Adult Atlantic Sturgeon *(Acipenser oxyrinchus oxyrinchus)* Habitat
Use and Run-Size in the Hudson River
Hyde Park Reach, NY

By

Amy Marie Comer

A Thesis

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This thesis is approved by the following members of the Final Oral Review Committee:

Dr. Dewayne Fox, Committee Chairperson, Department of Agriculture and Natural Resources, Delaware State University
Dr. Kevina Vulinec, Committee Member, Department of Agriculture and Natural Resources, Delaware State University
Dr. Dennis McIntosh, Committee Member, Department of Agriculture and Natural Resources, Delaware State University
Dr. John Madsen, External Committee Member, Department of Geological Sciences, University of Delaware

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Adult Atlantic Sturgeon *(Acipenser oxyrinchus oxyrinchus)* Habitat Use and Run-Size in the Hudson River Hyde Park Reach, NY

Amy M. Comer

Faculty Advisor: Dr. Dewayne Fox

ABSTRACT

Sturgeons (Acipenseridae) including the Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) are among the most threatened family of vertebrates. In the United States, Atlantic Sturgeon were listed under the Endangered Species Act in 2012. The listing delineated five Distinct Population Segments (DPS), four of which were classified as endangered (New York Bight (NYB), Chesapeake Bay, Carolina, and South Atlantic), while the Gulf of Maine was listed as threatened. Overall, Atlantic Sturgeon populations are significantly reduced from historic levels as a result of overfishing, habitat loss, and pollution.

In the Hudson River, Atlantic Sturgeons population size has been affected heavily due to overfishing in the late 1800's. For recovery of the species, it's important to understand their habitat requirements. The first objective of my thesis was to assess adult Atlantic Sturgeon habitat use during their annual spawning migration while on purported spawning grounds. During 2013 and 2014, I surveyed the Hyde Park Reach of the Hudson River, NY using side-scan sonar which is a non-invasive sampling option. In this region, Atlantic Sturgeon selected for sand and muddy sands with sands substrates. Within the study site, hotspots of Atlantic Sturgeon were delineated in the middle of the reach just south of Esopus Island, and in the southeastern

portion of the reach near Rogers Point. These likely spawners used multiple sediment types while in the riverine environment. The results of this study suggest Atlantic Sturgeon use the Hyde Park Reach as a possible spawning and staging site. These results also suggest that sediment type is not the only variable that is driving Atlantic Sturgeon presence.

My second objective was to estimate the 2014 likely spawners run size of Atlantic Sturgeon using Swept-Area and N-mixture modeling. Estimated run-size abundances in the Hyde Park Reach using swept-area were 113 – 188 Atlantic Sturgeon (95% CI's 74-275) for four-three consecutive surveys between 06/11/14 – 07/02/14 while N-mixture estimates were 171 – 306 Atlantic sturgeon (95% CI's 75 – 560). It is important to note that these estimates do not account for individuals occurring in the other spawning sites in the Hudson River. Comparing the two models, the N-mixture model produced estimates at approximately 1 – 2.3 times larger than swept-area estimates per time-period, likely due to the large variation in daily count data. In the case of a highly mobile species such as the Atlantic Sturgeon, it may be prudent to increase site sizes to include average movement of sturgeon, which would help to meet the assumptions of N-mixture modeling, and reduce variation in model estimates.

Through my research efforts, I have been able to successfully sample Atlantic Sturgeon while on proposed spawning grounds with a non-invasive technology, which allowed for fine-scale habitat and behavior information during an important life stage that is currently not well understood. Gaining insights into the Hyde Park Reach as a possible spawning and staging location, will help to serve as important with future management efforts. Furthermore, understanding that sediment type may not be the only important factor while adult Atlantic Sturgeon are in the riverine environment and that habitat features near spawning grounds may want to be considered when developing management actions and the critical habitat designations in the riverine environment. Data from this thesis further underscores the need to identify and protect critical habitats thereby fostering conservation and recovery of this imperiled species. Finally, through this research I was also able to integrate side-scan sonar and acoustic telemetry as an effective approach for estimating run-size abundance of in the Hyde Park Reach of the Hudson River. The approach presented here appears to be a viable option and can be fitted for Atlantic Sturgeon or other large species in other river systems, which could aid in the restoration of this endangered species.

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CHAPTER 1: ABSTRACT

Sturgeons (Acipenseridae) are among the oldest extant fishes, having survived over 75 million years, although today they are recognized worldwide as the most imperiled group of vertebrates. Populations of Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) in the Hudson River, NY have been reduced to less than 10% of their historic status due to a combination of overfishing and habitat loss. Although this species has been the focus of numerous studies, information on the specific habitat requirements of spawning adults is poorly understood. In this study, I used side-scan sonar to examine the habitat use and spatial distribution of presumed spawning Atlantic Sturgeon in the Hyde Park Reach of the Hudson River, NY in 2013 and 2014. A total of 104 adult Atlantic Sturgeon with a mean size of 1.9 m TL were imaged over three sampling dates in 2013, while in 2014, a total of 479 individuals (mean 2.0 m TL) were identified over 12 sampling days. Atlantic Sturgeon actively selected for 'sands' and 'muddy sands with sands' while avoiding other habitat types. An examination of their spatial distribution denoted significant hotspots while they used bedrock, muddy sands with sands, and sandy habitats. My findings suggest that the Hyde Park Reach serves the roles of both staging and spawning habitats for Atlantic Sturgeon, which further underscores the need to identify and protect critical habitats thereby fostering conservation and recovery of this imperiled species.

CHAPTER 1: INTRODUCTION

Sturgeons, family Acipenseridae, are comprised of 25 species in the northern hemisphere (Elvira et al. 2015) with fossils dating back almost 100 million years (Choudhury and Dick 1998). Unfortunately, sturgeons have suffered overharvest and habitat destruction, leading to their being more critically endangered than any other group of species by the International Union for the Conservation of Nature in 2010 (IUCN 2010). Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) historically ranged from the Baltic Sea in Europe (Ludwig et al. 2002) to the Atlantic coast of the United States and Canada where they occurred in all the major river systems from Hamilton Inlet, Labrador, Canada (Backus 1951) to the St. Johns River, Florida (Vladykov and Greeley 1963). Initially, overfishing in the late 1800's, triggered sharp declines in the Atlantic Sturgeon population coast-wide (Secor and Waldman 1999), and due to small population sizes and their lack of recovery, Atlantic Sturgeon were listed under the Endangered Species Act (NOAA 2012a, 2012b), with the Gulf of Maine distinct population segment (DPS) listed as threatened, while the southern four DPS, New York Bight, Chesapeake Bay, Carolina, and the South Atlantic were listed as endangered.

Atlantic Sturgeon are a long-lived species exhibiting late maturation, slow growth, and infrequent reproduction. Details of age, maturity and growth vary across the species range, but in the middle of the range, in the Hudson River, Atlantic Sturgeon can grow to be approximately 60 years of age, exhibit high fecundity (0.4-2.6 million eggs/spawning interval), with males maturing between 11-20, while females reach adulthood at 15-30 years of age (Dovel 1979; Dovel and Berggren 1983; Van Eenennaam et al. 1996). Spawning intervals vary by sex with females spawning every 3 to 5 years, and males capable of spawning at shorter intervals (Smith 1985). Although these life history traits diminish lifetime fecundity and population recovery, they also enable Atlantic Sturgeon to withstand years or even decades without proper spawning conditions (Secor and Waldman 1999).

The Atlantic Sturgeon requires a wide range of estuarine, freshwater, and marine habitats to complete their life cycle, including pre-spawning, spawning, early life stage survival, survival and growth of juveniles, and adult migrations (NOAA 1998). In order to spawn, Atlantic Sturgeon require freshwater, high DO, hard bottom habitat such as bedrock or gravel, and warm temperatures between 17° to 22° Celsius (Ryder 1888; Theodore et al. 1980; Sulak and Clugston 1999). Today, the tidally influenced Hudson River Estuary is thought to support one of the largest populations of both Atlantic and Shortnose Sturgeons (*A. brevirostrum*; Bain et al. 2007), and begins at the dam in Troy, NY (river kilometer (rkm) 246) and runs south to New York Harbor (rkm 0) (Figure 1-1). Atlantic Sturgeon are believed to spawn in several distinct regions including Clinton Point (rkm 112), Hyde Park (rkm 127 –138), and the Catskills (rkm 182) (Dovel and Berggren 1983; Van Eenennaam et al. 1996; Bain et al. 1998; Bain et al. 2000). Since the salt front (defined as 100 mg/l of chloride) is typically around rkm 82 on normal years, and can get as high as Poughkeepsie, NY (rkm 124) during drought years (USGS 2013), Clinton Point may not be suitable during low rainfall or drought years. Spawning is believed to take place from late May into early July, although historic records mention a fall spawn (Bain et al. 2000) and recent findings suggest that fall spawning takes place in some southern rivers (Collins et al. 2000; Balazik et al. 2012; Smith et al. 2015). Spawning habitat is characterized by regions of freshwater, high flows, and coarse grain or hard bottom habitats (Ryder 1888; Smith and Clugston 1997).

Atlantic Sturgeon return to their natal rivers to spawn, which make them increasingly vulnerable to human interactions. The sometimes challenging environmental conditions (high flows, dynamic and rocky substrates), and the increased mortality risk during warm temperatures makes traditional sampling methodologies such as gillnetting, a less attractive option for sampling the species while in the riverine environment. Hydroacoustic technology may serve as a non-invasive option when dealing with threatened or endangered species (Tao et al. 2009) including sturgeons. Hydroacoustics employ sound waves to provide information about the underwater environment, and have been widely used in oceanographic studies to map underwater features (Johnson and Helferty 1990), image microneketon (Domokos et al. 2007), and more recently hydroacoustics have become an attractive option for use on sturgeons to provide non-invasive estimates of abundance, distribution, and behavior (Nealson and Brundage 2007; Grothues et al. 2008; Flowers and Hightower 2013). The development of side-scan sonars for the use on small vessels, has allowed for increased sampling coverage (area), eliminated issues with invasive sampling, and allow for assessments of habitat in riverine and marine environments without direct handling of the target species (Flowers and Hightower 2013).

Side-scan sonar systems were first developed for geological exploration of the ocean floor (Chesterman et al. 1958; Donovan et al. 1961) by the British National Institute of Oceanography post World War II (Trabant 1984). Side-scan sonar systems are able to provide large spatial coverage compared to traditional narrow beam echo-sounders (Farmer et al. 1999). Fisheries applications of side-scan sonar have traditionally focused on habitat (Nealson and Tritt 2003) although recent advancements in power and frequency have allowed for greater image resolution including near photo like quality images of bottom structure. Higher resolution has also improved the appearance of acoustic shadows cast by fish in the water column. These acoustic shadows provide insights on the morphology of targets and in some cases allow for species identification (Langkau et al. 2012; Flowers and Hightower 2013).

Due to their relatively large body size and/or distinct morphological features, sturgeons have been identified as suitable for side-scan sonar studies (Nealson and Brundage 2007; Grothues et al. 2008; Tao et al. 2009), as they often produce shadows that yield shape information (Langkau et al. 2012). In the case where multiple species share morphological traits, it can be difficult if not impossible to distinguish between separate species. In the Hudson River for instance, Atlantic and Shortnose Sturgeons co-occur, and in the absence of size information differentiation would be extremely difficult. In the case of smaller (<1 m) fishes, targets elicit less defined shadows due to resolution constraints and may limit the ability to distinguish sturgeons from others species at shorter lengths (Flowers and Hightower 2013). When this is the case, relying on a secondary identification methodology may be necessary, such as a size distinction or coupling sampling methodologies (Flowers and Hightower 2013; Flowers and Hightower 2015).

Until its closure in 1996, the Hudson River Atlantic Sturgeon fishery was centered in the Hyde Park region. Evidence supporting this region's consideration as a spawning site included high abundances, the presence of gravid females (Van Eenennaam et al. 1996), and the presence of recently spent, and/or flowing males (Bain et al. 2000). Published studies (Van Eenennaam et al. 1996; Bain et al. 1998, 2000) and recent telemetry results (D. Fox, Delaware State University, unpublished data) suggest that Hyde Park is currently the largest of the Hudson River's presumed spawning sites or aggregations. Past studies show that this region is comprised of a mix of sandy mud, sandy gravel, and muddy sands (NYSDEC 2004) with limited hard-bottom habitat, which paradoxically provides little suitable spawning substrates for Atlantic Sturgeon. The exceptions are two small islands (Esopus and Bolles Islands) and one small outcropping on the southwest side of the main shipping channel (Figure 1-1) that likely provide suitable hard-bottom spawning substrates for Atlantic Sturgeon.

