Atlantic sturgeon in the Delaware River: contemporary population status and identification of spawning areas

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Introduction

The Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*) is one of 27 species within the family Acipenseridae and one of nine species/subspecies extant in North American waters (Cech and Doroshov 2004). Atlantic sturgeon historically occupied all major river systems along the Atlantic coast between Canada (Bachus 1951) and Florida (Vladykov & Greely 1963), with the Delaware River historically supporting the largest population (Secor and Waldman 1999). Atlantic sturgeon are anadromous with spawning in the southern portion of their range typically occurring in the early spring months followed by a general trend of later spawning times in northern rivers (Smith and Clugston 1997). The adhesive eggs are deposited on rocky or hard-bottom substrate and fertilized externally (Smith et al. 1980). The Atlantic sturgeon is a slow maturing fish (females reach sexual maturity at 16 years or older, males at least 12 years within the mid-Atlantic coast region (Van Eenennaam et al. 1996)). Fecundity of female Atlantic sturgeon is estimated to range from 400,000 – 8 million eggs (Smith et al. 1982, Van Eenennaam and Doroshov 1998, Dadswell 2006) with a spawning interval of 2-6 years (Vladykov and Greeley 1963, Van Eenennaam et al. 1996, Stevenson and Secor 1999). Larval Atlantic sturgeon emerge in roughly 4 - 6 days and begin to work their way downriver towards brackish waters (Smith et al. 1980). Juveniles may remain in brackish waters for months or years before moving out to sea, where they are known to migrate great distances (Smith and Clugston 1997).

Humans took advantage of the migratory behavior of spawning Atlantic sturgeon to develop a fishery for Atlantic sturgeon flesh and roe (i.e. caviar). Caviar production in the United States did not flourish until the late 19th century (Cobb 1900), subsequently transforming the Delaware River Atlantic sturgeon fishery from a small, flesh-driven business into the caviar capital of North America (Saffron 2002). By the late 1800's, the Delaware River Atlantic sturgeon fishery was the largest in the United States and produced 75% of the US sturgeon harvest from 1890-1899 (Townsend 1900). Between the collection roe from mature females for caviar production and the canning of the smoked flesh, the fishery provided a way of life for many people in search of post-Civil War prosperity (Saffron 2002). Delaware River landings reached a peak in 1888 with a total catch of nearly 3000 metric tons of Atlantic sturgeon (Smith 1894). The success of the fishery was short-lived, and by 1900 the total catch was less than 10% of the peak harvest totals (Ryder 1890; Cobb 1900).

Given the steep decline in landings, management intervention was required. In 1891 the State of New Jersey passed legislation to protect "mammose" (young sturgeon under 1m in length) sturgeon in the waters of Delaware River, bay, or tributaries within state jurisdiction (Cobb 1900). In 1990, the Atlantic States Marine Fisheries Commission (ASMFC) produced a Fishery Management Plan (FMP) for the Atlantic sturgeon with a stated goal of restoring the species throughout its range to allow an annual harvest of about 317 metric tons, which is approximately 10% of the peak catch totals (Smith and Clugston 1997). Following a petition to list the Atlantic sturgeon under the Endangered Species Act, a status review was conducted in 1998 that eventually determined the species did not warrant protection, although the ASMFC imposed a coastwide moratorium during the same year. In May of 1999, National Marine Fisheries Service (NMFS) extended the fishing ban into federal waters (North Carolina Division of Marine

Fisheries 2006). Currently there is no allowable commercial, recreational or tribal harvest in the United States as designated by the ASMFC (1998), however the fishing moratorium has not been in place long enough to generate measurable recovery (Auer 2004). In 2005, the NMFS initiated another status review of the Atlantic sturgeon based on the conclusions of a 2003 NMFS/USFWS joint committee. The status review team released their recommendations in February 2007 which stated three of the five distinct population segments of Atlantic sturgeon be listed as threatened under the ESA, including the Chesapeake regional population segment.

Since the height of the fishery in the late 1800s, the Delaware River Atlantic sturgeon stock has not recovered. Although most harvest ended by the start of the 20th century, there is little evidence of an extant spawning population. A number of factors have likely contributed to the lack of Atlantic sturgeon recovery in the Delaware River, including habitat loss primarily due to dredging, saltwater intrusion, water quality degradation, harvest pressure and bycatch mortality (Albert 1988; Stein et al. 2004). Estuarine and riverine habitat areas available to Atlantic sturgeon larvae, juveniles, and adults have been degraded over the last century (Albert 1988). Because Atlantic sturgeon are anadromous and utilize a combination of river, estuary and ocean habitats, damage to any of the three can have detrimental effects. The Delaware River became heavily industrialized throughout the latter half of the 19th century, and the increased activity resulted in rising water pollution to the point where large sections of the river became anoxic during summer months when Atlantic sturgeon occupy the system (Albert 1988). Siltation caused by the industrial coal industry drastically altered the substrate composition of the Delaware River (Albert 1988), which may have reduced available spawning habitat. The Delaware River has also experienced large-scale dredging to accommodate commercial shipping traffic, resulting in changes in substrate composition and tidal flows (Di Lorenzo et al. 1993; Walsh 2004). Within the period 1877 – 1987, the mean depth of the Delaware River increased by 1.6m and the mean cross-sectional area increased by nearly 3,000 m^2 (Walsh 2004). By 1973, the US Army Corps of Engineers (USACE) estimated that nearly 154,000,000 m^3 of material had been removed from the Delaware Estuary (Walsh 2004). The channel deepening process increased the tidal range in the upper estuary; simultaneously, extensive water removals and diversions were occurring within the non-tidal watershed, resulting in saltwater intrusion in the freshwater-tidal reach of the estuary. This displacement of freshwater habitat may have negatively affected any potential success for the contemporary spawning population.

A serious knowledge gap exists regarding temporal and spatial spawning patterns of Atlantic sturgeon in most river systems including the Delaware. The most comprehensive information regarding Atlantic sturgeon reproduction in the Delaware River is nearly 100 years old (Ryder 1890; Cobb 1900; Borodin 1925). Since the conclusions drawn concerning the location and timing of Atlantic sturgeon spawning are based primarily on information collected in fishery dependent sampling, it is possible that information on spawning locations may not be completely valid. The historically noted spawning areas were based on the fact that “ripe” fish were collected at these locations, where “ripe” pertains to adult Atlantic sturgeon that contained eggs ideal for caviar production rather than eggs ready for fertilization. Ripe eggs as defined for caviar production are actually premature in a reproductive sense. Eggs suitable for caviar typically have a higher polarization index, lighter color and firmer texture than eggs in the ovulatory stages (Van Eenennaam et al. 1996; Mohler 2003). Places such as Pea Patch Island, DE and Penn's Grove, NJ (rkm 85-110) were noted as likely spawning areas, but such locations are currently brackish habitat unsuitable for survival of larvae.

Additionally, the significance of historical information could increasingly lose relevance given the broad-scale environmental context shift caused by global climate change. Given the anthropogenic stressors already functioning within the Delaware River such as dredging and non-tidal watershed diversion rights combined with acknowledged climate change, the reliance of present day fisheries managers on 100-year-old fisheries dependent data becomes more problematic.

By identifying where spawning activity is currently taking place, essential fish habitat areas can be characterized for Delaware River Atlantic sturgeon. Young-of-the-year fish (342 mm TL) have been reported as recent as 2005 (Hal Brundage, ERC Ltd. pers. comm) supporting the existence of a remnant spawning population. Available information on the early life history of Atlantic sturgeon indicates a natal riverine/brackish water residency period for young-of-the-year (Bain 1997). Genetic evidence also supports the existence of a Delaware River specific haplotype (Tim King, USGS, Leetown, WV. pers. comm).

Because the Atlantic sturgeon is currently listed as a species of concern (Department of Commerce 2004) and limited data poses challenges for fishery managers, we will hopefully provide information that will ultimately help define Atlantic sturgeon habitat utilization patterns within the Delaware River. The primary research objectives were to 1) determine the contemporary status of Atlantic sturgeon in the Delaware River, 2) attempt to identify both the spatial and temporal extent of spawning, and 3) identify critical riverine habitats used during pre- and post-spawning movements and determine duration of fresh-water residency.

Materials and Methods

Sampling Locale: The study took place in the Delaware Bay and Delaware River, ranging from the entrance of the bay near Cape Henlopen, DE and Cape May, NJ to as far upriver as Trenton, NJ (Figure 1).

Collection of Specimens: Nine adult Atlantic sturgeon (FL>1.3m FL) were captured using monofilament and multifilament gill nets of varying mesh size (primary gear consisted of 30.5cm stretch-mesh monofilament nets using 1-4, 122m panels, 6.1m height), length, and height, and by fishing a combination of drift and anchored sets. Fishing occurred primarily in the region around Woodland and Primehook Beaches Delaware during April, near the Artificial Island anchorage area during May, then into the Cherry Island Flats region and the Marcus Hook anchorage area during May and June. Although the drift method had been used successfully to capture adult Gulf sturgeon by Fox et al. (2000), the local Delaware River fishing contingent as well as Delaware Natural Resources and Environmental Control (DNREC) fishery managers suggested using anchored net techniques as well as drift. Anchored fishing modeled that of the anchored striped bass commercial harvesters, where 30.5cm stretch-mesh gillnets were moored using commercial gillnet anchors and allowed to fish continuously, being tended at least once per day. Fishing locations were based on three variables: 1) advice from the local fishers and DNREC fishery managers, 2) having the capacity from a physical standpoint to allow fishing of nets exceeding 2000m^2 in size, and 3) striped bass fishing reports provided by DNREC that documented adult Atlantic sturgeon as bycatch.

