ebb |
| 20040706 | 2.4 | 37 33.434 | 75 38.340 | 9.2 | 7.6 | 28.5 | 28.4 | 31.6 | 31.5 | 5.77 | 5.78 | Low | Flood |
| 20040707 | 4.4 | 37 25.076 | 75 45.704 | 6.2 | 6.3 | 26.5 | 26.4 | 31.1 | 31.1 | 5.74 | 5.67 | High | Flood |
| 20040707 | 6.0 | 37 26.522 | 75 46.152 | 7.9 | 8.2 | 27.5 | 27.1 | 31.1 | 31.1 | 5.35 | 5.33 | High | Ebb |
| 20040707 | 9.6 | 37 29.474 | 75 47.549 | 7.8 | 8.3 | 29.1 | 29.1 | 30.6 | 30.6 | 4.30 | 4.30 | Low | Flood |
| 20040707 | 12.0 | 37 31.367 | 75 46.203 | 6.6 | 4.6 | 29.3 | 29.3 | 30.3 | 30.5 | 4.31 | 4.30 | Low | Ebb |
| 20040726 | 2.8 | 37 36.460 | 75 38.660 | 6.1 | 5.9 | 24.5 | 24.4 | 29.2 | 29.2 | 5.72 | 5.70 | Low | Flood |
| 20040726 | 2.4 | 37 33.248 | 75 38.819 | 8.1 | 6.0 | 24.5 | 24.5 | 30.7 | 30.8 | 6.45 | 6.46 | High | Flood |
| 20040726 | 6.1 | 37 37.661 | 75 40.691 | 4.1 | 1.4 | 24.5 | 24.6 | 23.7 | 24.9 | 4.22 | 4.11 | Low | Ebb |
| 20040726 | 2.0 | 37 35.211 | 75 38.517 | 7.2 | 7.5 | 25.1 | 24.9 | 30.9 | 30.9 | 6.70 | 6.54 | High | Ebb |
| 20040727 | 2.4 | 37 17.866 | 75 50.919 | 7.4 | 12.6 | 25.8 | 25.8 | 29.2 | 29.2 | 5.93 | 5.85 | Low | Ebb |
| 20040727 | 6.5 | 37 15.715 | 75 53.869 | 7.3 | 8.9 | 25.9 | 25.9 | 29.0 | 29.1 | 5.32 | 5.43 | Low | Flood |
| 20040727 | 7.7 | 37 13.511 | 75 55.428 | 5.2 | 5.5 | 26.6 | 26.5 | 29.1 | 29.1 | 5.60 | 5.58 | High | Ebb |
| 20040727 | 3.2 | 37 9.107 | 75 55.372 | 5.6 | 6.5 | 27.0 | 26.9 | 29.0 | 29.1 | 6.85 | 6.63 | High | Flood |
| 20040728 | 1.3 | 37 27.027 | 75 41.484 | 11.1 | 11.8 | 26.4 | 26.3 | 29.8 | 30.0 | 5.75 | 5.36 | Low | Flood |
| 20040728 | 4.1 | 37 28.235 | 75 44.355 | 6.3 | 4.3 | 26.8 | 26.6 | 28.5 | 28.9 | 5.51 | 5.49 | Low | Ebb |
| 20040729 | 4.4 | 37 25.284 | 75 45.727 | 7.4 | 7.1 | 26.7 | 26.8 | 27.8 | 28.2 | 5.13 | 5.01 | Low | Flood |
| 20040729 | 6.0 | 37 26.666 | 75 46.319 | 4.1 | 7.4 | 26.9 | 26.9 | 26.7 | 27.2 | 4.85 | 4.78 | Low | Flood |
| 20040729 | 9.6 | 37 29.049 | 75 47.968 | 6.8 | 7.3 | 27.0 | 27.2 | 25.3 | 26.8 | 4.58 | 4.56 | High | Ebb |
| 20040729 | 12.0 | 37 30.940 | 75 46.585 | 5.6 | 7.3 | 27.0 | 27.2 | 23.3 | 24.4 | 4.56 | 4.46 | High | Ebb |
| 20040730 | 1.6 | 37 29.219 | 75 40.725 | 5.8 | 6.4 | 24.7 | 24.7 | 30.3 | 30.3 | 6.04 | 6.00 | High | Flood |