The Hudson River population of Atlantic Sturgeon is one of the most studied, and a general framework has been developed for their patterns of occupancy (Breece 2012), movement (Dovel and Berggren 1983), and reproductive patterns (Van Eenennam et al. 1996; Van Eenennaam and Doroshov 1998). However, Atlantic Sturgeon habitat use while on their spawning runs is not well understood, and this knowledge could be necessary for the species' recovery. Limited knowledge of adult riverine requirements (ASSRT 2007) coupled with their current endangered listing status (NOAA 2012a, 2012b) underscores the need for an improved understanding of the drivers that dictate Atlantic Sturgeon habitat use during spawning migrations (Breece et al. 2013). While in the riverine environment, adult Atlantic Sturgeon require both staging (a holding location near the spawning site) and spawning habitats. In particular, male Atlantic Sturgeon will occupy staging habitats and then make several directed spawning runs of 10-50 km to and from spawning habitats (Hatin et al. 2002; Breece et al. 2013). As spawning has not been confirmed within Hyde Park Reach, it begs the question as to whether Hyde Park is serving as a spawning site, or whether it is a staging site, and what habitats are being used during their occupancy. My thesis therefore focused on Atlantic Sturgeon spawning run habitat use while in the Hyde Park Reach of the Hudson River. By understanding Atlantic Sturgeon habitat use while on their spawning runs, the importance of the Hyde Park region for conservation and recovery may be determined, as it may encompass pre-spawning (Breece et al. 2012), spawning, and/or post-spawning habitats (Bain et al. 2000), and may help to protect and foster the recovery of this imperiled species. This information can be used as managers look to both designate and protect critical habitats and to help inform conservation and recovery efforts in other systems where habitat alteration may have greatly impacted habitat availability and or suitability of spawning and staging habitats. These data from the Hudson River and from this study can serve as baseline data for other systems to use for the conservation and recovery of this endangered species.

CHAPTER I: METHODS

Study Site

My study was conducted in the Hyde Park Reach of the Hudson River, between Rogers and Dinsmore Points (rkm 127 – 138; Figure 1-1). The channelized portion of the Hudson River primarily consists of sand and clay, has a mean depth 10 m, and a tidal amplitude of 0.8 to 1.4 m (Limburg et al. 1989; Bain 1997). West Point, NY (rkm 82), generally marks the transition between the freshwater and estuarine portions of the Hudson River (Cooper et al. 1988) and due to the Federal Dam at Troy, diadromous fishes are limited to the lower 246 rkm (Limburg et al. 1989; Figure 1-1). The tidal portion of the Hudson River is a drowned fjord with a primarily U-shaped bathymetric profile and steep bluff banks (Grotheus et al. 2008). Within the Hyde Park Reach, depths range from 6.1 m – 38.1 m (NYS DOS OPD 2012), the water is fresh (Grotheus et al. 2008), and the bottom habitat consists of combinations of mud and sand (NYSDEC 2004; Figure 1-1).

Study Timing and Design

2013

To classify both the distribution of benthic habitats and assess Atlantic Sturgeon distribution, I employed a side scan sonar and completed 12 transects to provide coverage across the entire study over a three-day period (6/18/13 – 6/20/13; Figures 1-2, 1-3). The effective swath width for each transect was 70 m of the river bottom, allowing for roughly 10% overlap with the previous transect to ensure that a full mosaic of the river bottom could be generated. Originally, sampling was scheduled for two, non-consecutive week-long sampling periods, coinciding with the presumed peak of Atlantic Sturgeon reproduction in the Hudson River (Bain et al. 2000; Amanda Higgs, NYSDEC, personal communication). However, equipment malfunctions limited sampling to the three-day period.

2014

During 2014, I assumed that the distribution of benthic sediments had not markedly changed in the previous year, so I focused my efforts on the habitat use and spatial distribution of Atlantic Sturgeon. Four three consecutive day sampling periods occurred from June 11, 2014 – July 2, 2014 (6/11-6/13; 6/17-6/19; 6/23-6/25; 6/30-7/02). Prior to the initiation of sampling, I stratified the Hyde Park Reach into 20% blocks of cross sectional river area as determined by Google Earth (river width from west to east: A: 0%-20% (0-167 m); B: 21%-40% (168-335 m); C: 41%-60% (336-503 m); D: 61%-80% (504-670 m); E: 81%-100% (671-836)). Within strata, I used a random number generator (Microsoft Excel 2010) to randomly select a starting point which was repeatedly sampled each sampling day. This resulted in five transects (transects A-E) covering approximately 70 km of linear river bottom/day with a beam width of 70 m or 41% of available habitat (Figures 1-2, 1-3). Finally, a second random number generator (Microsoft Excel 2010) was used to select the order of the five transects (A-E) on each sampling day. It should be noted that on the first and last sampling day (06/11 and 07/02), only four of the five transects were scanned due to logistics and weather issues, respectively.

Side-Scan Sonar

An Edgetech 4125-P sonar system consisting of a towfish with 400/900 kilohertz (kHz) (2013) or 600/1600 kHz (2014) dual frequency transducer, equipped with a portable topside processor, and laptop running EdgeTech© Discover acquisition software (EdgeTech, West Wareham, MA) was used during data collection (Figure 1-4). The use of different sonar transducers was the result of a towfish failure in 2013 and subsequent replacement in 2014. The boat's location was determined using a Garmin GPS unit, while the position of the towfish was calculated relative to the boat's position by calculating length of cable deployed (layback), and measuring the offsets of 0.9 m to starboard and 1.5 m aft for the position of the cable tow point relative to the mounted GPS antenna. The sonar was towed at speeds of 4.5– 10.0 km/h and towed at a targeted depth of 5 m above bottom, but ranged from 2 – 15 m above bottom, or occasionally more if the depth exceeded the length of the tow cable (max = 25 m).

Although Atlantic Sturgeon are generally thought to be benthically oriented (Nelson et al. 2013), they are occasionally seen breaching. A previous side-scan sonar survey of Atlantic Sturgeon within the Hyde Park Reach, showed individuals averaging an altitude of 1.8 m above bottom (0.7 m S.D.; Grothues et al. 2008). To ensure proper depth placement of the towed side-scan sonar, a hull mounted side-scan sonar (Humminbird 1198c-455/800 kHz dual frequency) was also used to evaluate the presence of fish above the side-scan sonar depth. There were few incidents where a fish was observed above the towed side-scan sonar (Dewayne Fox, personal observation). Based on previous work (Grothues et al. 2008) and unpublished results (D. Fox Delaware State University; personal observation) I felt confident in my ability to image the majority of Atlantic Sturgeon in the survey area.

Atlantic Sturgeon Identification

Post-processing of side-scan sonar data was conducted using SonarWiz5© software (Chesapeake Technology, Mountain View, CA). Classification of hydroacoustic data is often subjective and may vary based on observer experience as well as the size and shape of targets

(Woodd-Walker et al. 2003; Flowers and Hightower 2013). To account for this, one observer processed all side-scan data and classified targets, a second observer independently reviewed 25% of the data and classified targets. An identification probability was generated by evaluating the agreement and taking the mean count difference between the readers.

During post-processing, I was able to assign bottom tracking to all of the side-scan files, which allowed for use of the SonarWiz selection tools to estimate each target's position (i.e. latitude and longitude). When a target was observed, I noted its position, length (m), height off bottom (m), and each target was classified as "yes", "no," or "suspected" adult Atlantic Sturgeon (Figures 1-5, 1-6) based on size and morphology (shadow shape). Body or target length was the standard measurement, however, in cases where the target body image was distorted or obscured, the length of the target's shadow was used (estimated use at <1%; Flowers and Hightower 2013). If a target's shape was distorted in a way that was likely to affect the length measurement (Figure 1-7), all information but length was used. Furthermore, in an attempt to avoid positively biased estimates, I constrained my analyses to targets that were classified as "yes" sturgeon. Due to their morphological similarity, I was not able to distinguish between Atlantic and Shortnose Sturgeons solely on the basis of body shape. However, I chose to censor "yes" Atlantic Sturgeon to a ≥1.5 m size class, which should have left little opportunity for misidentification of a Shortnose Sturgeon as an Atlantic Sturgeon, as Shortnose Sturgeon reach a maximum size of <1.3 m Fork Length (FL) or 1.4 m Total Length (TL; Birstein 1993). All "yes ≥1.5 m" adult Atlantic Sturgeon targets were then exported into ArcGIS 10.2 (ESRI, Redlands, CA) for assessment of habitat use and spatial distribution.

Habitat Classification

Post-processing of the habitat data were provided by Dr. John Madsen (University of Delaware). Available habitat, including sediment grain size texture classes, were based on both the dominant and largest subdominant components as defined by a modified Wentworth scale (Wentworth 1922). A total of seven habitat classifications were used for this analysis: 1) muds and sandy muds, 2) sandy muds with sands, 3) muddy sands, 4) muddy sands with sands, 5) sands, 6) boulders, gravels and sands and 7) bedrock (Table 1-1). It should be noted that the bottom sediment types mapped in this study were not independently verified by grab sample analyses. Instead, characteristic side-scan sonar images of bottom types were compared with existing grain-size classification of the study area (Nitsche et al. 2007). Using the correlation of the characteristic high-resolution side-scan sonar images with existing bottom type classification scheme, all side-scan sonar data were visually examined and the bottom sediment types were determined by Dr. Madsen.

Habitat Use

In an attempt to examine Atlantic Sturgeon habitat preferences, all adult Atlantic Sturgeon targets were overlaid on the 2013 habitat layers in ArcGIS. A spatial join was used to yield a table with a habitat type associated with each target information and target location. Habitat use was assessed using a chi-square analyses (Neu et al. 1974). When habitat-use significantly differed from availability, a Bonferroni-z statistic was used to construct Bonferroni-z confidence intervals to identify the habitat categories that were used more or less frequently than expected. Significance levels were set at 95% ($\alpha = 0.05$) for all analyses.

Spatial Distribution

I examined spatial distribution of adult Atlantic Sturgeon in two ways. First, I assessed whether there was a north to south or east to west spatial distribution component. To assess a north south component, I split the study site into three (3) equal distance bins (North, Middle, and South Bin). To assess an east-west component, I evaluated the total counts at the five transects (A-E). These data were used to evaluate the count of total individuals per east to west region, to see if there was a spatial component of sturgeon in the study site. For the second spatial distribution analysis, I used the Optimized Hotspot Analysis tool in ArcGIS 10.2 (ESRI 2011), using count incidents within fishnet polygons analysis field, to generate a hotspot analysis. The tool works by identifying statistically significant spatial clusters (hotspots), it aggregates data, identifies an appropriate scale of analysis, and corrects for both multiple testing and spatial dependence. The analysis then generates hotspot polygons, with an associated data-table and associated p-value and z-value for each hotspot polygon.

Passive Telemetry

Collaborative research efforts have been undertaken along the species range, to implant acoustic transmitters in Atlantic Sturgeon in order to track movements, learn about mortality, and more. As a part of research at Delaware State University (D. Fox Lab), Atlantic Sturgeon are intercepted during their migration near Delaware waters. Upon capture, Atlantic Sturgeon are placed into a live well (≈ 1,100L), with water pumped directly from the ocean to maintain ambient conditions. All individuals are measured to fork length (FL), total length (TL), weighed (kg), and scanned for the presence of passive integrated transponder (PIT) tag, using an AVID Power Tracker VIII or Biomark FST2001FT PIT tag reader. Individuals are also monitored for the presence of a VEMCO Ltd. Acoustic transmitter using a VEMCO Ltd. VR-100 receiver and

VH165 hydrophone. In instances where no PIT tag was present, one (Biomark model IMI 1000, 400 kHz) PIT tag was inserted at the base of the left dorsal fin. A small tissue sample then gets collected from the caudal fin and placed in 95% ethanol for genetic analysis. A United States Fish and Wildlife Service (USFWS) plastic T-bar tag would then be inserted on the left side of the fish at the base of the dorsal fin following established protocols (Damon-Randal et al. 2010). Atlantic Sturgeon large enough to be considered mature (>1.3 m FL; Van Eenennaam et al. 1996) would then be implanted with acoustic transmitters. A full description of methodologies can be found in Breece 2012.

A collaborative (DSU, New York State Department of Environmental Conservation (NYSDEC), Stony Brook University) array of passive acoustic receivers (VEMCO Ltd. VR2W) was deployed to monitor the presence of telemetered sturgeons in the Hudson and East Rivers, as well as New York Harbor (Figure 1-1). Receivers were affixed, with permission, to United States Coast Guard Aids to Navigation. The DSU portion of the array was deployed on June 9 -10th, 2014 – October 13th, 2014, and comprised the majority (25/43) of receiver's present.