Upon capture, the sturgeon were placed in a live well, approximately 680L in capacity, where water was pumped in directly from the river system, maintaining ambient temperature, salinity and dissolved oxygen levels. Each fish was then implanted with an ultrasonic transmitter (Vemco Ltd. (V-16, 6-H, 69.0 kHz).

A reward system was also established to allow us to work with local commercial striped bass harvesters, where they were paid $300.00 for a live Atlantic sturgeon of adult size (>1.3m FL). Each harvester involved in the program was first required to obtain permission from the DNREC to handle the species beyond a normal release. Authorized local striped bass commercial harvesters were allowed to retain an adult Atlantic sturgeon whenever they encountered one as bycatch. Once the fish was secured to an anchorage point, the catch was reported to Delaware State University researchers. An immediate response was made to each reported catch, whereupon Dewayne Fox or Phil Simpson took possession of the fish and implanted it with an ultrasonic transmitter.

Tags not utilized for adult Atlantic sturgeon were implanted into juvenile Atlantic sturgeon after water temperatures exceeded 25^{o} C, the likely threshold for spawning activity (Dovel and Beggren 1983). There is presently only limited research available regarding juvenile Atlantic sturgeon seasonal migrations, nursery areas, overwintering habits, and movement patterns in the Delaware River. The most recent findings (Shirey 1997), identified two important holding areas (near river kilometers 88 and 125, respectively) utilized by juvenile Atlantic sturgeon during the spring and summer months in the Delaware Bay and Delaware River. Additionally, sampling reports from Shirey during the period 1991-1997 showed a decline in catch rates from a reported 32.2 fish/hr to 1.4 fish/hr. This additional juvenile information may aide future researchers by determining optimal sampling times and locations, as well as policy makers who may better identify habitat zones important to the growth and survival of Atlantic sturgeon.

Surgical Procedures: The ultrasonic transmitters used in this study were 90mm in length, 16mm diameter, and weighed 14g (in water). The transmitters were coated with Dow Corning Silastic® biologically inert silicone elastomer in an attempt to minimize rejection rates (Fox et al. 2000).

Upon capture, each fish was placed in the live well. The TL and FL (cm) and, when available, weight (kg) was measured and recorded. Any captured Atlantic sturgeon were scanned thoroughly for the presence of an existing PIT tag. If no tag was present, a 16mm Biomark® PIT tag was inserted on left side of fish at the base of the dorsal fin. A barbel sample was taken and placed in 95% ethanol for future genetic analysis. A plastic-tipped dart tag was inserted on the left side of the fish below the fourth dorsal scute. Surgical implantation of the Vemco ultrasonic transmitter followed the protocol established by Fox et al. (2000).

Telemetry: Telemetered Atlantic sturgeon were monitored once a week using the telemetry techniques described below. Riverine waters were surveyed weekly, weather and personnel permitting, from June until October, or until most or all of the fish had moved out of the survey range. Fixed survey stations were set at one kilometer intervals and listening occurred for at least two minutes using an omni-directional hydrophone. Once a tagged fish was detected, a directional hydrophone was used to determine the exact location of the fish. The location and depth were recorded along with water quality parameters (temperature, salinity, conductivity, and dissolved oxygen).

A passive array of VR2 receivers was also be established and periodically checked to determine broad scale fish movements (Figures 1-2). These receivers were attached to the United States Coast Guard navigational aides (Figure 3) and were distributed throughout the river and bay in order to maximize the potential for monitoring upstream and downstream movements of telemetered Atlantic sturgeon. An additional array for a separate DSU research project which utilized anchored receivers in two linear arrays was positioned between Slaughter Beach and Cape Henlopen, DE. Data sharing with the privately owned research firm Environmental Research and Consulting, Inc. also utilizing Vemco VR2 receivers within the Delaware River, allowed for an overall increase in the amount of data collected by all parties.

The average detection range of the VR2 receivers was determined by a series of tests. Each test documented a percent of possible tag detections at varying distances and directions from the VR2 receiver. Starting at the receiver, a test transmitter similar to the ones used for this study was attached to a weighted line and deployed at a depth approximately two meters off the river bottom to mimic the presumed benthic nature of Atlantic sturgeon. Simultaneously using a VR100 manual hydrophone and a handheld GPS unit, the time of each transmittance was recorded along with the location. Deploying the tag for no less than three minutes, the number of detections recorded by the VR2 receiver was compared to the number of possible detections to produce a percent transmittance. This process was repeated at distances of 500m, 1km, and 1.5km for each north, south, east and west headings. Although numerous tests have been conducted in prior research (Domeier 2005; Szeldlmayer and Schroepfer 2005) and claims made about the detection capabilities of the VR2 receivers are well documented (Miller and Sadro 2003; Simpfendorfer 2006), the detection range can vary significantly because of both physical and biological factors (Heupel et al. 2006). The probable detection range, according to the available literature, may reach 90% in a static water setting (Clements et al. 2005) but may decline and potentially reach a maximum between 400m – 800m (Heupel and Hueter 2001; Hildebrand and Hildebrand 2004), but can also be as low as 300m (Semmens et al. 2005), or in extreme cases as low as 45m (Finstad et al. 2005). Telemetry methods and habitat characterization techniques were identical for adult and juvenile Atlantic sturgeon.

Habitat Characterization: Habitat parameters such as water depth (m), temperature (^{o}C), dissolved oxygen (mg/L), salinity (ppt) and conductivity (mS) were measured and recorded at each capture location and relocation point. The manual telemetry relocations of Atlantic sturgeon were plotted using ArcMap and overlaid with sediment-type data collected by Sommerfield and Madsen (2003) to determine habitat selection. Sommerfield and Madsen utilized sidescan sonar methods to produce a benthic map of the Delaware River from the region just north of Pea Patch Island (approximately river kilometer 110) upriver to approximately Bridgeport, NJ. Each relocation point was classified by sediment type based on the location of the point within the benthic mosaic developed by Sommerfield and Madsen. The total area comprised of each habitat type within the region of relocations was calculated, and an individual Chi-square analysis was performed to determine if Atlantic sturgeon are selecting habitat based on sediment type. Similar methods were utilized to assess Atlantic sturgeon depth preferences using data obtained from the USACE.

Additionally, overall movement of telemetered Atlantic sturgeon was cross-plotted with water temperature (^oC) as well as river flow (ft^3/s) data obtained from the United States Geological Survey gaging station in Philadelphia, PA to determine if a correlation exists between overall migration patterns of juvenile Atlantic sturgeon and either of the two environmental variables.

Reproductive status: Gonadal biopsies were prepped using standardized histological techniques and were staged using the classification criteria established by Van Eenennaam and Doroshov (1998).

Egg Collection: Abrasive surface artificial substrate pads suitable for adherence of eggs have been successfully used for white and Gulf sturgeon egg collection (McCabe and Beckman 1990; Marchant and Shutters 1996; Fox et al. 2000). Egg mats (diameter 56cm) were deployed in areas of the river where spawning was believed to be occurring based on active telemetry data and substrate sampling. When rocky or gravel substrate was collected using a petite ® Ponar grab, egg mats were deployed approximately 10-15m from each other and checked for deposited eggs at a maximum of every third day (based on the hatch times established by the Northeast Fishery Center (Mohler 2003)) until spawning fish were no longer in the area.

Results

The 2005 sampling season began on May 10, and concluded on September 22. The 2005 fishing efforts produced only juvenile Atlantic sturgeon (Table 1). Beginning May 10, fishing efforts were directed towards adult Atlantic sturgeon. On June 30, efforts shifted to juvenile Atlantic sturgeon as water temperatures approached 26^{o}C. Out of the 23 total juvenile Atlantic sturgeon captured, 12 were implanted with transmitters (using a minimum total length 80.0cm as size criteria) . The sizes of fish captured ranged from 65.3cm – 131.0cm (Table 2). The fishing efforts for the season concluded on September 22, 2005. During May and early June, fishing occurred primarily in the upper bay off Woodland Beach and Bombay Hook. Efforts shifted towards Artificial Island from mid-June to the end date of September 22, with some nets deployed near Cherry Island Flats (rkm 110) and Marcus Hook (rkm 125) as well (Figure 4).

During 2006, netting began April 12, however the first three Atlantic sturgeon implanted with transmitters were obtained as a result of the reward system. The first of these fish was below the adult size threshold (FL >1.3m) and therefore was considered juvenile. The reward program ceased on May 1 as the commercial striped bass season came to a close. From May 10, under the guidance of commercial striped bass fisherman Larry Voss, six 30.5cm stretch-mesh gillnets, each 91 meters in length, were anchored in upper Delaware Bay. These nets were checked at least once per day for captured adult Atlantic sturgeon. Using these methods, a third Atlantic sturgeon of adult size was captured and tagged May 18. We continued to fish using this style of anchored sets until May 26. At this point, netting efforts were moved upriver (river kilometer (rkm) 85-90) as potentially reproductive Atlantic sturgeon were believed to move upriver.