| 20040730 | 3.7 | 37 30.473 | 75 43.045 | 9.1 | 2.8 | 25.0 | 25.0 | 30.1 | 30.1 | 5.92 | 5.85 | High | Ebb |
| 20040804 | 1.4 | 37 21.977 | 75 45.503 | 11.0 | 11.3 | 24.7 | 24.7 | 30.0 | 30.0 | 8.18 | 7.91 | High | Flood |
| 20040804 | 4.5 | 37 23.767 | 75 47.638 | 5.7 | 5.0 | 25.4 | 25.3 | 29.4 | 29.4 | 8.38 | 8.27 | High | Ebb |
| 20040804 | 9.1 | 37 20.901 | 75 52.929 | 5.3 | 2.5 | 28.0 | 26.2 | 28.3 | 28.9 | 4.78 | 4.22 | Low | Ebb |
| 20040804 | 7.4 | 37 19.206 | 75 53.383 | 11.1 | 6.0 | 27.3 | 26.8 | 29.1 | 29.2 | 5.01 | 4.46 | Low | Ebb |
| 20040823 | 2.8 | 37 36.551 | 75 38.67 | 4.8 | 7.4 | 24.3 | 23.8 | 29.6 | 30.0 | 5.68 | 5.77 | High | Flood |
| 20040823 | 6.1 | 37 37.172 | 75 40.447 | 3.6 | 4.6 | 26.0 | 25.9 | 25.7 | 26.4 | 4.72 | 4.77 | High | Ebb |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20040824 | 4.4 | 37 25.562 | 75 45.759 | 6.4 | 6.0 | 24.3 | 24.0 | 29.3 | 29.4 | 5.87 | 5.74 | High | Flood |
| 20040824 | 6.0 | 37 27.060 | 75 46.886 | 7.5 | 5.6 | 24.4 | 24.1 | 28.9 | 29.1 | 5.83 | 5.60 | High | Ebb |
| 20040824 | 12.0 | 37 31.329 | 75 46.240 | 6.3 | 4.8 | 26.1 | 26.2 | 15.9 | 17.1 | 3.58 | 3.60 | Low | Ebb |
| 20040824 | 9.6 | 37 29.806 | 75 47.666 | 9.5 | 4.5 | 26.2 | 26.2 | 18.6 | 18.7 | 4.01 | 4.01 | Low | Flood |
| 20040831 | 7.4 | 37 19.307 | 75 53.366 | 8.5 | 4.6 | 26.4 | 26.4 | 29.2 | 29.2 | 5.95 | 5.96 | High | Flood |
| 20040831 | 9.1 | 37 20.944 | 75 52.894 | 3.6 | 2.6 | 26.5 | 26.4 | 29.3 | 29.3 | 5.94 | 5.89 | High | Ebb |
| 20040831 | 1.4 | 37 21.638 | 75 44.992 | 6.9 | 9.5 | 27.1 | 26.8 | 29.7 | 29.8 | 7.31 | 7.14 | Low | Ebb |
| 20040831 | 4.5 | 37 23.760 | 75 48.284 | 4.9 | 4.3 | 27.7 | 27.7 | 29.2 | 29.3 | 7.26 | 7.37 | Low | Flood |
| 20040901 | 1.3 | 37 27.026 | 75 41.458 | 12.3 | 12.6 | 24.7 | 24.2 | 30.6 | 30.7 | 7.04 | 7.14 | High | Ebb |
| 20040901 | 4.1 | 37 28.291 | 75 44.522 | 5.0 | 9.4 | 25.7 | 25.7 | 30.1 | 30.1 | 6.06 | 6.14 | High | Flood |
| 20040901 | 1.6 | 37 29.205 | 75 40.704 | 4.1 | 7.9 | 26.4 | 25.8 | 30.4 | 30.4 | 6.18 | 6.72 | Low | Ebb |
| 20040901 | 3.7 | 37 30.496 | 75 43.059 | 7.7 | 3.5 | 26.8 | 26.7 | 30.3 | 30.3 | 6.14 | 6.17 | Low | Flood |
| 20040921 | 2.4 | 37 33.253 | 75 38.815 | 10.2 | 6.9 | 21.6 | 21.5 | 30.9 | 30.9 | 8.59 | 8.50 | High | Flood |