For the purposes of this study, all Atlantic Sturgeon that entered the Hudson River and moved upriver beyond Con Hook, NY (rkm 79) were considered presumed spawners. This geographic definition encompasses all previously hypothesized spawning areas (Bain et al. 1998), and represents a marked change in the characteristics of the river. Telemetered adult Atlantic Sturgeon from other populations (based on genetic assignments) are seldom observed upstream Con Hook, NY (Kazyak et al., in preparation), suggesting the criteria is reasonable to identify Hudson River spawners. These telemetry data were used to assess Atlantic Sturgeon distribution within the river and within the Hyde Park Reach. Arrival of telemetered Atlantic Sturgeon in the Hudson River was defined as day of first detection at Con Hook, NY (rkm 79).

River departure was defined as the last day an individual was detected at Con Hook, NY (rkm 79). Residency time within the Hudson River north of Con Hook, NY (rkm 79) was estimated by subtracting the arrival date from the departure date. Residency within Hyde Park was calculated as the total days observed in the Hyde Park Reach study site. In 2014, receivers were deployed late (6/10), which missed the river entry for most Atlantic Sturgeon. In these cases, mean river entry date and residency time were not calculated.

CHAPTER I: RESULTS

Atlantic Sturgeon Identification

Reader one independently reviewed the side-scan sonar data and identified sturgeon. A secondary reader subsampled 25% of the survey dates to help calculate an identification probability. Reader one, whose data were used in this study, was more conservative in adult Atlantic Sturgeon identification than reader two, with an identification probability estimated at 86.9%. It should be noted that substrate type likely influenced detection probabilities as sturgeon associated with sand, mud, or a combination of the habitat types were more pronounced in comparison to times when they occupied coarse materials and or regions with more complexity. It should also be noted that reader one identified all targets that reader two identified, however, reader one identified them as ‘suspected.’

Over the three-day 2013 sampling period, a total of 144 targets were classified as sturgeon, of these 104 (mean: 35/day; range: 13-59) met the >1.5 m TL (mean 1.9 m TL, range 1.5 m – 4.6 m) minimum size criteria and were deemed adult Atlantic Sturgeon (Figure 1-8). The adult Atlantic Sturgeon were positioned an average of 1.1 m above bottom (range 0.1 m – 4.3 m; Figure 1-9). In 2014, over the 12 sampling days, 609 targets were classified as sturgeon, of which 479 (mean: 40/day, range: 11-75) met the >1.5 m minimum size requirement. The targets had a mean length of 2.0 (1.5 m – 4.3 m; Figure 1-8), and were positioned at a height of 1.8 m above bottom (range 0.1 m – 14.5 m; Figure 1-9).

Habitat Identification

Based on the habitat designations from the side-scan sonar data collected in 2013, the availability of suitable Atlantic Sturgeon spawning habitat (bedrock and gravels) was 6.3% of the total available habitat. In particular, exposed bedrock represented approximately 2% of available habitats (Table 1-2) with the majority present along the western side of Esopus Island as well as in the vicinity of Bolles Island (Figure 1-10). Areas of exposed boulders, gravels, and course sands were generally located in the surrounding vicinity of bedrock and near Esopus and Bolles Island, and covered approximately 4.3 % of the survey area. Regions dominated by sands constituted approximately 5.5 % of the survey area (Table 1-2). In the northern to middle portions of the survey area, the sands bordered primarily areas of boulders, gravels, and sands, and thus occur predominantly along the banks of the river (Figure 1-10). In the southern portion of the survey area, muddy sands with sands occurred close to the riverbanks while sands were common in the central portion of the river, and are characterized by prominent <1-meter sand waves. The areas identified as muddy sands with sands comprised of 33 % of the study site (Table 1-2) followed by muds and sandy muds and muddy sands with each constituting approximately 25 % of the area. These muddy sands regions are especially prevalent in the northern part of the survey area along the western portion of the river channel and along the eastern portion of the channel in the southern part of the river channel (Figure 1-10). The finer-grain sediments are most prominent along the river channel to the north of Esopus Island, to the west of the island, and in the central to southern portion of the survey area (Figure 1-10).

Habitat Use

The locations of the 2013 and 2014 adult Atlantic Sturgeon contacts were overlain on the bottom sediments generated in 2013 (Figures 1-11, 1-12). Habitat categories listed in the methodology, their associated total area (km^2), and the observed side-scan adult sturgeon targets, were used to assess habitat preferences. In 2013, adult Atlantic Sturgeon statistically selected for sands while avoiding muds and sandy muds, and muddy sands ($X^2 = 39.62$, df = 6) (Table 1-3; Figures 1-11, 1-13). In 2014, Atlantic Sturgeon also exhibited habitat selection, by statistically preferring muddy sands with sands over 50 % of the time, and sands next predominantly at 22 % of the time ($X^2 = 406.11$, df = 6), while statistically avoiding other habitat types (Table 1-4, Figures 1-12, 1-14).

Adult Atlantic Sturgeon Distribution

Atlantic Sturgeon were observed throughout the Hyde Park Reach during both 2013 and 2014. In 2013, Atlantic Sturgeon were generally observed to be more tightly aggregated in the northeast and southeast portions of the river, although only a three day snapshot may not be representative of their true distribution. In 2014, adult Atlantic Sturgeon were densely aggregated on the eastern side of the river (Transects D and E; Figures 1-12, 1-14, 1-15) with the majority (68 %) of Atlantic Sturgeon in the southern third of the study site (Figure 1-16), with the remainder in the middle (23 %) and northern (9 %) portions of the study site.

In an effort to further refine the spatial distribution of adult Atlantic Sturgeon, a Hotspot Analysis in ArcGIS 10.2 was generated for the 2013 and 2014 data. The 2013 data yielded no statistically significant hotspots. However, the 2014 data yielded two significant hotspots within the study site (p-values and z-values in Appendix A), which were located near Esopus Island, and near Rogers Point (Figure 1-17). Benthic sediments for the hotspot between Esopus and Bolles Islands was dominantly bedrock, with the second most dominant sediment being muddy sand with sands (Figure 1-18). The southeastern hotspot near Rogers Point had habitat primarily consist of muddy sands with sand, muds and sandy muds, and sands. Of importance, may also be the presence of sand waves in this reach as most Atlantic Sturgeon in the southeastern hotspot near Rogers Point were observed hovering behind sand waves (Figure 1-19).

Passive Telemetry Spatial Distribution

In 2013, a total of 38 DSU telemetered, likely spawning adults, were detected migrating into the Hudson River past Con Hook (rkm 79) in 2013, of which there were 25 males, six females, and seven of unknown sex (Table 1-5). They began migrating into the Hudson River in late April 2013 and continued through the spring and into the summer months. These telemetered individuals entered the Hudson River on a mean date of May 25 (range April 24 – July 26), and remained in the Hudson River for a mean residency of 49 days (range 13 - 154). They departed on a mean date of July 13 (May 30 – October 11) (Table 1-5). A majority (92 %; 35/38) of the Atlantic Sturgeon that entered the Hudson River were detected in the Hyde Park Study site, of which a large number (14/35) of those fish spent the majority (>50%) of their river residency in the study site, and the vast majority (34/35) spent more than a quarter of their time at the study site.

A total of 35 DSU telemetered individuals were detected entering the Hudson River in 2014, consisting of 24 males, three females, and eight of unknown sex (Table 1-6). These telemetered individuals entered the Hudson River on a mean date of June 8 (range May 25 – August 22), and resided in the Hudson River for a mean of 36 (10 - 116) days. They departed on a mean date of July 14 (June 10 – September 29) (Table 1-6). A majority (80%; 28/35) of the Atlantic Sturgeon that entered the Hudson River in 2014 were detected in the Hyde Park Reach. Receivers were deployed late, on June 10, 2014, which missed a majority (92 %) of river entry.

A river entry date was not assumed for those individuals, and the proportion of time spent at the study site, was only calculated when there was river entry date (Table 1-6). Of the available fish, 23 % (3/13) spent more than 50 % of their river residency in the study site.

CHAPTER I: DISCUSSION

Traditional sampling gears, including gillnets, can cause harm or even mortality on target species. Fortunately, advances in technology and the decreased cost of hydroacoustic systems allow for less invasive approaches that pose no mortality risk on the target species. Studies have shown that Atlantic Sturgeon are especially sensitive to sampling stress when on spawning runs, and in some cases the stress from netting may cause individuals to abort their spawning run, and return to the ocean without a successful spawn (Kahn and Mohead 2010). Through this chapter, I was able to use a non-invasive technology to image habitat use and spatial distribution while sturgeon were in the riverine environment and while on likely spawning grounds.

Size and Behavior

An unexpected finding of this study was the collection of in-situ behavioral information on Atlantic Sturgeon. Behavioral information can be difficult to collect, as all sampling methodologies have the potential to effect fish behavior. Furthermore, most behavior studies assess jumping or noise behaviors. Instead, through side-scan sonar imagery, I was able to observe Atlantic Sturgeon in the southeastern portion of the study site, hovering behind sand waves. A majority of the targets were observed using at a depth of less than 1.6 m from bottom, and the sediment type was dominated by muddy sand or sand. Although it was beyond my scope to study why Atlantic Sturgeon were using these sand waves, I hypothesize they were using them as an energy savings tactic during staging, although additional studies are needed to validate this hypothesis. This is one of the first studies evaluating Atlantic Sturgeon behavior during such an important and difficult to study part of their life cycle. These types of studies could have the potential to help managers understand this endangered species critical habitats, but also their behavior when found in this habitat.

The sturgeon imaged in this study measured an average of 2.0 m TL, suggesting these were reproductively mature individuals (Van Eenennaam et al. 1996) that migrated into the Hudson River to spawn. A majority (92%) of the sturgeon that were tracked by telemetry entering the Hudson River on a spawning run in 2013, used the habitat in the Hyde Park Reach.

The distribution of Atlantic Sturgeon in the water column varied by individual. Few Atlantic Sturgeon were imaged swimming in close proximity (< 0.25 m) of the river bottom, which would be expected if individuals were feeding. Instead, Atlantic Sturgeon varied between 0.5 m to 14.5 m above bottom. Although sturgeon have been described as benthic cruisers (Findeis 1997), the results of this study add to the growing body of evidence suggesting they are suspended off the bottom (Flowers and Hightower 2013) and not actively feeding. These data also suggest that Rogers Point (rkm 128) is likely being used as staging grounds. Alternatively, the height off bottom could suggest behavioral changes or environmental differences, although none were explored (e.g. flow, tide, habitat features, temperature, dissolved oxygen, etc.). In fact, a previous study done in Maine showed that as tidal height increased, sturgeon depth increased, and as tidal height decreased, so did the sturgeon’s depth (Dunbar 2015), although my study did not explore these factors.

Habitat Use

Habitat use studies of Atlantic Sturgeon have been limited by small population sizes (e.g. small numbers of tagged fish; Collins et al. 2000) or by the inability to collect in-situ habitat data on a small enough scale. Luckily, the Hudson River has one of the largest extant populations of Atlantic Sturgeon (Bain 2000) which can make the species easier to study than in other systems. Although the Hyde Park Reach is believed to support the largest existing spawning aggregation of Atlantic Sturgeon (Van Eennennaam et al. 1996; Bain 1998), my findings suggest that suitable spawning habitat represents a fraction (10 %) of available habitats. Instead it appears that adult Atlantic Sturgeon are actively selecting for muddy sands, sands, muds and sandy mud habitats while in the Hyde Park Reach of the Hudson River. Even more surprising, only 6 % of the total habitat in Hyde Park consists of the sands category, yet it was a preferred habitat choice. In fact, in 2013 and 2014 respectively, only 10 (9.6 %) and 14 (2.9 %) Atlantic Sturgeon used hard-bottom habitats that are associated with spawning (rock, boulders, and gravel). This is likely because my study design enabled me to observe snapshots in time. Although I didn't observe Atlantic Sturgeon using spawning habitats, it's likely that I scanned them while they were staging and not during active spawning.