Starting May 30, we moved our fishing efforts towards Artificial Island (river kilometer 88). Gill nets were anchored at slack tide and allowed to fish until the subsequent slack water event. A fourth adult Atlantic sturgeon was captured June 1 and fitted with an ultrasonic transmitter. Sampling continued until June 18, and gradually moved upriver into the Cherry Island Flats/Marcus Hook Bar region (rkm 110-125) as well as riverine sections approaching Trenton, NJ (Figure 4), using relocations of the four tagged adult Atlantic sturgeon as a guide to direct fishing efforts (Table 3). The gonadal biopsies collected from each fish identified all four fish as males, each of them potentially of reproductive size. Histological examination of the 2006 gonad samples indicated potentially two out of four individuals had reached a near-term spawning maturation phase.

By mid-July, tracking data indicated the telemetered adult Atlantic sturgeon had moved out of probable spawning areas and returned to brackish waters. Additionally, water temperatures began to exceed the reported maximum (25^{o}C) for spawning activity (Dovel and Berggren 1983). At this point, the focus again turned to juvenile Atlantic sturgeon. Beginning July 24, smaller mesh nets (15-20cm) were deployed near Artificial Island (rkm 88) in addition to the large mesh nets used previously. Ten more juvenile Atlantic sturgeon were tagged in the summer of 2006 (Table 4).

During 2005 and 2006 a total of 27 Atlantic sturgeon were tagged, producing 181,999 passive relocations coupled with 183 manual relocations (Table 5). Telemetry results point to a late spring/early summer inward migration, followed by a period of dampened movement during the warm summer months of August and September, then an outmigration during October and November. During the summer months juvenile

Atlantic sturgeon displayed little movement compared to spring and fall months (Figure 6a – 6c). Juvenile Atlantic sturgeon concentrated in three specific areas, two of which (Artificial Island, Cherry Island Flats) had been identified by previous research conducted on the Delaware River (Figure 5). The previously unidentified area, however, is situated in the Marcus Hook anchorage zone (rkm 125). According to manual relocation data, juvenile Atlantic sturgeon are selecting for depth (Figure 7a) but are not selecting for substrate type (Figure 7b).

Of the four adult size Atlantic sturgeon tagged during 2006, one individual, Vemco ID #1744, migrated into freshwater-tidal reaches of the Delaware River (Figure 8), although the histological examination of the gonads of this fish indicated it was sexually immature. Atlantic sturgeon #1744 moved upriver to Tinicum Island (rkm 136) immediately after it was tagged, and remained there from June 4 – June 10. Initial sediment sampling was performed near the relocation points at Tinicum Island during this time period, however by June 12; this individual had migrated towards Trenton, NJ (rkm 211) where it remained until June 27. By July 7, Atlantic sturgeon #1744 had returned to the location where it was originally captured.

Once Atlantic sturgeon #1744 entered the upper river near Trenton, NJ, habitat characterization began through the use of a Ponar grab in order to classify the substrate as hard-bottom, and egg mats were deployed where hard-bottom, rocky substrate was prevalent (Figure 9). A total of 75 egg mats were deployed on June 16 between river kilometers 197 – 210 in clusters of 12-16 pads and fished until June 28, as river flow measured at Trenton, N.J. rose from 8,000 CFS to over 200,000 CFS within a 24-hour period. Only one-third of this gear was recovered following the flood event. No eggs were collected during the study.

Preliminary range tests following our described methodology indicate that transmitter detection success is less than 50% at distances of 500m or more. These findings stem from tests performed on nearshore receivers in depths not exceeding 8m. However, based on other analysis methods, there is evidence that the VR2 receivers can detect transmitters at distances of greater than 2km. There were multiple instances where two receivers deployed in close proximity to one another detected a transmitter simultaneously. The most extreme example of this scenario occurred at Tinicum Island (rkm 136 and rkm 141), where the inter-receiver distance is 5.7 km. If a transmitter is detected by both receivers, then each receiver must have a minimum detection range of 2.8 km. While percent transmittance values are not obtainable using this analysis method, we can get some idea as to the maximum detection range of the receivers.

Discussion

The Delaware River once supported the largest population of Atlantic sturgeon known to exist (Secor and Waldman 1999) and although our telemetry results are not conclusive, coupled with the collection of ripe adults, and preliminary genetic analyses, they strongly suggest that a remnant spawning population exists today. The telemetry results from Atlantic sturgeon obtained during 2006 provide some insights about the probable spatial and temporal extent of spawning behavior. Given the fact that sexually mature male Atlantic sturgeon were captured in Delaware Bay between mid-April and June 1, our findings for the Delaware River agree with those of Dovel and Beggren

(1983) regarding Atlantic sturgeon spawning times reported for the Hudson River. Additionally, the rapid upriver migration made by Atlantic sturgeon #1744 to freshwater habitat where hard-bottom substrate is prevalent would indicate that spawning for Atlantic sturgeon may occur much further upriver than the historical reports of "ripe fish" observations made by Cobb (1899) as well as Borodin (1925). Spawning habitat of Atlantic sturgeon may also be shared with the closely related shortnose sturgeon (*A. brevirostrum*) in the Delaware River. These findings differ from Bain's (1997) conclusions for Hudson River shortnose and Atlantic sturgeon where such a spatial overlap is not thought to occur regularly.

Based on our findings, it seems likely that the present day lower limit of Atlantic sturgeon spawning may be in the area of the upper limit of salt water intrusion near Tinicum Island (river kilometer 136) while the upper limit is likely at the fall line near Trenton, NJ (river kilometer 211). Dovel and Beggren (1983) reported that early in the season (late May), Atlantic sturgeon spawning in the Hudson River occurred near the salt wedge, and then continued upstream into June and early July. Atlantic sturgeon #1744 appeared to fit the profile for a spawning adult sturgeon (e.g. Fox et al. 2000), occupying areas around Tinicum Island (negligible salinity) during early June then making a rapid directly movement upstream towards Trenton, where it remained until late June before making a downriver migration in early July. However, the histological analysis of the gonad sample obtained from Atlantic sturgeon #1744 proved inclusive and indicated this fish had undifferentiated gonads. However, we hypothesize that the gonadal biopsy of this individual missed the reproductively active portion of the gonad since the gonads of

Atlantic sturgeon may exhibit different stages of development throughout the gonadal tissue (Joel VanEenennaam, pers comm).

Atlantic sturgeon #1225 migrated as far upriver as the mouth of the Schuylkill River (rkm 148) on May 31st, 2006; however, the duration of the stay was less than 24 hours and did not appear indicative of spawning behavior. After quickly returning to the upper bay waters (rkm 80), Atlantic sturgeon #1225 returned to the area of Marcus Hook Bar (river kilometer 134) on June 28. Again, the visit was short and, within one day, the fish returned to the upper bay. Nevertheless, this migration may indicate this fish was searching for a mate and could indicate the presence of other spawning adult Atlantic sturgeon near the regions of Marcus Hook Bar and Tinicum Island during the month of June. Additionally, the histological results from this individual indicate that it was sexually mature and ready to spawn, suggesting that spawning may occur between Tinicum Island (rkm 136) and the mouth of the Schuylkill River (rkm 148).

The discussion pertaining to the section of river between Marcus Hook Bar and the mouth of the Schuylkill River becomes more significant when the idea of habitat selection is introduced. Atlantic sturgeon not only require freshwater for spawning but also hard-bottom substrate (Gilbert 1989, Smith and Clugston 1997). Based on Sommerfield and Madsen (2003), there are multiple zones of hard-bottom substrate within the Marcus Hook-Schuylkill River area that are considered freshwater. This area has been classified as freshwater (0.0 to 0.5 ppt upstream of Marcus Hook) by the Army Corps of Engineers (1997). Sommerfield and Madsen classify much of this area as "Mixed-grained reworking" where the dominant sediment types are "mixed gravel, sand, and mud," or "Coarse-grained bedload" with "moderately well-sorted sand and gravel" as the dominant sediment types and “Non-deposition where the dominant sediment types are “cobble and bedrock.”

Based on the findings of Sommerfield and Madsen (2003), the substrate composition between Marcus Hook and Tinicum Island may represent suitable spawning habitat for Atlantic sturgeon. The majority of the hard-bottom substrate zones, particularly the coarse-grained bedload areas, either neighbor or are within the shipping channel, indicative of suitable spawning depths (Smith and Clugston 1997). However, the presence of hard-bottom substrate within the shipping channel may also be a limiting factor in terms of spawning success, potentially exposing adult Atlantic sturgeon to mortality due to boatstrike.

The identification of spawning areas in the Delaware River is difficult because of the limited data received from telemetered adult Atlantic sturgeon and the lack of fertilized egg collections. The Delaware River, between Marcus Hook (rkm 125) and Trenton (rkm 211), could be considered potential spawning habitat based on availability of freshwater and hard-bottom substrate. Because males tend to be more active (Fox et al. 2000) than females during spawning events, it is difficult to apply the telemetry data to spawning habitat quantification. For example, Bain described males as occupying a stretch of the Hudson River greater than 100km in length during the spawning season; however females were relegated to two concentration zones totaling about 20km in length (1997). Although telemetry of a mature female and egg collections is nearly essential to begin the quantification of potential spawning habitat, some assumptions can be drawn based on the telemetry of adult male Atlantic sturgeon.