| 20040921 | 2.0 | 37 35.167 | 75 38.589 | 8.4 | 6.6 | 21.7 | 21.7 | 30.9 | 31.0 | 8.78 | 8.64 | High | Ebb |
| 20040922 | 3.7 | 37 30.950 | 75 43.099 | 3.7 | 8.7 | 21.0 | 20.8 | 31.3 | 31.4 | 7.96 | 7.67 | Low | Ebb |
| 20040922 | 1.6 | 37 29.157 | 75 41.068 | 7.7 | 5.9 | 21.0 | 21.1 | 31.3 | 31.4 | 7.40 | 7.61 | Low | Flood |
| 20040922 | 4.1 | 37 27.839 | 75 44.003 | 8.1 | 6.0 | 21.7 | 21.5 | 31.3 | 31.3 | 8.77 | 8.57 | High | Ebb |
| 20040922 | 1.3 | 37 27.213 | 75 40.899 | 7.7 | 10.6 | 22.1 | 22.1 | 31.3 | 31.3 | 9.60 | 9.48 | High | Flood |
| 20040923 | 1.4 | 37 21.704 | 75 44.997 | 11.6 | 10.7 | 21.6 | 21.5 | 31.1 | 31.2 | 8.69 | 8.76 | Low | Ebb |
| 20040923 | 4.5 | 37 23.753 | 75 48.321 | 4.8 | 5.0 | 21.7 | 21.6 | 31.1 | 31.1 | 7.19 | 7.21 | Low | Flood |
| 20040923 | 7.4 | 37 19.215 | 75 53.377 | 10.9 | 5.1 | 21.7 | 21.6 | 30.9 | 30.9 | 7.74 | 7.66 | High | Flood |
| 20040923 | 9.1 | 37 20.888 | 75 52.920 | 4.1 | 4.1 | 21.9 | 21.7 | 30.7 | 30.7 | 8.00 | 7.86 | High | Flood |
| 20040927 | 2.8 | 37 37.051 | 75 38.728 | 4.1 | 6.6 | 23.2 | 23.3 | 31.0 | 31.1 | 6.72 | 7.08 | Low | Flood |
| 20040927 | 6.1 | 37 37.164 | 75 40.461 | 4.7 | 2.0 | 23.7 | 23.7 | 29.7 | 29.7 | 6.65 | 6.64 | Low | Ebb |
| 20040930 | 3.2 | 37 09.306 | 75 55.455 | 5.7 | 6.3 | 21.9 | 21.9 | 30.9 | 31.0 | 7.56 | 7.47 | High | Flood |
| 20040930 | 7.7 | 37 13.525 | 75 55.405 | 4.8 | 6.9 | 22.1 | 22.1 | 31.1 | 31.1 | 6.68 | 6.68 | High | Ebb |
| 20040930 | 6.5 | 37 16.251 | 75 53.849 | 7.7 | 8.2 | 23.1 | 22.5 | 31.1 | 31.1 | 7.72 | 7.67 | Low | Ebb |
| 20040930 | 2.4 | 37 17.864 | 75 50.824 | 7.1 | 8.7 | 23.1 | 22.9 | 31.1 | 31.1 | 7.63 | 7.46 | Low | Flood |
| 20041001 | 9.6 | 37 29.060 | 75 47.948 | 7.2 | 8.1 | 22.5 | 22.4 | 30.8 | 30.8 | 6.84 | 6.85 | High | Ebb |
| 20041001 | 4.4 | 37 25.602 | 75 45.744 | 7.1 | 5.3 | 22.4 | 22.4 | 30.8 | 30.8 | 7.04 | 7.01 | Low | Flood |
| 20041001 | 6.0 | 37 27.036 | 75 46.610 | 6.1 | 3.8 | 22.5 | 22.5 | 30.7 | 30.7 | 6.53 | 6.54 | Low | Flood |
| 20041001 | 12.0 | 37 30.948 | 75 46.600 | 5.9 | 8.4 | 22.5 | 22.5 | 30.6 | 30.7 | 6.57 | 6.53 | High | Ebb |

| Date | Dist. (km) | Latitude | Longitude | St.Depth (m) | E.Depth (m) | S.Temp(C) | B.Temp(C) | S.Sal(ppt) | B.Sal(ppt) | S.DO(ppm) | B.DO(ppm) | Tide | Current |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 20041019 | 3.2 | 37 09.326 | 75 55.423 | 6.6 | 4.8 | 16.0 | 15.9 | 29.4 | 30.1 | 9.25 | 9.15 | Low | Flood |