Habitat use by Atlantic Sturgeon while on spawning runs, and not actively spawning, is poorly understood. What is known is that male Atlantic Sturgeon migrate into their natal rivers before females, and spend time on the staging grounds waiting for females to arrive (Dovel and Berggren 1983; Van Eenennaam et al. 1996). The telemetry results in 2013 and 2014 support those findings. In 2013, males arrived on a mean date of May 19 (April 27 – June 18; n = 19), while females arrived on a mean date of June 9 (May 17 – July 19; n = 6). The 2014 telemetry data is more difficult to interpret since the DSU receivers were deployed after a majority of sturgeon entered the river (entry was before 5/25/14 for 18 males and one female). However, from the available individuals, males arrived on a mean date of June 17 (June 15 – June 21; n = 6) and females on a mean date of August 7 (August 6 – August 9; n=2). Due to the longevity of individuals found in the area near Rogers Point (mean of 19 days in 2013, maximum of 50 days), it suggests Atlantic Sturgeon males are using this area for staging. It's likely that males wait on the staging grounds near Rogers Point, and as females come along they ascend to the spawning grounds in the Hyde Park Reach or farther north in the Catskills (rkm 179-183). Further investigation, including egg sampling would be needed to substantiate this claim. Not only do these data suggest that Atlantic Sturgeon are staging in Hyde Park, but that they have a preference for sandy and muddy sand habitats, particularly those with predominant sand waves. These habitat types and habitat features near spawning grounds should be taken into consideration when developing management actions and the critical habitat designations in the riverine environment.

Due to logistics and safety concerns, surveys were only conducted during daylight hours and I assumed that Atlantic Sturgeon presence and habitat use did not vary based on the diel schedule. Atlantic Sturgeon are generally found to be most active during dawn and dusk, however, time of day does not seem to be a significant predictor of movement (Mclean 2013). Nocturnal behavior has been described for other sturgeons, including the White Sturgeon (*A. transmontanus)*, which increased swimming speeds at night and occupied shallower waters than during the day (Parsley et al. 2008). Although interesting, those movement studies were evaluating juveniles and adults that were not participating in a spawning run. Lake Sturgeon (*A. fulvescens*) however, have been observed spawning both during the day and at night (Bruch and Binkowski 2002). It may be worthwhile for future studies to assess Atlantic Sturgeon movement from staging to spawning grounds, to evaluate whether spawning is based on the diel cycle, or whether Atlantic Sturgeon are like Lake Sturgeon and do not have a preference.

Spatial Distribution

Adult Atlantic Sturgeon exhibited patterns strongly suggesting that they were selecting for specific regions within the Hyde Park Reach, which included two hotspots. The first hotspot was located between Esopus and Bolles Islands, on the east side of the river, with a dominate habitat type of bedrock (Figures 1-17, 1-18). Although predominantly bedrock, muddy sands with sands was the other fairly common habitat type found at this hotspot. To successfully spawn, Atlantic Sturgeon require hard-bottom habitat. Due to this fact and the presence of this habitat within a statistically significant hotspot, I may have identified an extant spawning location in Hyde Park Reach, although confirmation would require more detailed examination of movements and the collection of fertilized eggs. Although not overly detailed, a study done from 1993 – 1998 identified a spawning site on "one side of the river, among rock islands with irregular bedrock and substrate of silt and clay" (Bain 2000). Although I cannot be sure, the description Bain gave sounds similar to the location of the first identified hotspot. These results are interesting and could suggest that the reach near Esopus and Bolles Islands (rkm 135) could potentially be the main spawning ground for the Hyde Park Reach, as it's one of the only areas where Atlantic Sturgeon were imaged and where the habitat that would allow for successful spawning. The second hotspot was near Rogers Point, in the southeastern part of the study site (Figure 1-17). Habitat in this area is dominated by muddy sands with sands, sands, and muds and sandy muds (Figure 1-18). This area is close to the Rogers Point marina dock, and is adjacent to hard-bottom habitat that is on the west and east side of the river (Figure 1-10).

Although Atlantic Sturgeon preferred habitat in this study, isn't traditionally associated with successful spawning, my findings suggest that we may need to rethink the traditional model of in-river habitat requirements for spawning Atlantic Sturgeon as they are spending prolonged periods of time in habitat where spawning is unlikely (muddy and sandy habitats). At the same time, these non-spawning habitats are helping meet some yet undefined role in the complex life cycle of this species. These habitat use and spatial distribution data are increasingly important as the United States Coast Guard (USCG) has put in a proposal to provide more anchorage areas in the Hudson River (USCG 2016). The current USCG proposal is to add ten additional anchorage sites (2,400-acres), which would allow up to 43 berths for barges on the Hudson River. Not only do large ships increase the likelihood for ship strike mortalities which is a problem in other NYB Rivers (D. Fox, Delaware State University, unpublished data), but anchoring could have negative consequences including by adversely modify bottom habitats and or disrupting behavior. Without having a full understanding of Atlantic Sturgeon habitat requirements, and an understanding of where Atlantic Sturgeon are staging and spawning, an ill placed anchorage in critical habitat such as a staging or spawning site, could negatively impact the restoration of this endangered species. The overall impact of ship disturbances (e.g. anchoring) on the benthic communities, should be well understood before new anchorages or other marine or riverine planning proceeds as negatively disturbing benthic communities could change how the Atlantic Sturgeon use habitats in the Hudson River.

Through this study, I was able to further enhance the understanding of Atlantic Sturgeon habitat requirements while on spawning runs. I non-invasively identified the habitat types that Atlantic Sturgeon were selecting, and recognized that they were selecting non-spawning type habitats, thus suggesting they were using the Hyde Park reach for both staging and spawning. It is increasingly important to collect these data, as NMFS is required to develop critical habitat designations under the endangered species act for the Atlantic Sturgeon (NMFS 2016). Gaining data on habitat requirements is an important piece of the puzzle for Atlantic Sturgeon recovery and these data should be considered evidence for including muddy sand with sands and sand habitats, especially when those habitats have characteristic sand waves, as critical habitat when located near spawning sites. My study also provided in-situ measures on the behavior (e.g. height off bottom, hovering behind sand waves) of Atlantic Sturgeon that may prove important in the recovery of this species. Additionally, this thesis will help provide managers additional insights into the spatial distribution of Atlantic Sturgeon while they are in the Hyde Park Reach, which in light of anchorage proposals, may help to protect and make informed decisions. Finally, I demonstrated that data can be collected by the non-invasive side-scan sonar, and can be used to assess spatial distribution and habitat use in other rivers with similar results.

Table 1-1. Grain Size texture classes. Classification of mud (clay and silt), sand, and gravel follows the Wentworth scale (Wentworth 1922).

Grain Size Class	Dominant	Subdominant
Mud	Mud (silt and clay)	<10% sand and <10% gravel
Sandy Mud	Mud	>10% sand (sand > gravel)
Gravelly Mud	Mud	>10% gravel (gravel > sand)
Muddy Sand	Sand	>10% mud (mud > gravel)
Sand	Sand	<10% mud and <10% gravel
Gravelly Sand	Sand	>10% gravel (gravel > mud)
Muddy Gravel	Gravel	>10% mud (mud > sand)
Sandy Gravel	Gravel	>10% sand (sand > mud)
Gravel	Gravel	<10% sand and <10% mud

Table 1-2. Habitat classifications in the 11 rkm (127-138 rkm) Hyde Park Reach study site, in the Hudson River, Hyde Park, NY. Habitat was classified from the 2013 side-scan sonar data, enumerated and identified by John Madsen, University of Delaware.

Habitat Type	Total Area Per Habitat Type (Km^2)	Proportion of Total Area ($P_{i\ o}$)
Muddy Sands with Sands	2,206	0.33
Sands	368	0.06
Muds & Sandy Muds	1,659	0.25
Muddy Sands	1,699	0.25
Sandy Muds with Sands	344	0.05
Boulders, Gravels, and Sands	287	0.04
Bedrock	115	0.02
Totals	**6,678**	**1.00**

Table 1-3. The 2013 habitat use analysis to evaluate adult Atlantic Sturgeon habitat preference in the Hyde Park Reach, using side-scan sonar data. Analysis was performed using the Neu et al. (1974) Bonferroni-z statistic. (*) denotes significance set at α <0.05.

Habitat Type	Percent of Total Area	Observed Atlantic Sturgeon	Expected Atlantic Sturgeon	Percentage of Atlantic Sturgeon observed in each habitat type (Pi)	95% Confidence Interval ($\alpha = 0.05$)
Muddy Sands with Sands	33%	37	34	36%	0.274 - 0.387
Sands	6%	18*	6	17%	0.011 - 0.100
Muds & Sandy Muds	25%	16*	26	15%	0.206 - 0.291
Muddy Sands	25%	15*	26	14%	0.213 - 0.296
Sandy Muds with Sands	5%	8	5	8%	0.020 - 0.083
Boulders, Gravels, and Sands	4%	6	4	6%	0.016 - 0.070
Bedrock	2%	4	2	4%	0.000 - 0.040
Totals	100%	104	104	100%	

Table 1-4. The 2014 habitat use analysis to evaluate Atlantic Sturgeon habitat preference at the Hyde Park study site, using side-scan sonar data. Analysis was performed using the Neu et al. (1974) Bonferroni-z statistic. (*) denotes significance set at α= 0.05.

Habitat Type	Percent of Total Area	Observed Atlantic Sturgeon	Expected Atlantic Sturgeon	Percentage of Atlantic Sturgeon observed in each habitat type (Pi)	95% Confidence Interval ($\alpha = 0.05$)
Muddy Sands with Sands	33%	255*	158	53%	0.303 - 0.358
Sands	6%	106*	26	22%	0.032 - 0.078
Muds & Sandy Muds	25%	47*	119	10%	0.232 - 0.265
Muddy Sands	25%	43*	122	9%	0.239 - 0.270
Sandy Muds with Sands	5%	14*	25	3%	0.042 - 0.061
Boulders, Gravels, and Sands	4%	12*	21	3%	0.034 - 0.052
Bedrock	2%	2*	8	0%	0.014 - 0.021
Totals	100%	479	479	100%	

Table 1-5. The 2013 Biological characteristics and timing of DSU telemetered Atlantic Sturgeon that entered the Hudson River, and into the Hyde Park Reach in 2013. River residency is defined as the number of days between river entry and river departure past Con Hook, NY (rkm 79). Grey highlight indicates fish that entered the river in both 2013 and 2014 sampling years and (*) denotes individuals who entered the Hudson River but not the Hyde Park.

Serial Number	Year of Capture	Date of Entry	Date of Departure	River Residency (days)	Hyde Park Residency (days)	Hyde Park Residency (%)	Sex	Fork Length (cm)	Weight (kg)
1052415	2009	4/24	6/18	55	3	5%	male	186	69
1052423	2009	5/9	6/21	43	21	49%	male	150	45
1052434	2009	5/21	8/28	99	38	38%	male	156	42
1052443	2009	6/13	7/16	33	27	82%	male	153	n/a
1052446	2009	5/1	5/30	29	3	10%	male	157	48
1067085	2009	5/11	6/16	36	13	36%	male	160	21
1067088	2009	7/25	10/11	78	19	24%	unknown	153	42
1067112	2009	5/24	6/27	34	28	82%	male	188	74
1067115	2009	5/3	10/4	154	29	19%	unknown	138	31
1084952	2010	6/13	8/20	68	26	38%	male	174	55
1084959	2010	5/18	7/17	60	16	27%	male	138	31
1084961	2010	6/3	7/6	33	26	79%	male	165	52
1084962	2010	5/3	6/9	37	14	38%	male	172	56
1084967	2010	7/15	8/3	19	12	63%	female	230	110
1100263	2011	4/27	6/6	40	4	10%	male	167	45
1111913	2011	5/20	6/7	18	6	33%	female	211	95
1111914	2011	5/15	6/15	31	11	35%	male	159	n/a
1111915	2011	5/7	6/8	32	18	56%	male	177	43
1111920	2011	5/20	9/28	131	*	*	female	174	65
1122464	2012	5/15	6/11	27	9	33%	male	152	35
1122468	2012	5/3	6/14	42	29	69%	male	165	48
1122469	2012	5/21	6/20	30	13	43%	male	176	52
1122476	2012	5/11	6/21	41	6	15%	male	170	42
1122479	2012	5/17	6/21	35	10	29%	female	160	42
1122483	2012	5/8	8/31	115	12	10%	male	164	46
1122486	2012	5/9	6/29	51	36	71%	unknown	183	57
1122496	2012	6/1	6/29	28	22	79%	male	172	60
1122500	2012	5/4	6/17	44	7	16%	male	190	66
1122504	2012	7/5	10/8	95	50	53%	male	171	51
1122507	2012	6/3	7/5	32	8	25%	male	178	57
1122510	2012	5/30	6/12	13	8	62%	female	236	118
1122511	2012	5/28	8/2	66	48	73%	male	177	60

1134243	2012	7/26	9/8	44	*	*	unknown	92	5
1147038	2013	6/5	7/10	35	27	77%	male	174	54
1147041	2013	6/1	6/27	26	*	*	female	189	68
1152286	2013	5/23	6/12	20	11	55%	unknown	184	56
1152291	2013	6/18	9/11	85	48	56%	unknown	154	36
1152297	2013	6/5	6/22	17	2	12%	unknown	153	35

Table 1-6. The 2014 biological characteristics and timing of DSU telemetered Atlantic Sturgeon that entered the Hudson River. Receivers were deployed late (6/10/14) and after most Atlantic Sturgeon had already entered the river. All Atlantic Sturgeon who's date of entry was missed due to receivers being deployed late, received a (n/a) in "date of departure, a (*) after river residency days, and a n/a in Hyde Park Residency Percentage. (**) Indicates fish that migrated into the river, but not into the Hyde Park Study Site.