The upriver migrations made by Atlantic sturgeons #1744 and #1225 are also significant when compared to the movements of juveniles documented during 2005-2006. Only in a few isolated incidences were relocations of telemetered juvenile Atlantic sturgeon made above the Commodore Barry Bridge (rkm 135); the majority of relocations occurred in the area of Marcus Hook (rkm 125) or below. This may indicate some spatial separation between adult and juvenile Atlantic sturgeon, and would be inconsistent with the findings of prior research (Bain 1997; Fox et al. 2000; Hightower et al. 2002), where no spatial separation existed between spawning adults and juveniles.

Although a population assessment is not one of the specific objectives of this research, the low numbers of Atlantic sturgeon collected given the effort expended is worth some discussion. Our low CPUE is troubling considering in 1888, nearly 3.0 million kilograms of Atlantic sturgeon were harvested from the Delaware River (Secor and Waldman 1999). Ultimately, during 2005 and 2006, fishing efforts were almost completely fruitless, especially those targeted at adult Atlantic sturgeon. Although sampling restrictions (not being able to sample within the shipping channel) may have limited our catch rates, restrictions alone cannot account for such a low CPUE.

However low the CPUE, the fact remains that sexually mature Atlantic sturgeon were captured in Delaware Bay. A problem that is of growing concern to the continued existence of Atlantic sturgeon in the Delaware River is mortalities of Atlantic sturgeon by boat strikes. This is not a new problem as it has been observed anecdotally over the last few years. During each of the past two years approximately 5-10 adult (>1.3m) Atlantic sturgeon have been observed with blunt trauma that is indicative of being struck by a boat. Results provided through this study indicate that Atlantic sturgeon (juveniles and adults) often inhabit main channel habitats (Figure 7a) The navigation depth of this channel is currently maintained at 12.2m by the USACE. Aside from being the largest free flowing river on the East Coast, the Delaware River is also the busiest freshwater commercial port. Large commercial ships often have limited bottom clearance (<2m) when transiting the Delaware River. This fact coupled with Atlantic sturgeon occupying main channel habitat increases the probability that a boat strike incident will occur.

Our results indicate that juvenile Atlantic sturgeon occupy specific sections of the Delaware River for prolonged periods during the summer months. Based on our telemetry results we have identified three riverine concentration areas of telemetered juvenile Atlantic sturgeon: Artificial Island (rkm 89), Cherry Island Flats (rkm 110), and Marcus Hook Anchorage (rkm 125). The lower two sites, Artificial Island and Cherry Island Flats, were previously identified and it was noted that substrate composition may play a role as a unifying characteristic for the two sites (Shirey 1997). A recent study looking at the substrate composition of the upper two areas note that they are predominated by mixed gravel and sand sediments with areas of non-depositional substrate, however not necessarily due to the presence of slag deposits (Sommerfield and Madsen 2003).

Based on our recapture data, many juvenile Atlantic sturgeon within Delaware Bay and River likely do not stem from Delaware River genetic stock. While a specific genetic haplotype has been identified for the Delaware River Atlantic sturgeon population (Tim King, pers comm.), our netting efforts and telemetry results, as well as mark-recapture data collected by DNREC (Greg Murphy, pers comm.) indicate juvenile Atlantic sturgeon collected and or spawned in other rivers are using the Delaware River and Bay as a nursery habitat. In terms of management implications, the lack of a distinctive stock could significantly alter recovery efforts. If stocking programs were ever to be implemented, such genetic considerations would come into play.

Conclusions

Our telemetry results coupled with the collection of ripe male Atlantic sturgeon although not conclusive provide strong evidence to suggest that a remnant population of spawning Atlantic sturgeon exists in the Delaware River. Although the location of spawning habitat has not been confirmed, our telemetry results together with information on substrate and water quality data indicate that spawning may be occurring between mid-June - late June in freshwater-tidal reaches between north Philadelphia, PA (rkm 176) and Trenton, NJ (rkm 211). These spawning areas are located much further upriver than historically reported spawning grounds (rkm 75 – 130; Ryder 1890, Cobb 1899) which may, in part, be due to increased saltwater intrusion. The effects of increased saltwater intrusion on Atlantic sturgeon in the Delaware River although not well understood, may continue to play a role in the slow recovery of this population especially with the political and socio-economic pressure to expand dredging efforts in the river potentially furthering the saltwater intrusion and reducing available habitat.

Atlantic sturgeon bycatch mortality is known to occur in both the Delaware Estuary and nearby continental shelf regions (Stein et al. 2004), and undoubtedly has played a role in slowing the recovery of this population. We became aware of an additional source of mortality during the course of this study as we documented numerous reports of adult and juvenile Atlantic sturgeon mortalities, many of which were likely caused by propeller strikes. The Delaware River serves as one of the most important shipping ports in the US and is the number one east coast port for petroleum shipments. This strategic importance must be weighed against the costs to the ecological integrity of the Delaware River Estuary. At present there are numerous large-scale shipping and refining projects proposed for the Delaware Estuary. We propose that managers should apply a precautionary approach to the approval of any such projects and take into account how their potential impacts can alter the recovery trajectory for what was once the largest population of Atlantic sturgeon.

Acknowledgements

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Figure 1. Passive receivers (Vemco VR2) used for Atlantic sturgeon telemetry, 2005.

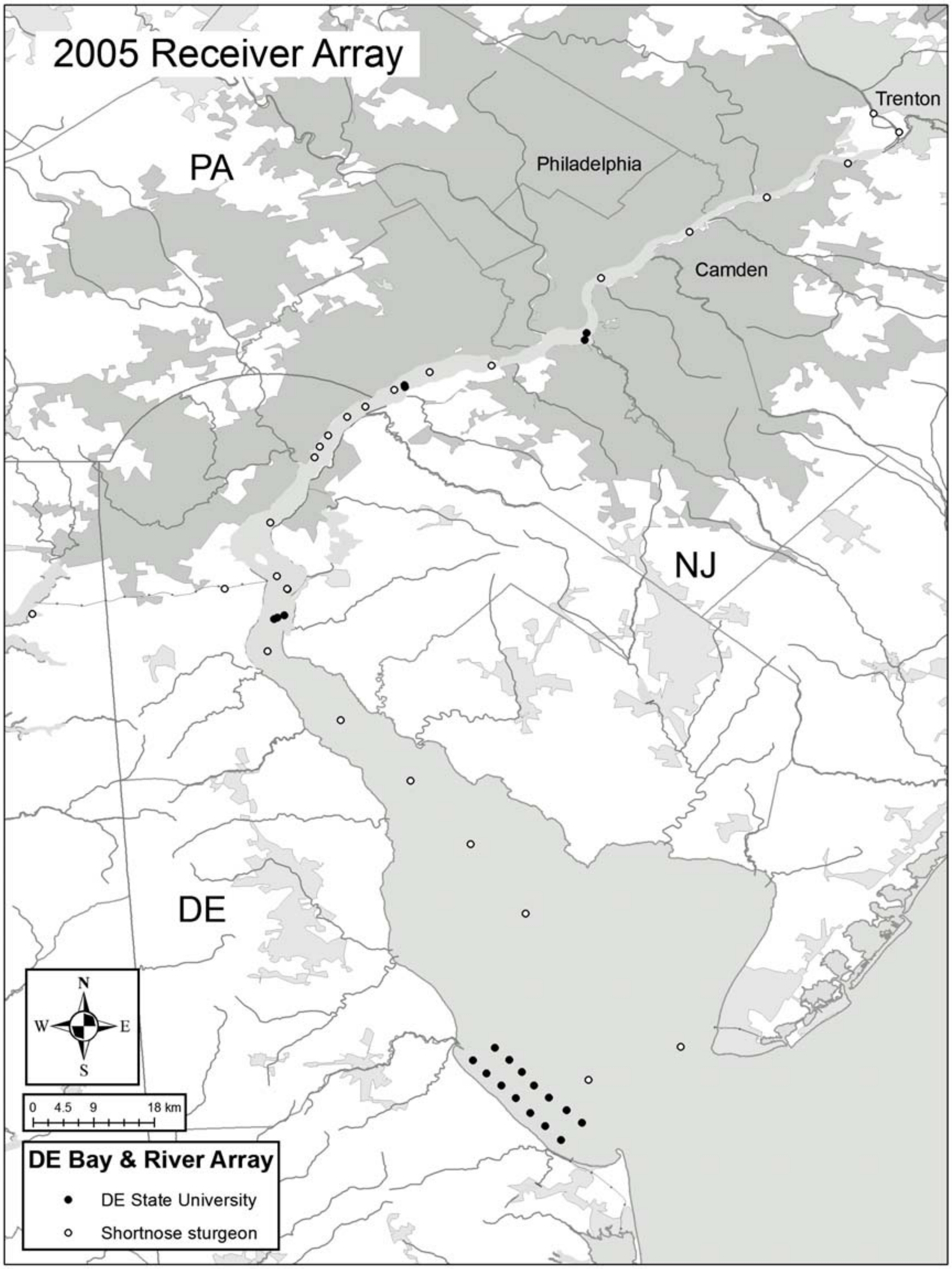

Figure 2. Passive receivers (Vemco VR2) used for Atlantic sturgeon telemetry, 2006.