| 20041019 | 7.7 | 37 13.534 | 75 55.370 | 4.7 | 5.1 | 16.1 | 16.1 | 29.8 | 29.8 | 9.13 | 9.15 | Low | Flood |
| 20041019 | 6.5 | 37 15.666 | 75 53.856 | 7.2 | 7.3 | 16.1 | 16.6 | 30.5 | 30.5 | 9.30 | 9.33 | High | Flood |
| 20041019 | 2.4 | 37 17.875 | 75 50.358 | 7.3 | 8.2 | 16.8 | 16.8 | 30.6 | 30.7 | 9.87 | 9.90 | High | Ebb |
| 20041025 | 4.5 | 37 23.763 | 75 48.304 | 5.5 | 5.2 | 13.6 | 13.6 | 30.3 | 30.3 | 9.66 | 9.62 | Low | Flood |
| 20041025 | 9.1 | 37 20.906 | 75 52.906 | 4.3 | 4.9 | 14.3 | 14.3 | 30.2 | 30.2 | 9.49 | 9.47 | High | Ebb |
| 20041025 | 7.4 | 37 19.209 | 75 53.374 | 9.9 | 6.0 | 14.3 | 14.4 | 30.1 | 30.3 | 9.45 | 9.47 | High | Ebb |
| 20041025 | 1.4 | 37 21.938 | 75 45.446 | 9.6 | 5.9 | 14.9 | 14.8 | 30.6 | 30.6 | 10.23 | 10.23 | Low | Ebb |
| 20041026 | 12.0 | 37 30.943 | 75 46.620 | 5.5 | 6.9 | 14.5 | 14.6 | 28.0 | 28.2 | 9.31 | 9.27 | Low | Ebb |
| 20041026 | 9.6 | 37 29.512 | 75 47.547 | 7.9 | 7.0 | 15.2 | 14.6 | 29.1 | 29.0 | 9.44 | 9.31 | Low | Flood |
| 20041026 | 4.4 | 37 24.988 | 75 45.713 | 5.7 | 5.1 | 15.1 | 15.0 | 30.6 | 30.6 | 10.05 | 9.97 | High | Ebb |
| 20041026 | 6.0 | 37 27.000 | 75 46.613 | 5.7 | 6.5 | 15.0 | 15.1 | 30.6 | 30.6 | 9.91 | 9.92 | High | Ebb |
| 20041027 | 1.3 | 37 27.190 | 75 40.929 | 7.4 | 11.7 | 15.0 | 15.1 | 30.5 | 30.6 | 9.65 | 9.62 | Low | Ebb |
| 20041027 | 1.6 | 37 29.142 | 75 40.704 | 7.5 | 8.2 | 15.3 | 15.4 | 30.5 | 30.5 | 9.97 | 9.79 | High | Ebb |
| 20041027 | 4.1 | 37 27.805 | 75 43.987 | 3.4 | 8.1 | 15.5 | 15.4 | 30.6 | 30.6 | 10.16 | 10.09 | Low | Ebb |
| 20041027 | 3.7 | 37 30.498 | 75 43.073 | 5.1 | 3.1 | 15.5 | 15.6 | 30.4 | 30.5 | 9.74 | 9.76 | High | Flood |
| 20041029 | 6.1 | 37 37.150 | 75 40.420 | 2.6 | 3.8 | 14.6 | 14.6 | 29.3 | 29.3 | 9.06 | 9.09 | High | Flood |
| 20041029 | 2.0 | 37 35.205 | 75 38.471 | 7.4 | 8.7 | 15.4 | 15.3 | 30.2 | 30.2 | 9.67 | 9.67 | Low | Ebb |
| 20041029 | 2.4 | 37 33.447 | 75 38.309 | 8.3 | 10.4 | 15.7 | 15.7 | 30.4 | 30.5 | 9.92 | 9.92 | Low | Ebb |
| 20041029 | 2.8 | 37 36.567 | 75 38.666 | 8.0 | 3.3 | 15.5 | 15.5 | 30.4 | 30.4 | 10.03 | 10.02 | High | Ebb |

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