Serial Number	Year of Capture	Date of Entry	Date of Departure	River Residency (days)	Hyde park Residency (days)	Hyde Park Residency (%)	Sex	Fork Length (cm)	Weight (kg)
1052415	2009	*n/a*	6/12	18*	1	n/a	male	186	69
1052443	2009	*n/a*	6/17	23*	6	n/a	male	153	n/a
1052446	2009	*n/a*	6/15	21*	**	n/a	male	157	48
1067085	2009	*n/a*	6/19	25*	5	n/a	male	160	21
1067116	2009	*n/a*	6/15	21*	3	n/a	unknown	160	57
1084953	2010	*n/a*	7/4	40*	10	n/a	male	175	57
1084959	2010	*n/a*	6/19	25*	1	n/a	male	138	31
1084961	2010	*n/a*	7/9	45*	19	n/a	male	165	52
1084962	2010	*n/a*	6/14	20*	**	n/a	male	172	56
1084964	2010	*n/a*	6/16	22*	3	n/a	male	185	62
1084971	2010	*n/a*	7/25	61*	28	n/a	male	177	51
1084981	2010	8/6	8/17	11	2	18%	female	168	48
1094974	2010	*n/a*	6/14	20*	**	n/a	female	225	n/a
1094976	2010	*n/a*	7/20	56*	37	n/a	male	161	52
1100261	2011	*n/a*	6/14	20*	1	n/a	male	170	46
1111912	2011	8/9	9/24	46	**	*	female	148	37
1111914	2011	*n/a*	7/1	37*	11	n/a	male	159	n/a
1111914	2011	*n/a*	6/17	23*	**	n/a	male	177	43
1111927	2011	6/24	9/20	88	12	14%	unknown	192	65
1111946	2011	6/18	6/28	10	3	30%	unknown	202	72
1111947	2011	*n/a*	7/20	56*	4	n/a	male	178	55
1111964	2011	6/19	8/7	49	**	*	male	164	37
1147038	2013	6/15	8/19	65	8	12%	male	174	54
1147043	2013	7/5	8/13	39	6	15%	unknown	186	61
1147440	2013	8/22	9/29	38	31	82%	unknown	99	5
1152286	2013	*n/a*	6/10	16*	**	*	unknown	184	56
1185313	2014	6/19	7/4	15	11	73%	male	156	40
1185319	2014	*n/a*	9/18	116*	8	n/a	male	170	44
1185320	2014	*n/a*	6/16	22*	3	n/a	male	165	41
1185325	2014	6/21	7/25	34	3	9%	male	167	45

1185331	2014	6/19	7/24	35	13	37%	male	183	55
1185335	2014	*n/a*	7/2	38*	5	n/a	unknown	172	55
1185340	2014	6/14	8/9	56	11	20%	male	180	54
1185342	2014	*n/a*	6/27	33*	13	n/a	male	168	44
1185346	2014	6/10	6/30	20	10	50%	unknown	184	57

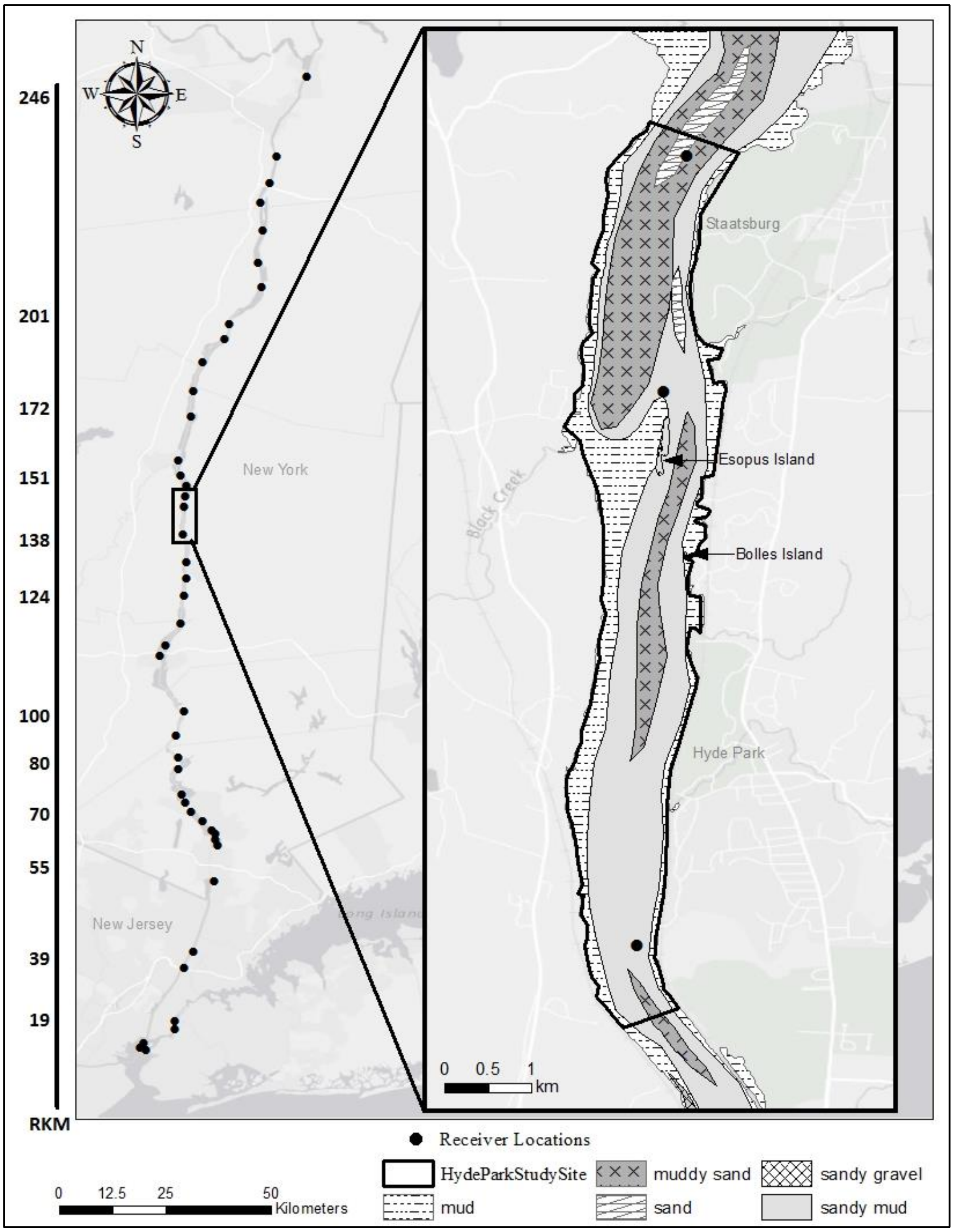

Figure 1-1. The location of the 2013 and 2014 passive acoustic receiver array with the survey site (rkm 127-138), overlain with sediment type generated by NYSDEC 2004 (inset). Note the presence of the three acoustic receivers within the study site, and the presence of Esopus and Bolles Islands.

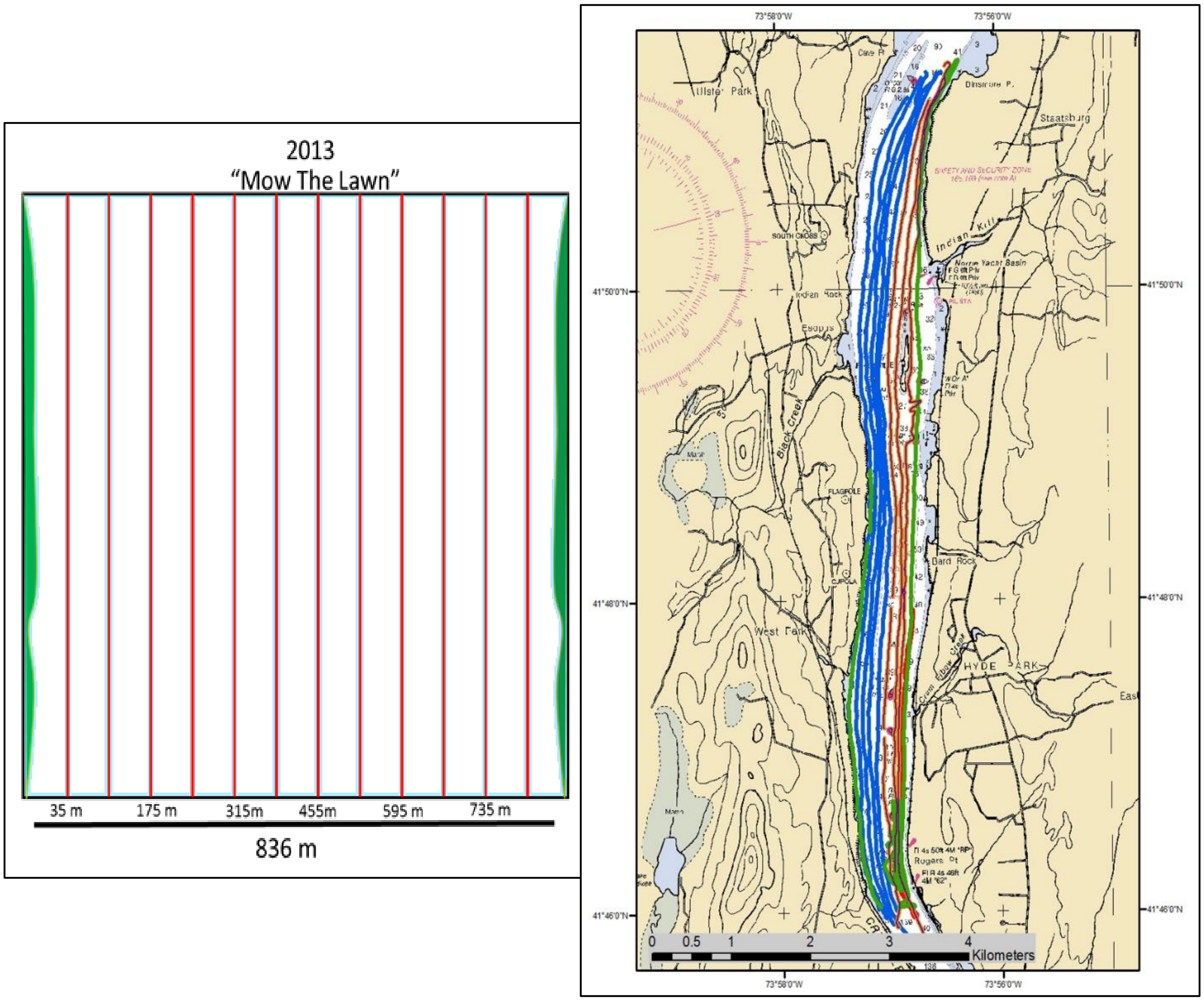

Figure 1-2. The 2013 sampling design. On the left is the schematic, and on the right is an example of the transect lines from 06/18/2013 – 06/20/2013. Colors represent individual sampling days within the sampling period. Sampling was completed using a “mow the lawn” transect design to image the full river.