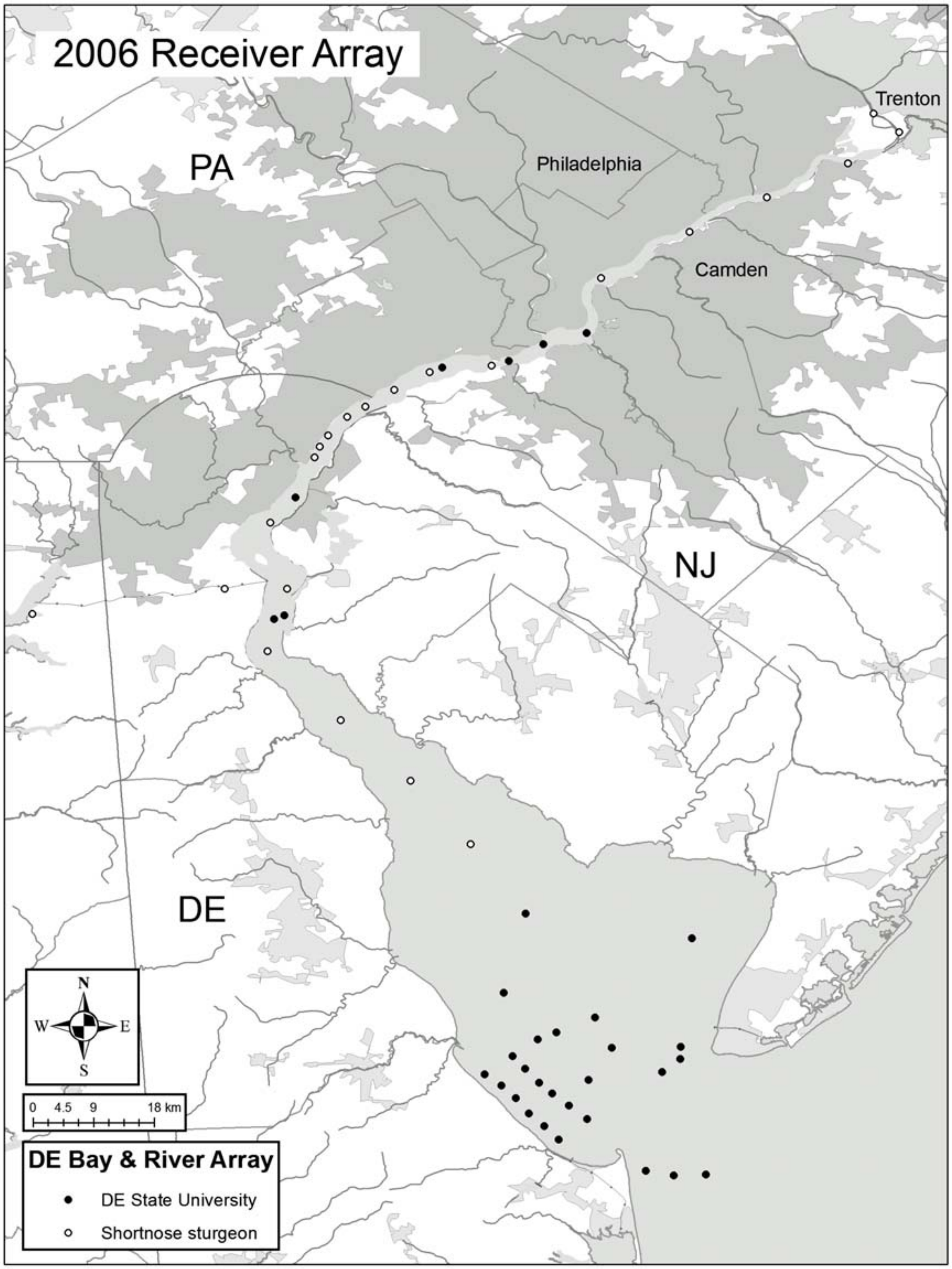

Figure 3. Schematic of VR2 deployment using USCG navigational aide.

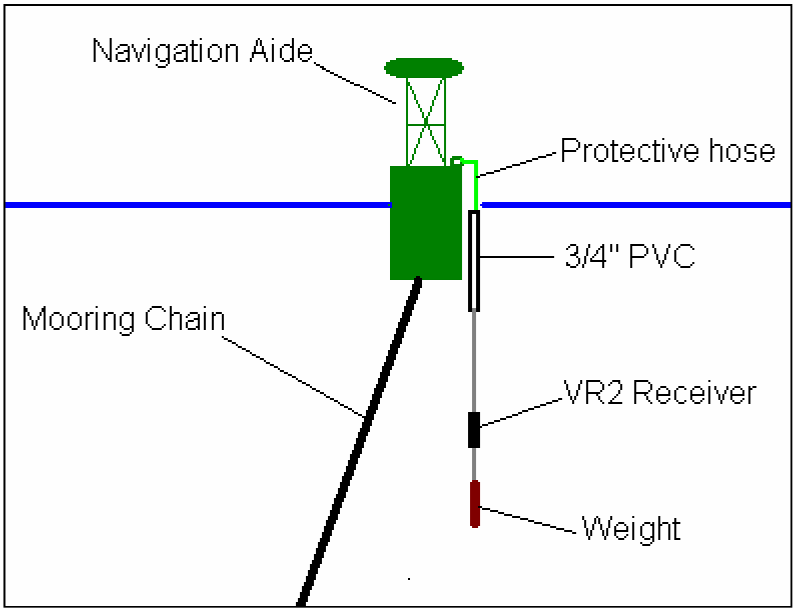

Figure 4. Atlantic sturgeon netting and capture locations, 2005-2006.

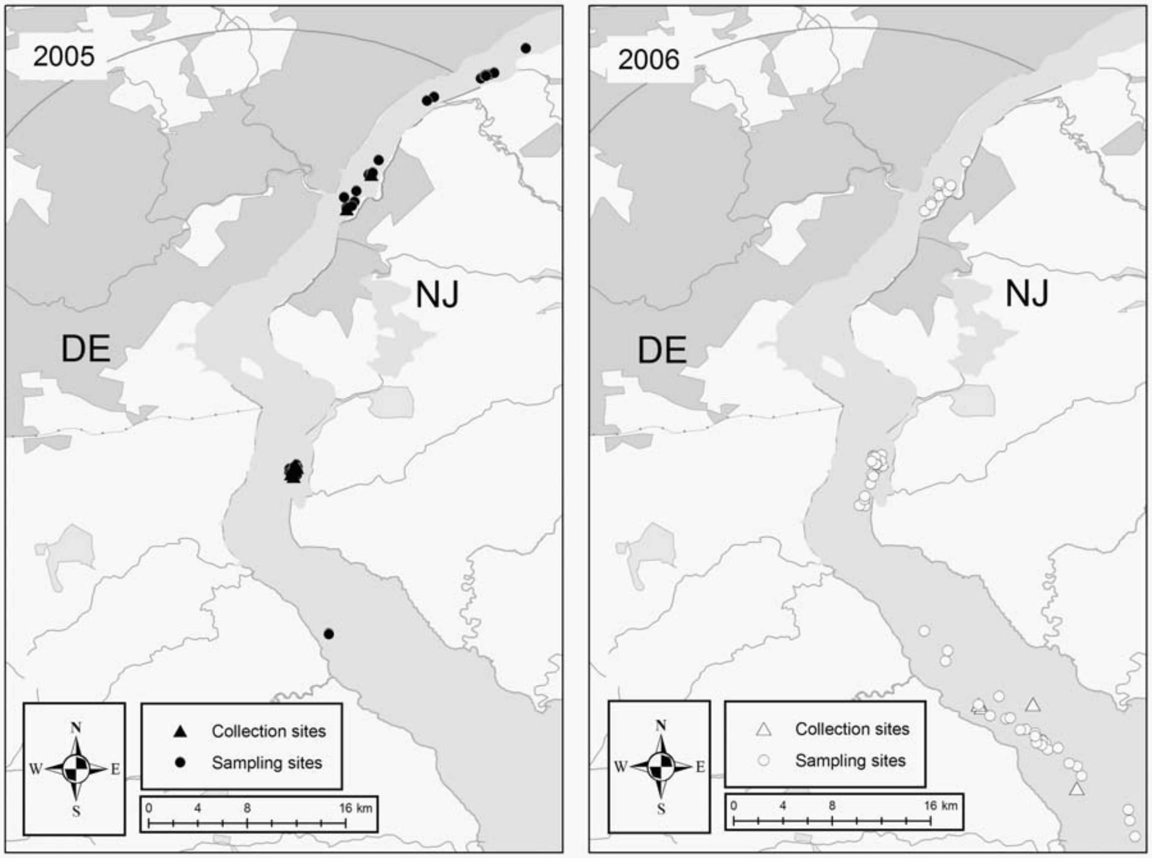

Figure 5. Passive relocations for juvenile Atlantic sturgeon, 2005-06.

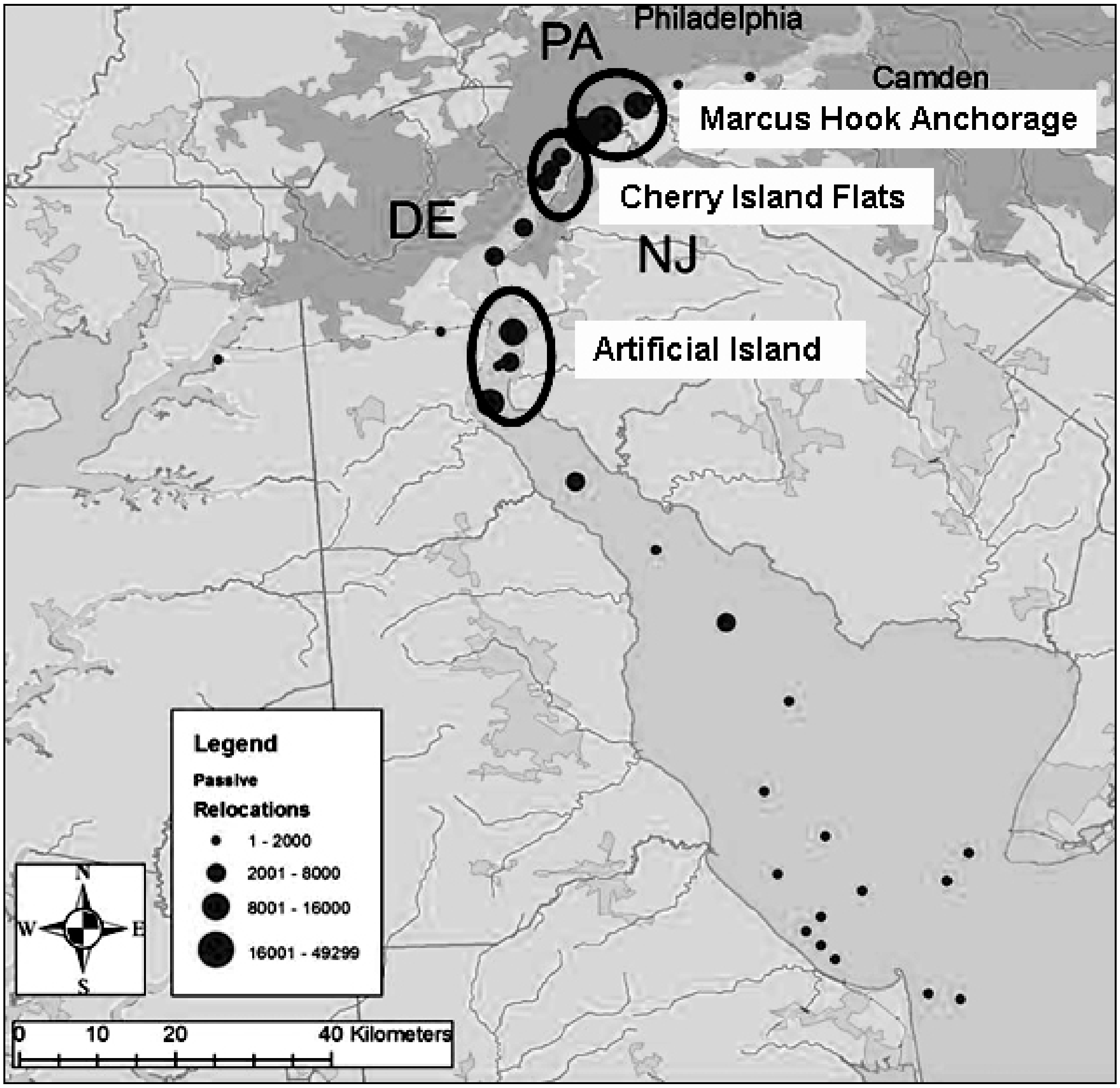

Figure 6a. 2005 Atlantic sturgeon movement.

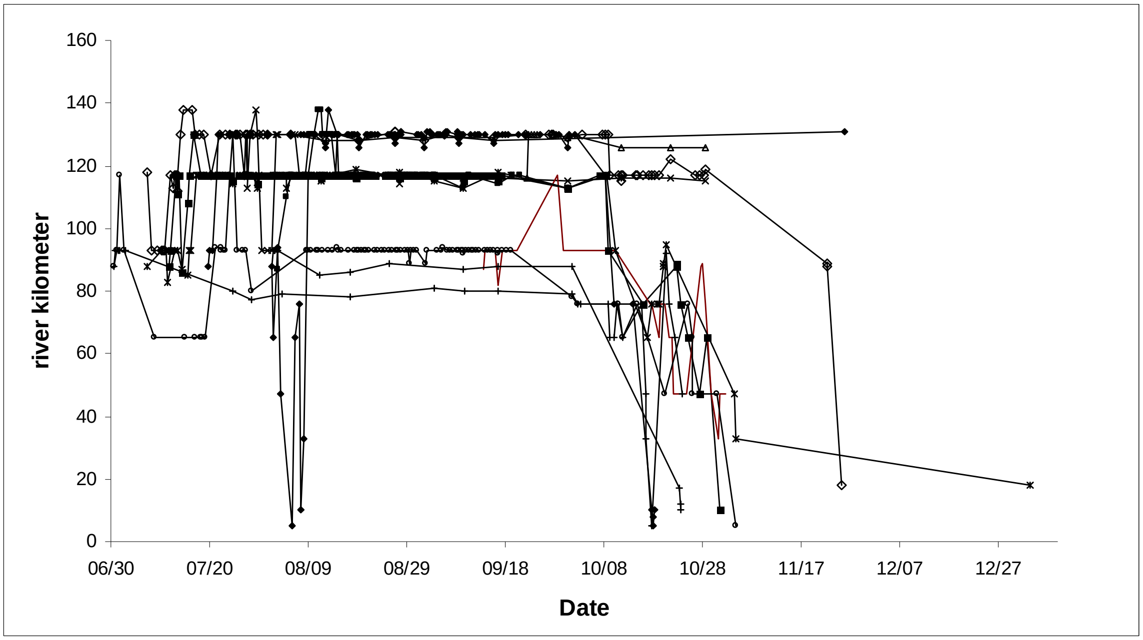

Figure 6b. 2006 Juvenile Atlantic sturgeon movement.

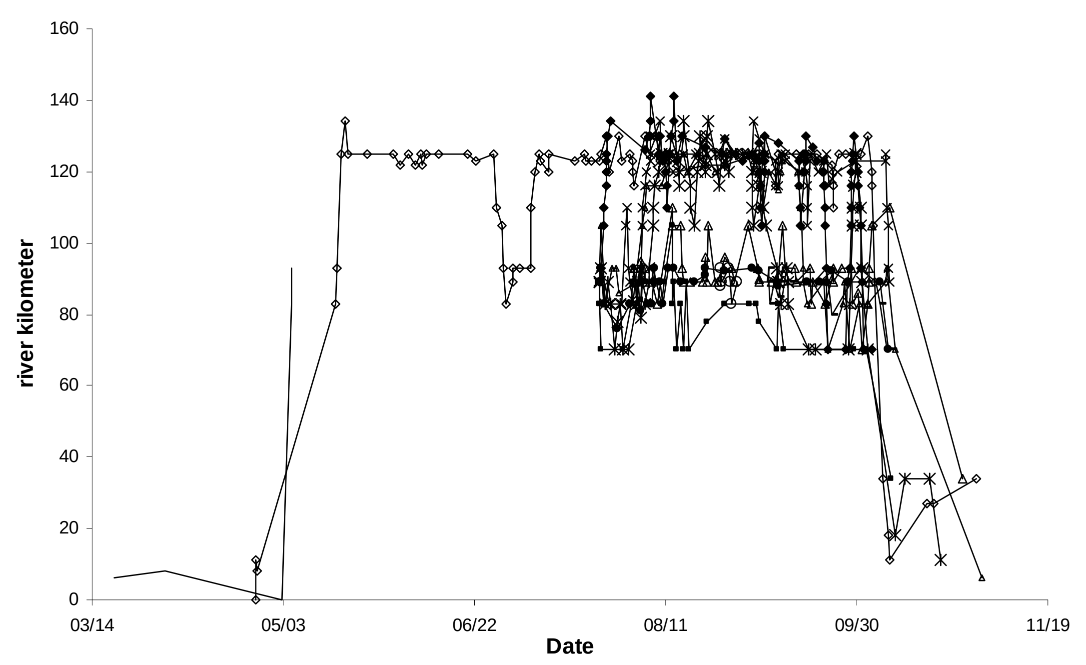

Figure 6c. 2006 Adult Atlantic sturgeon movement.