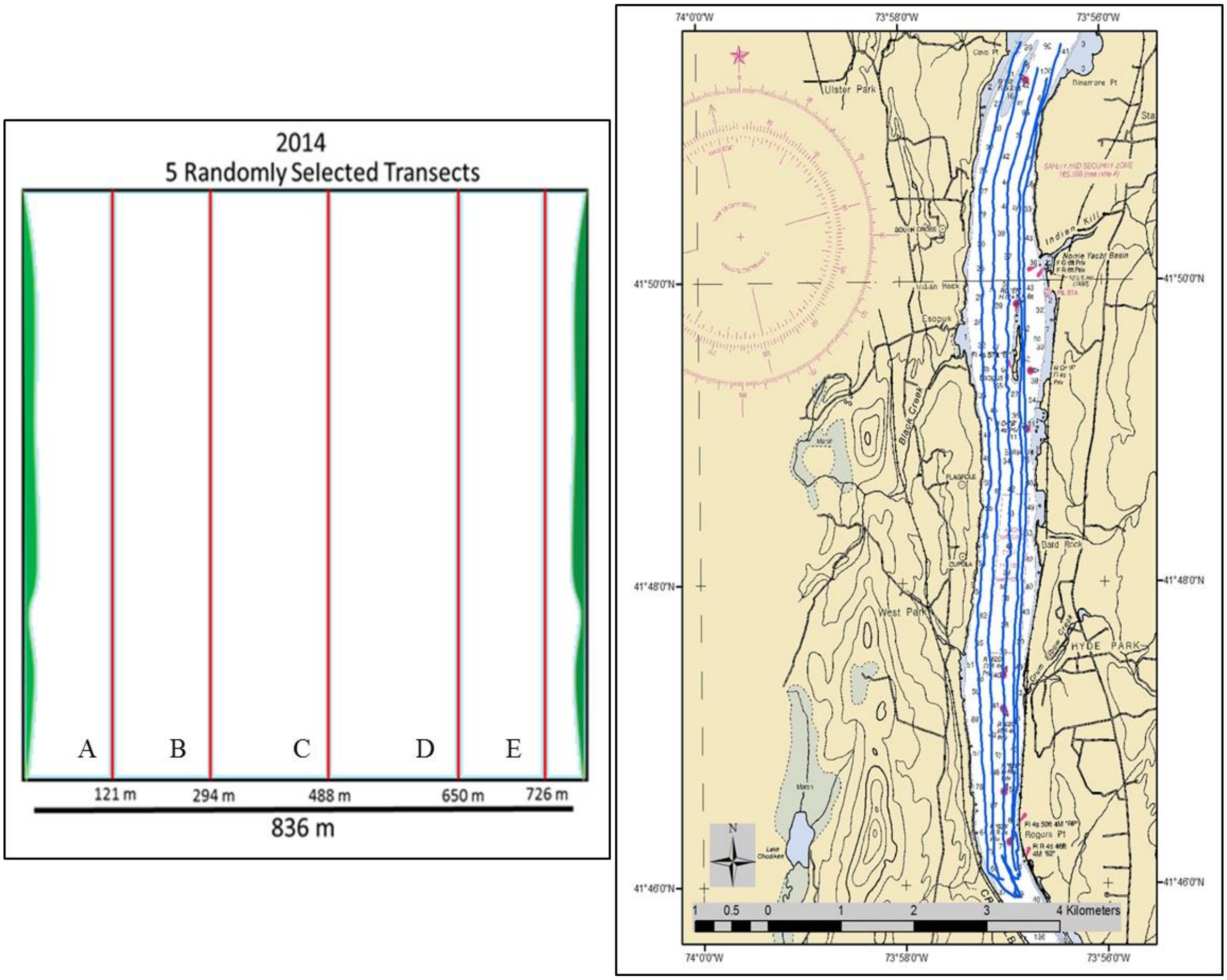

Figure 1-3. The 2014 sampling design. On the left is the schematic, indicating transects A-E. On the right is example of the transect lines from sampling period two. Transects were completed using way-points at proportions of the river width.

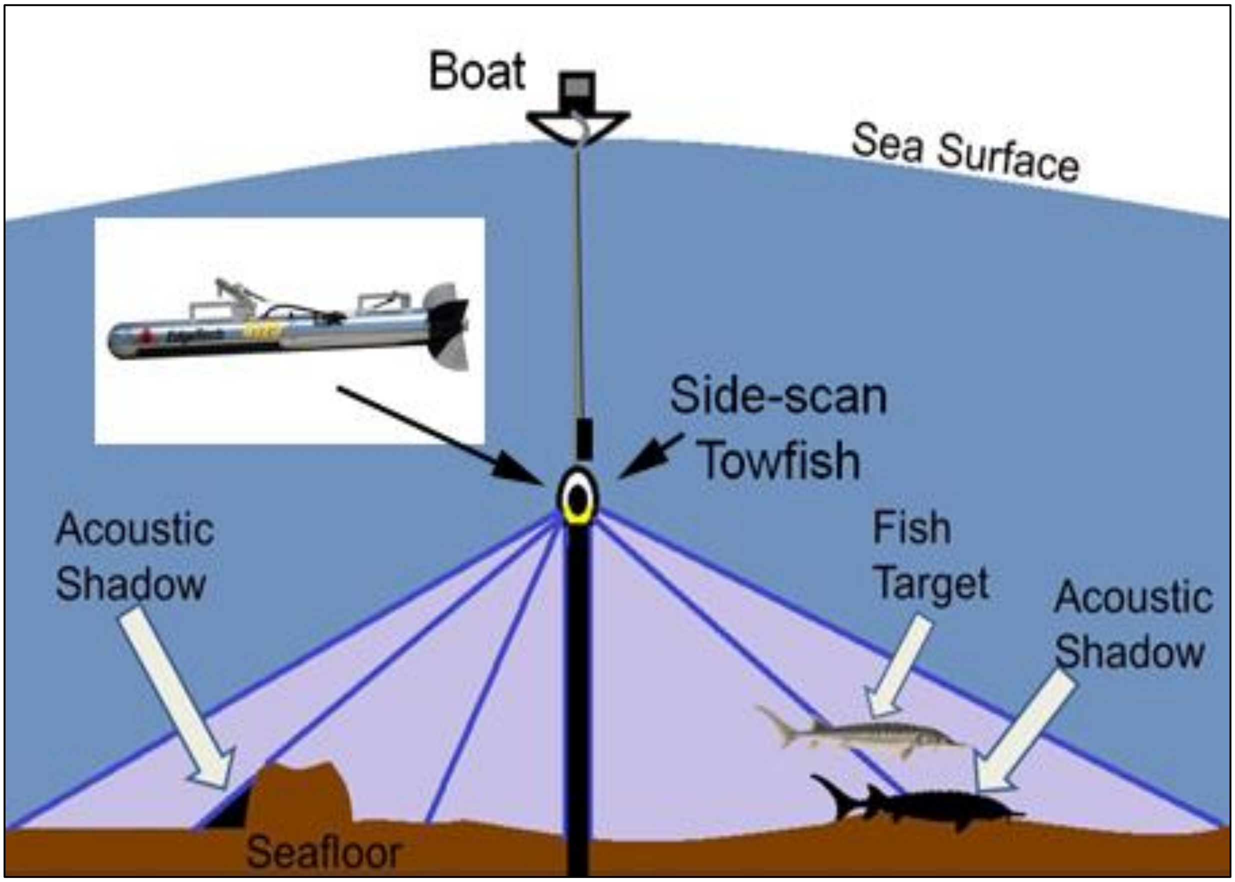

Figure 1-4. Visual representation of side-scan sonar data collection. The towfish transducer emits dual high frequency (400/900 or 600/1600 kHz) sound pulses that reflect off the seafloor (river bottom). The intensity and variation in the acoustic returns can be used to determine bottom characteristics. Objects in the water column (e.g., sturgeon) also reflect acoustic energy and generate a corresponding shadow zone in the side-sonar bottom image.

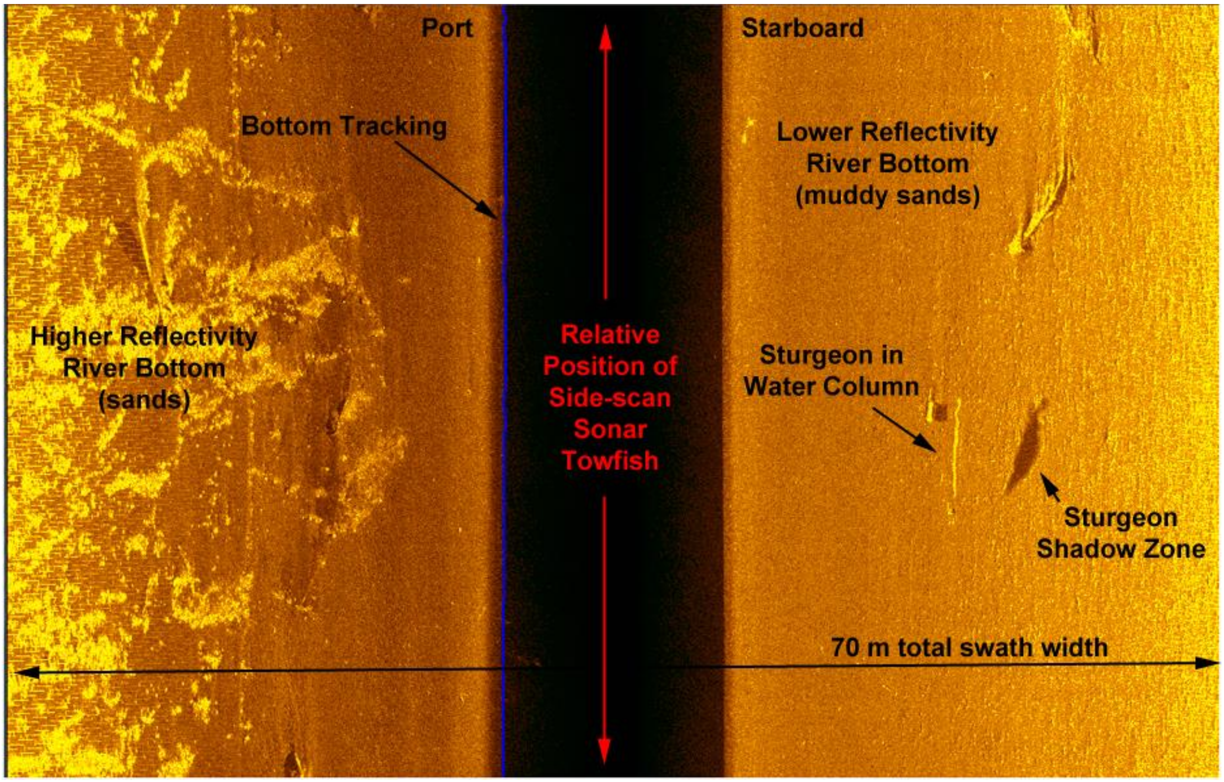

Figure 1-5. Example of bottom tracking and Atlantic Sturgeon targets (identification of the initial location of the bottom ensonified by the side-scan sonar). In this example, the bottom tracking (denoted by blue line) is performed on the port (left) side. Dark region beneath the side-scan towfish is the nadir zone, where due to the "side" looking nature of the system, the bottom has not been ensonified. Note the variance in reflectivity of bottom returns. The varying intensities are associated with different sediment types. Example also shows ensonified sturgeon in the water column with an associated shadow zone on the river bottom. Figure provided by John Madsen.

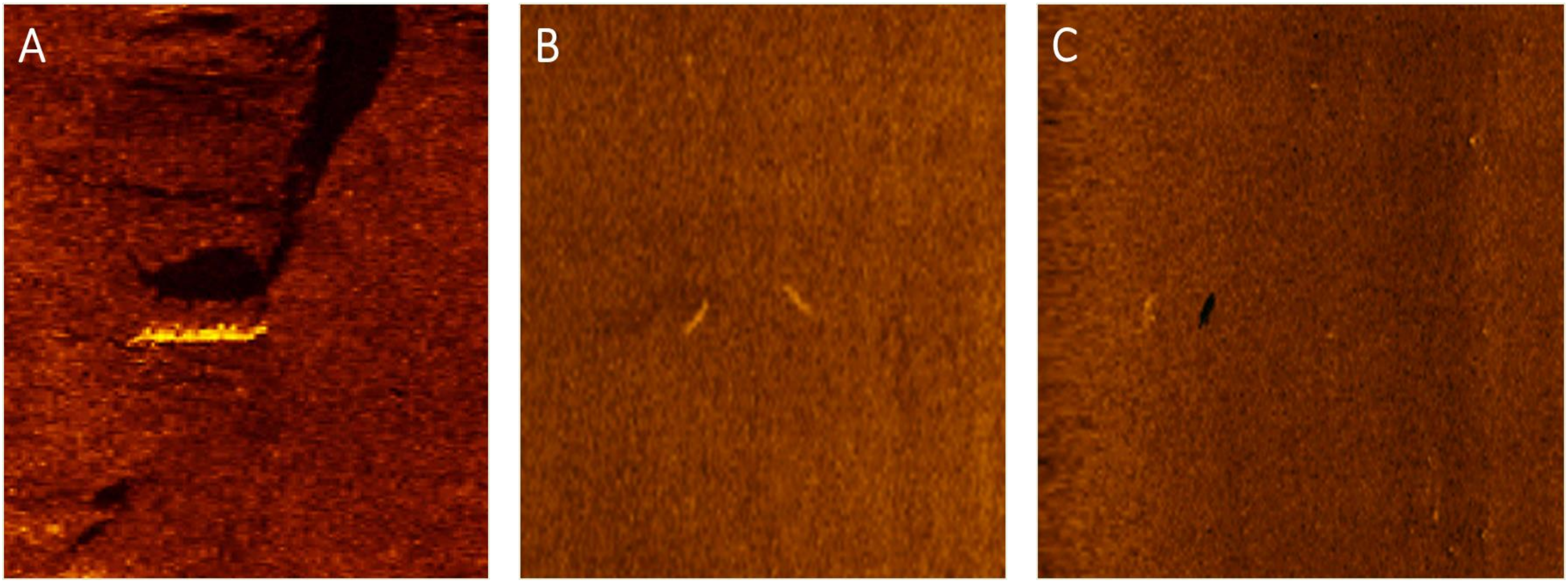

Figure 1-6. Examples of side-scan sonar targets. 6A. identified as “yes” an Atlantic Sturgeon based on length, and morphological features. 6B. Both targets are identified as “maybe.” Length of targets are both approximately 1.3 m in length and show no distinguishing features on the targets or corresponding shadows. 6C. Length of target is 0.8 m, and there is nothing distinguishing of the target or shadow.