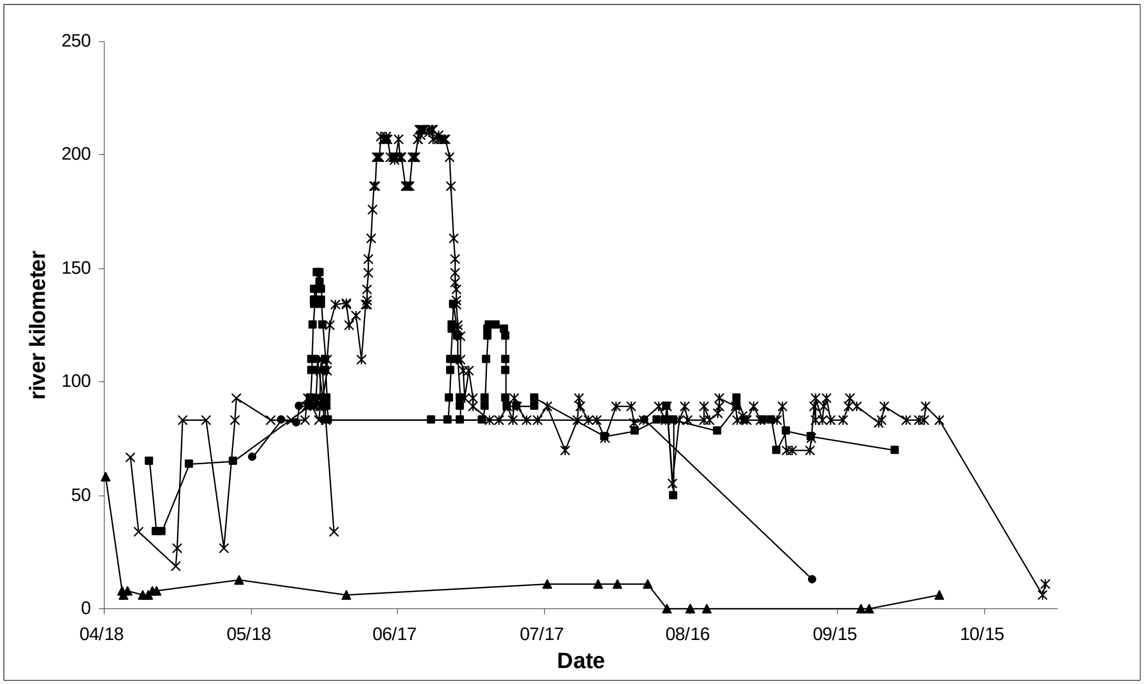

Figure 7a. Atlantic sturgeon utilized vs. available depth. Based on manual relocation data, 2005-2006.

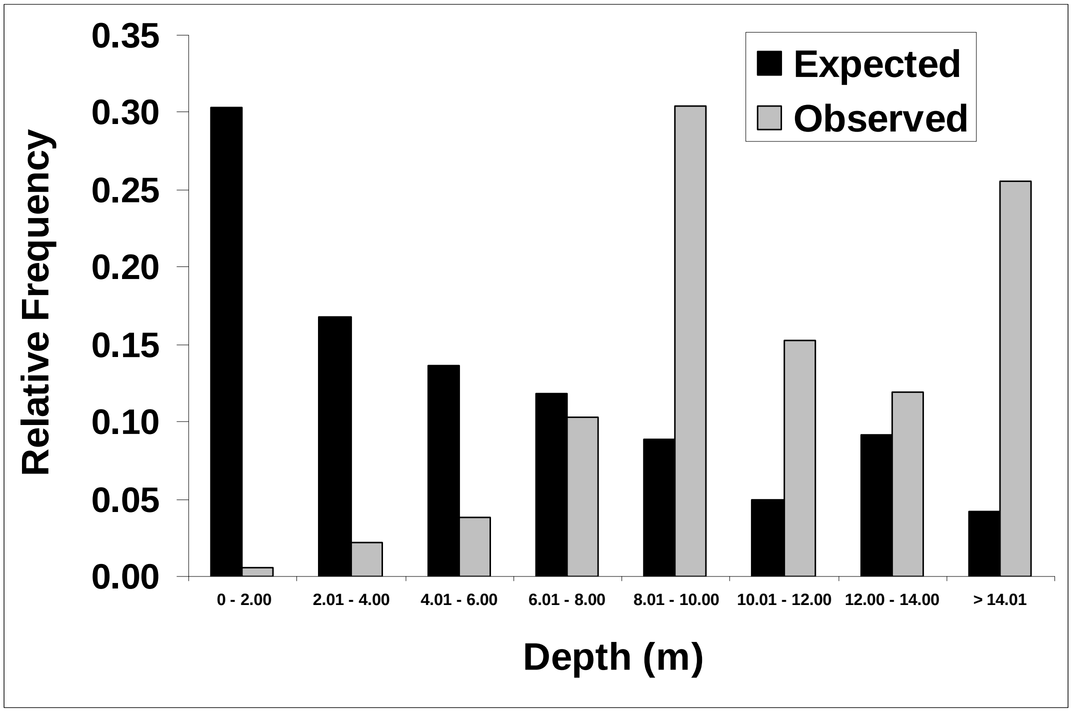

Figure 7b. Atlantic sturgeon utilized vs. available substrate type.
Based on manual relocation data, 2005-2006.

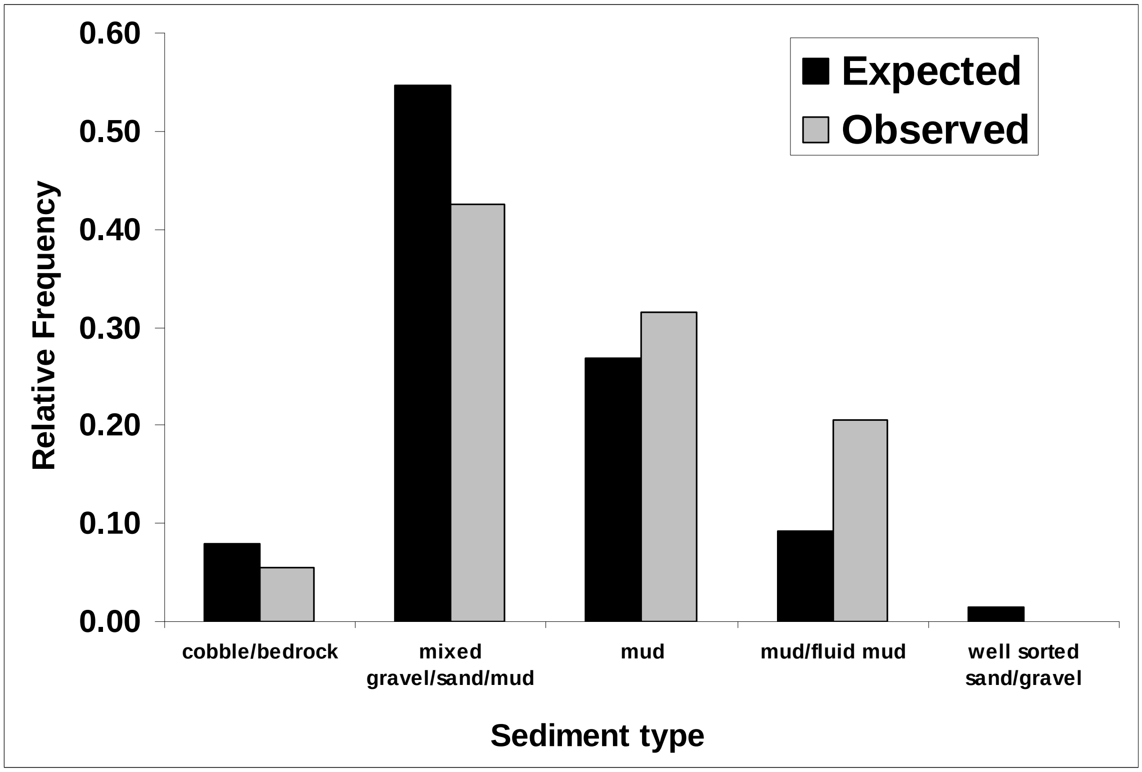

Figure 8: Summary movement patterns for ripe male adult Atlantic sturgeon which was implanted with transmitter # 1744 on June 1, 2006.

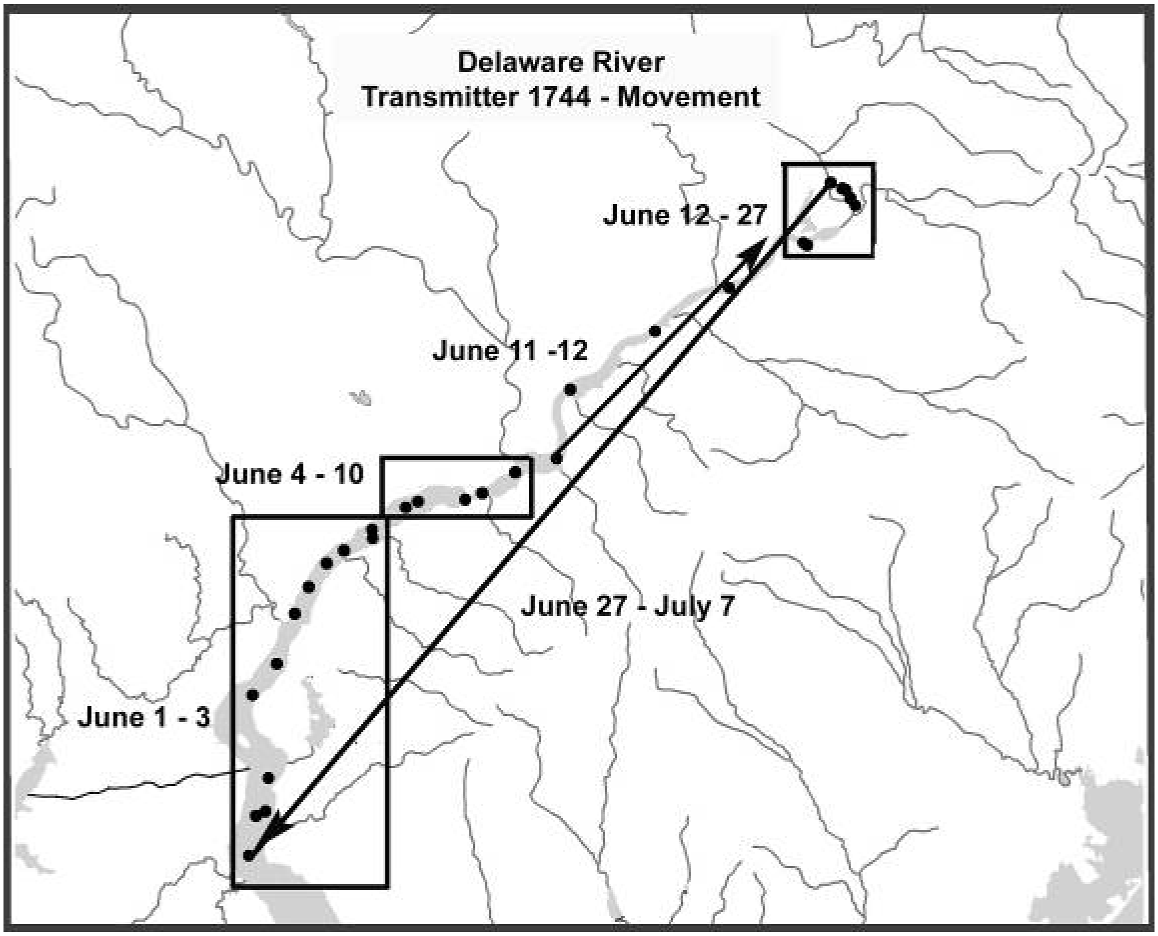

Figure 9. Atlantic sturgeon egg pad deployment locations, 2006.

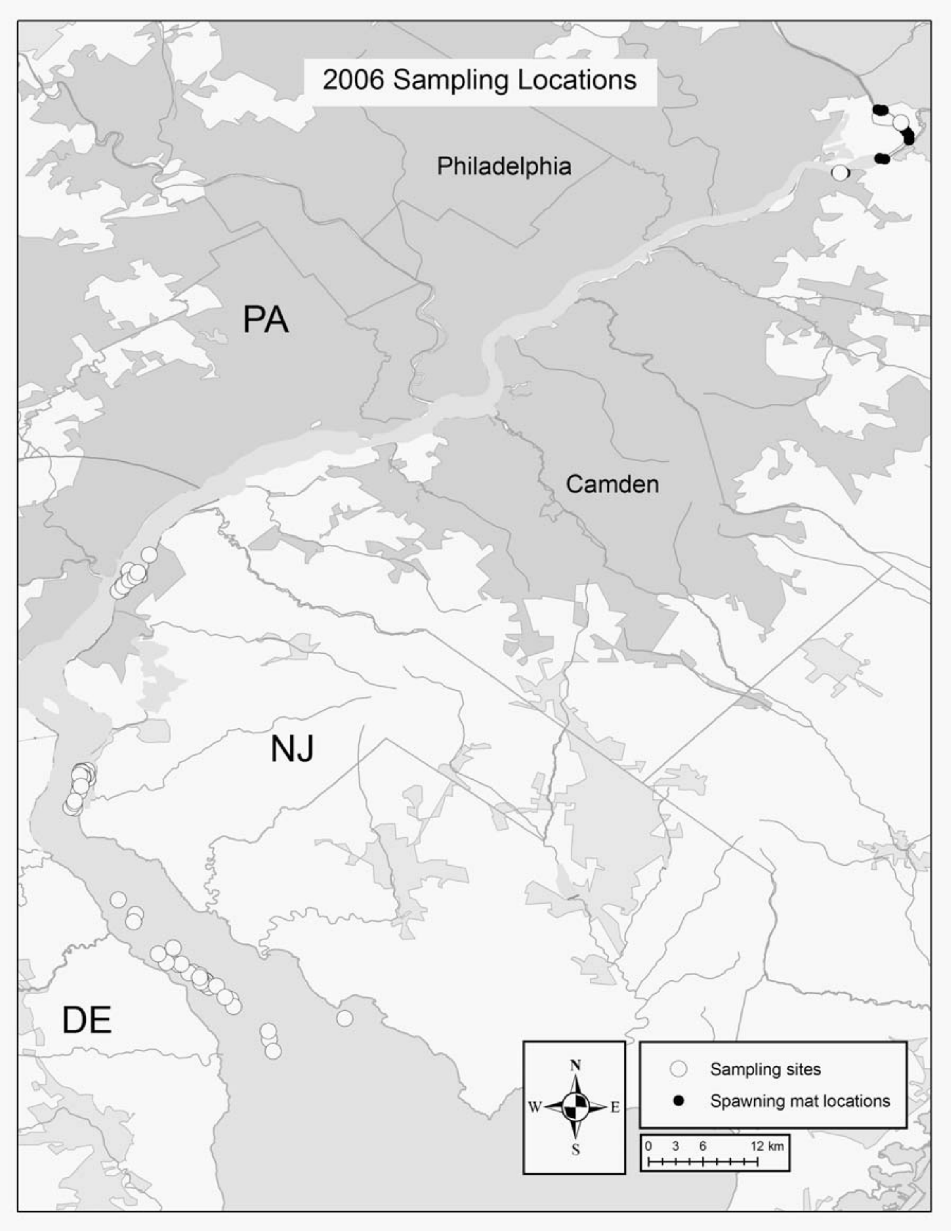

Table 1. Catch per unit effort, 2005.

Total Net Fished (m^2)	115998.7
Total Hours Fished	253.3
Total Catch	23
CPUE (catch/m^2/hr)	7.83E-07

Table 2. Length summary for captured and telemeterd Atlantic sturgeon, 2005.

	Minimum	Maximum
Fork Length (cm), non-telemetered captures	56.0	94.0
Weight (kg), non-telemetered captures	1.6	2.9
Fork Length (cm), telemetered captures	78.4	122.5
Weight (kg), telemetered captures	4.2	10.0

Table 3. Catch per unit effort, 2006.

Total Net Fished (m^2)	73046.9
Total Hours Fished	2585.0
Total Catch	18
CPUE (catch/m^2/hr)	7.41E-08

Table 4. Length summary for captured and telemeterd Atlantic sturgeon, 2006.

	Minimum	Maximum
Fork Length (cm), non-telemetered captures	57.4	71.2
Weight (kg), non-telemetered captures	1.5	2.1
Fork Length (cm), telemetered captures	67.8	158.0
Weight (kg), telemetered captures	2.5	28.4

Table 5. Atlantic sturgeon relocation summary 2005-2006.

Fish ID	Date Captured	Fork Length (mm)	Passive Detections	Manual Detections	Total Detections	Date Last Relocated
1232	6/30/2005	820	761	10	771	8/18/2006
1234	6/30/2005	913	4132	5	4137	5/5/2006
1233	7/7/2005	880	1002	15	1017	11/3/2005
1229	7/7/2005	851	50754	20	50774	10/31/2006
1224	7/11/2005	784	2121	13	2134	4/25/2006
1223	7/19/2005	950	7606	8	7614	4/26/2006
1222	7/27/2005	1225	499	11	510	10/28/2005
1221	8/1/2005	940	2641	7	2648	11/25/2005
1230	8/1/2005	970	534	6	540	5/28/2006
1231	8/2/2005	1140	881	8	889	9/30/2005
1227	9/13/2005	785	5133	3	5136	11/1/2005
1235	9/22/2005	857	4900	5	4905	1/6/2006
1226	4/18/2006	1210	1770	0	1770	10/5/2006
1228	4/23/2006	1550	1436	0	1436	6/3/2006
1225	4/27/2006	1580	3169	8	3177	9/26/2006
1747	5/18/2006	1370	714	1	715	9/9/2006
1744	6/1/2006	1370	13877	15	13892	10/27/2006
1731	7/24/2006	796	15722	7	15729	10/3/2006
1732	7/24/2006	969	5604	5	5609	10/9/2006
1733	7/24/2006	782	14788	6	14794	10/8/2006
1740	7/24/2006	800	4596	7	4603	10/8/2006
1742	7/24/2006	780	14292	7	14299	10/21/2006
1746	7/24/2006	818	9459	6	9465	11/1/2006
1739	8/2/2006	722	1	1	2	8/2/2006
1741	8/2/2006	678	8720	7	8727	10/27/2006
1750	8/25/2006	808	800	0	800	8/29/2006
1734	9/6/2006	754	6087	2	6089	10/9/2006
Total Passive Detections			181999			
Total Manual Detections				183		
Total Detections					182182	