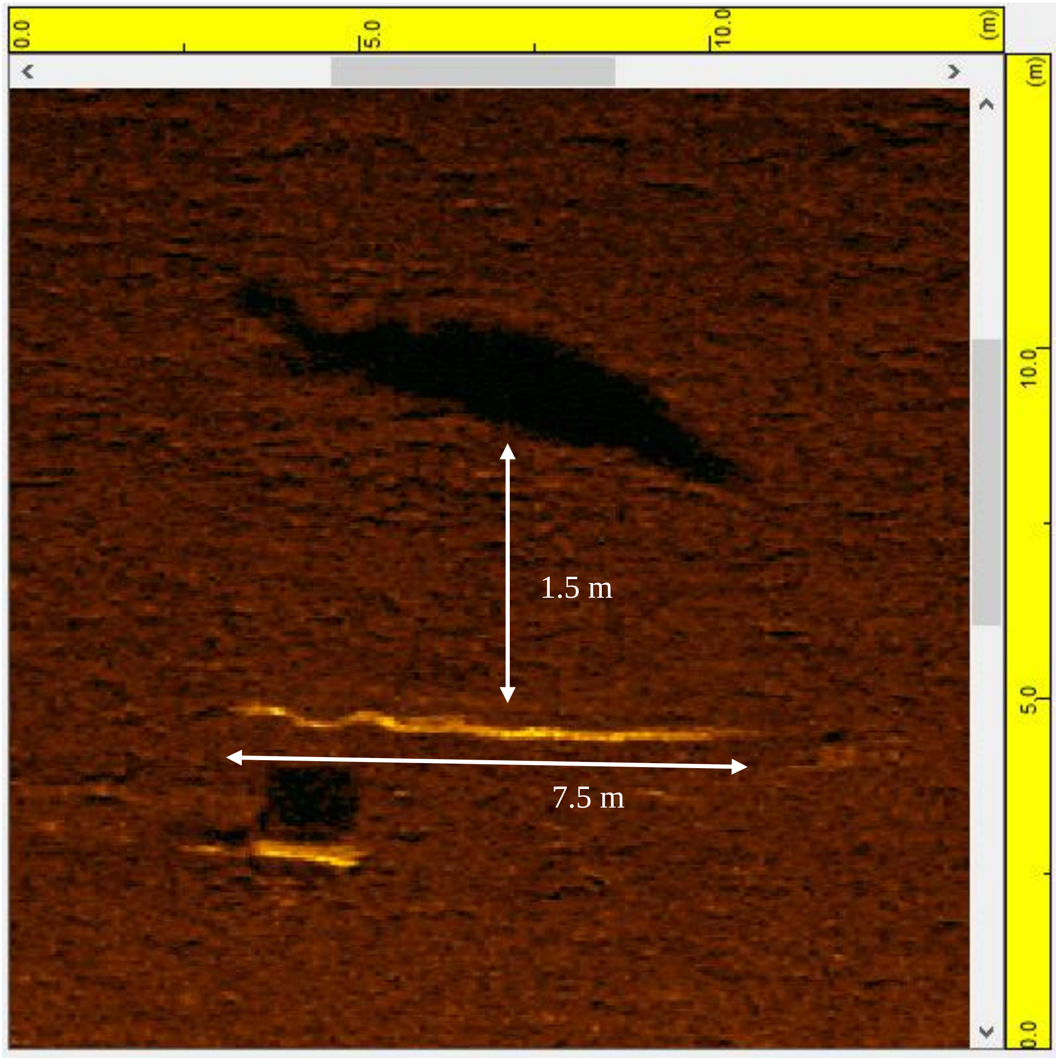

Figure 1-7. Example of a target identified as a “yes” sturgeon that measured at 7.5 m TL and the target measured at 1.5 m off bottom. Target shape shows classic signs of distortion (wavy target shape), and the size measurement is unrealistic at 7.5 m. Distorted targets measurements, like this, were not included in analysis.

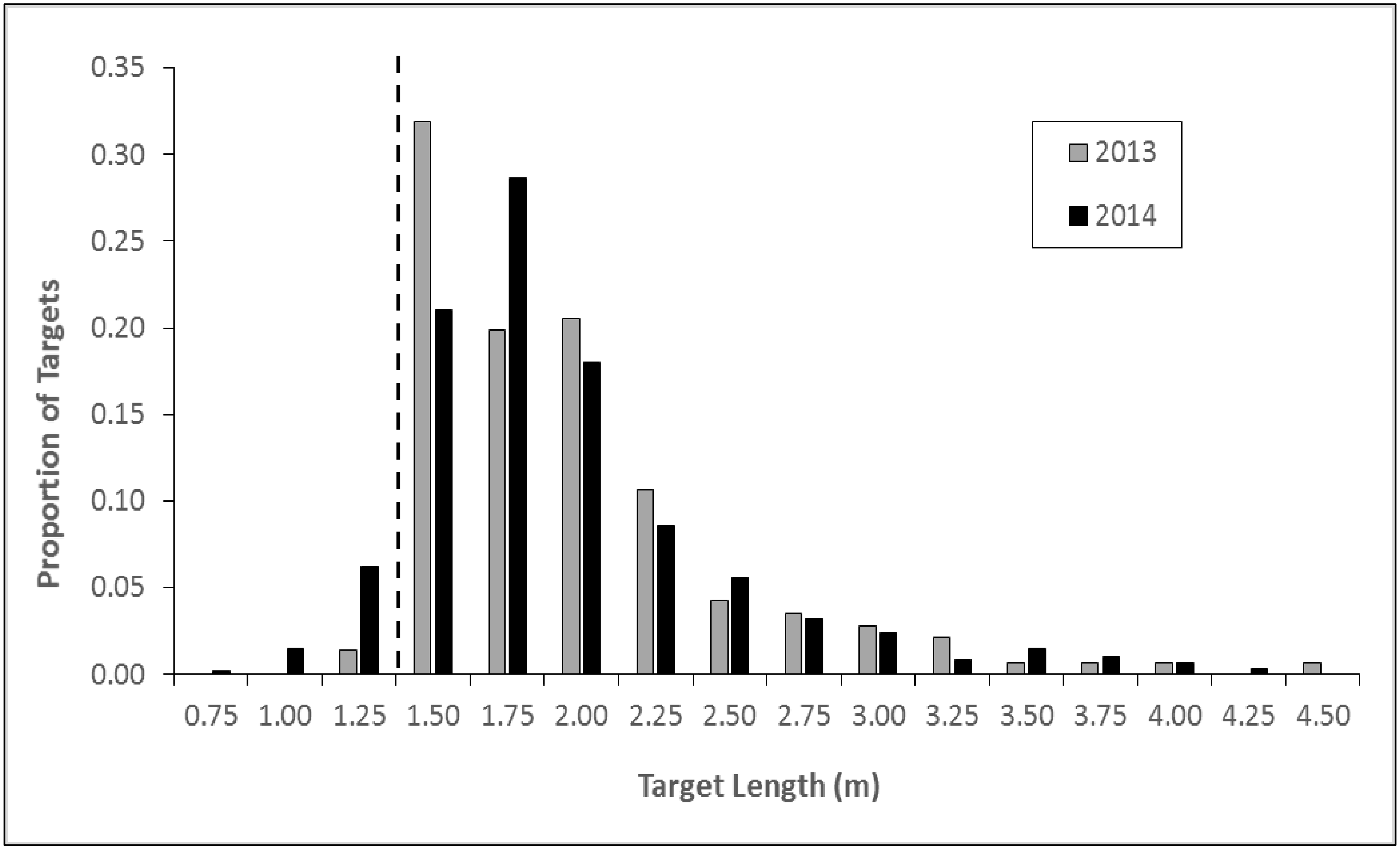

Figure 1-8. Size distribution of Atlantic Sturgeon targets in 2013 and 2014, collected by side-scan sonar, in the Hyde Park Reach, Hudson River, NY. Note, the dotted line represents the 1.5 m size designation that was used as the filter for all analysis. Any targets less than 1.5 m were likely Atlantic Sturgeon, but could not be identified and distinguished between the Shortnose Sturgeon.

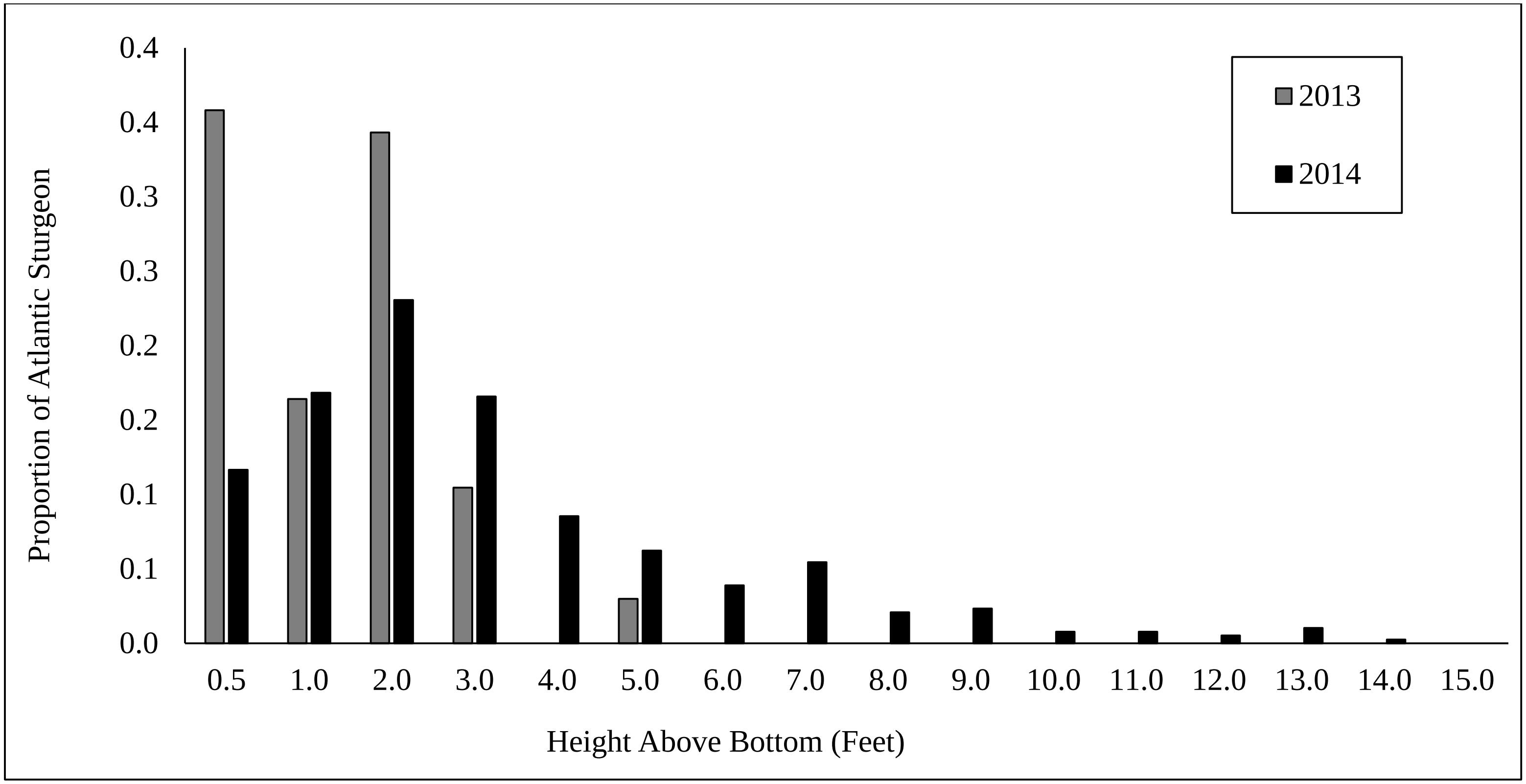

Figure 1-9. Observations of adult Atlantic Sturgeon height above bottom, in the Hyde Park Reach, Hudson River, New York. Observations were made from side-scan sonar data from June 18-20, 2013 on 12 sampling days from June 11 – July 02, 2014 (June 11-13, June 17-19, June 23-25, and June 30 – July 02). These data represent 104 targets in 2013, and 479 targets in 2014.

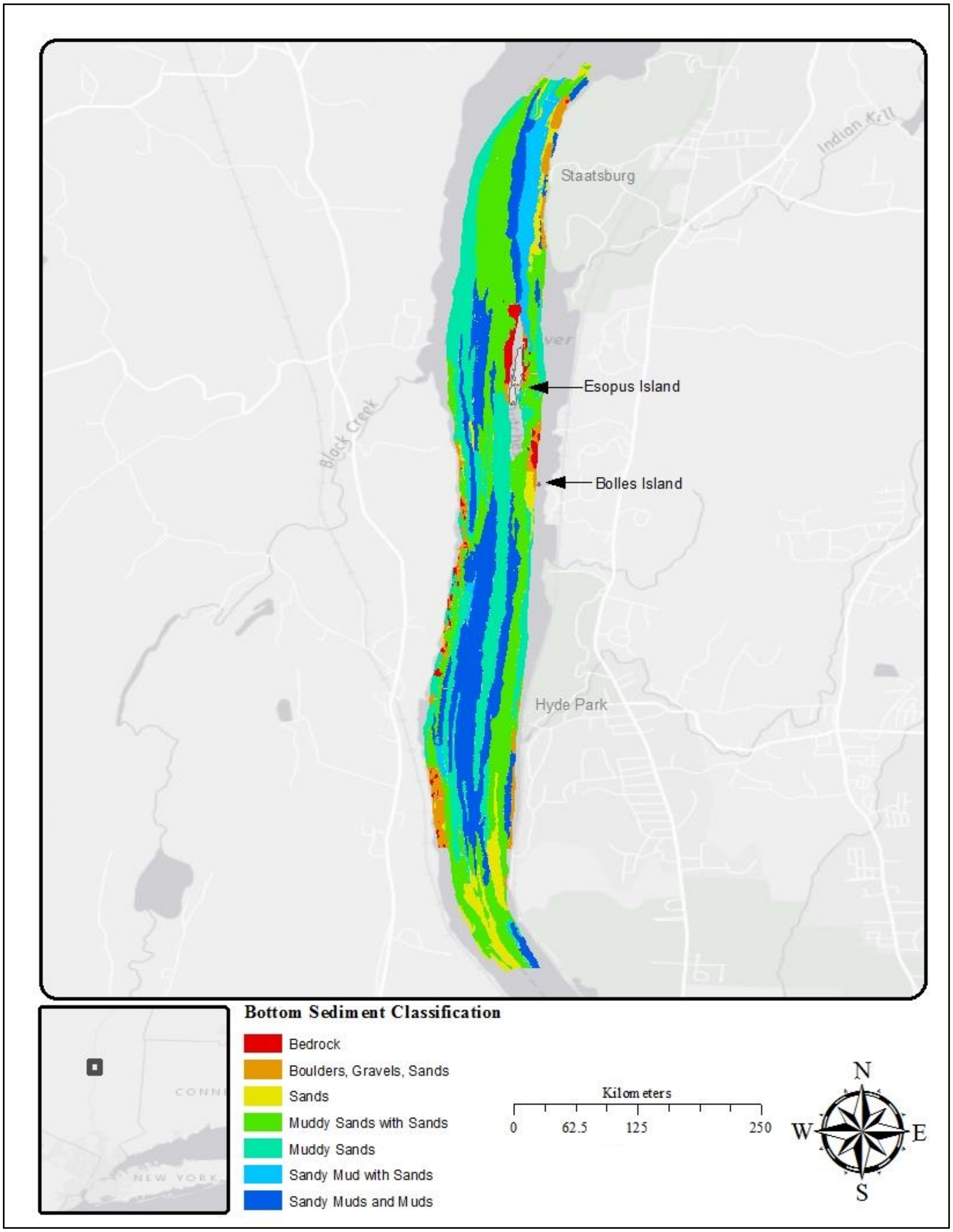

Figure 1-10. Distribution of bedrock and grain size texture classes based on 2013 side-scan sonar data, in the Hyde Park study site. Note the limited presence of bedrock and boulders and gravel, which are associated with successful Atlantic Sturgeon spawning.

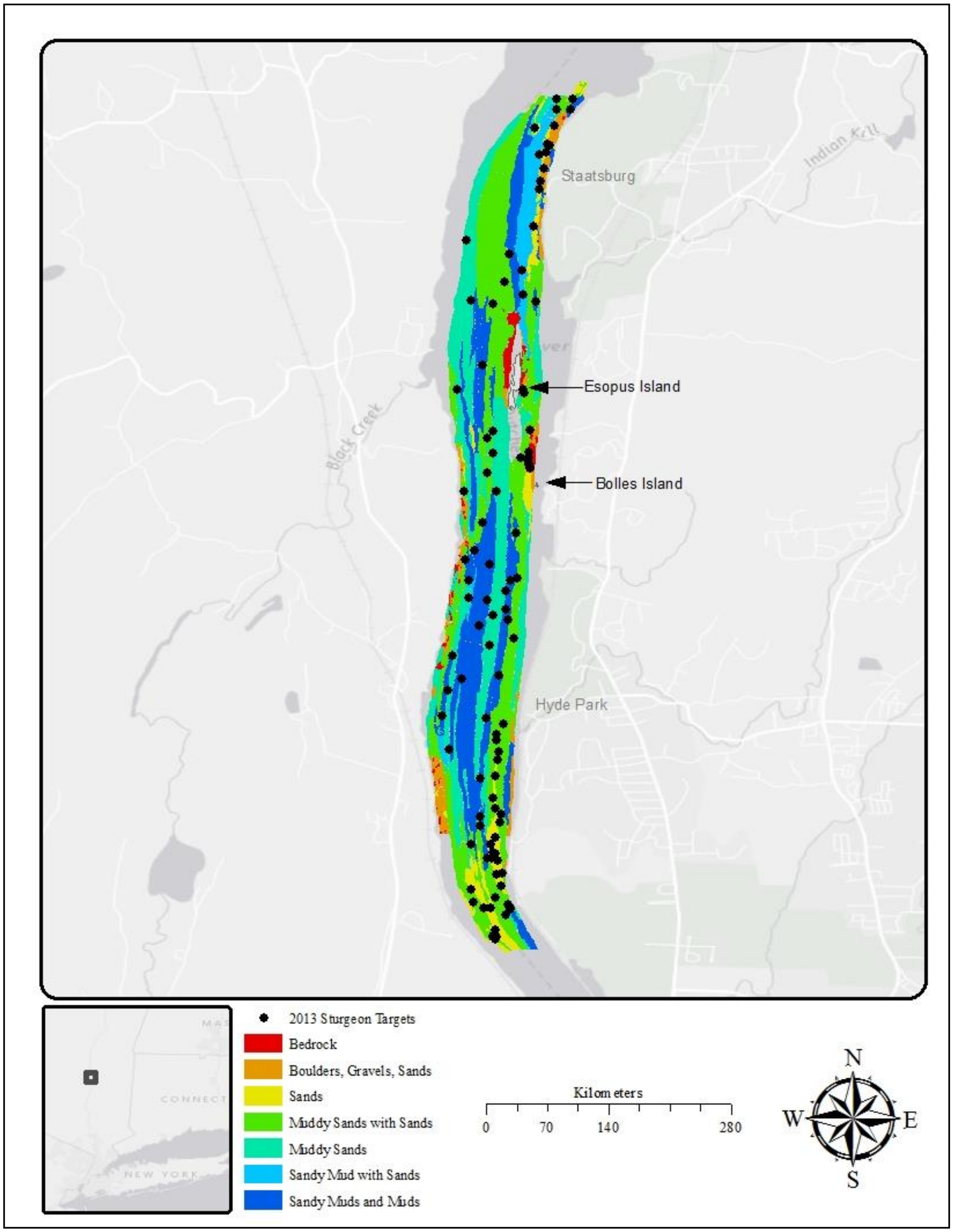

Figure 1-11. The 2013 side-scan sonar observed adult Atlantic Sturgeon overlain on the bedrock and grain size texture class data, in the Hyde Park Reach, Hudson River, NY. Targets are all identified as Atlantic Sturgeon and meet the ≥ 1.5 m size requirement. Identification of targets was completed using SonarWiz5. A total of 104 sturgeon were detected from June 18-20, 2013.

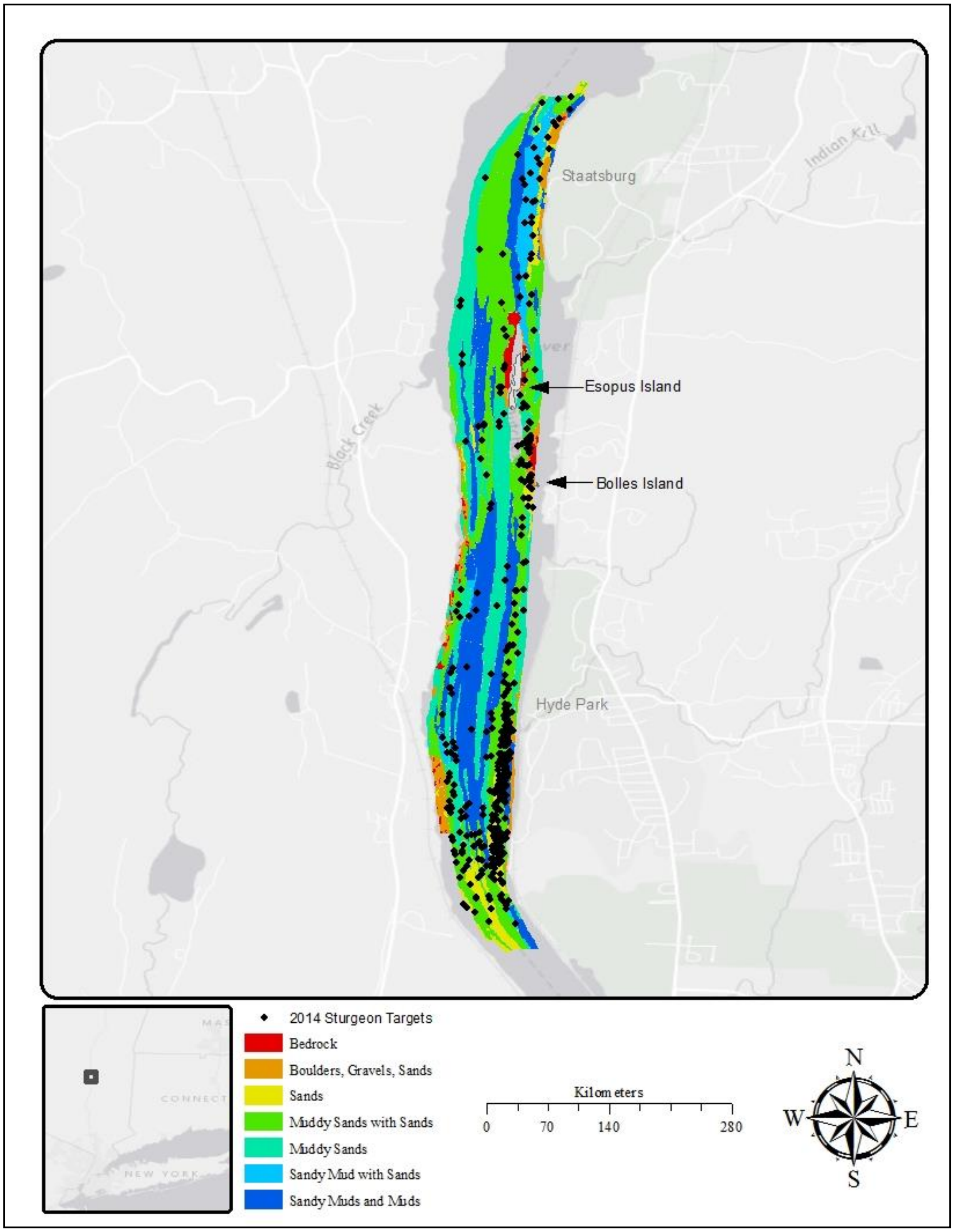

Figure 1-12. The 2014 side-scan sonar observed Atlantic Sturgeon overlain on the bedrock and grain size texture class data, in the Hyde Park Reach, Hudson River, NY. Targets are all identified as Atlantic Sturgeon and meet the >1.5 m size requirement. Identification of targets was completed using SonarWiz5. A total of 479 sturgeon were detected on 12 sampling days from June 11 – July 02, 2014 (June 11-13, June 17-19, June 23-25, and June 30 – July 02).

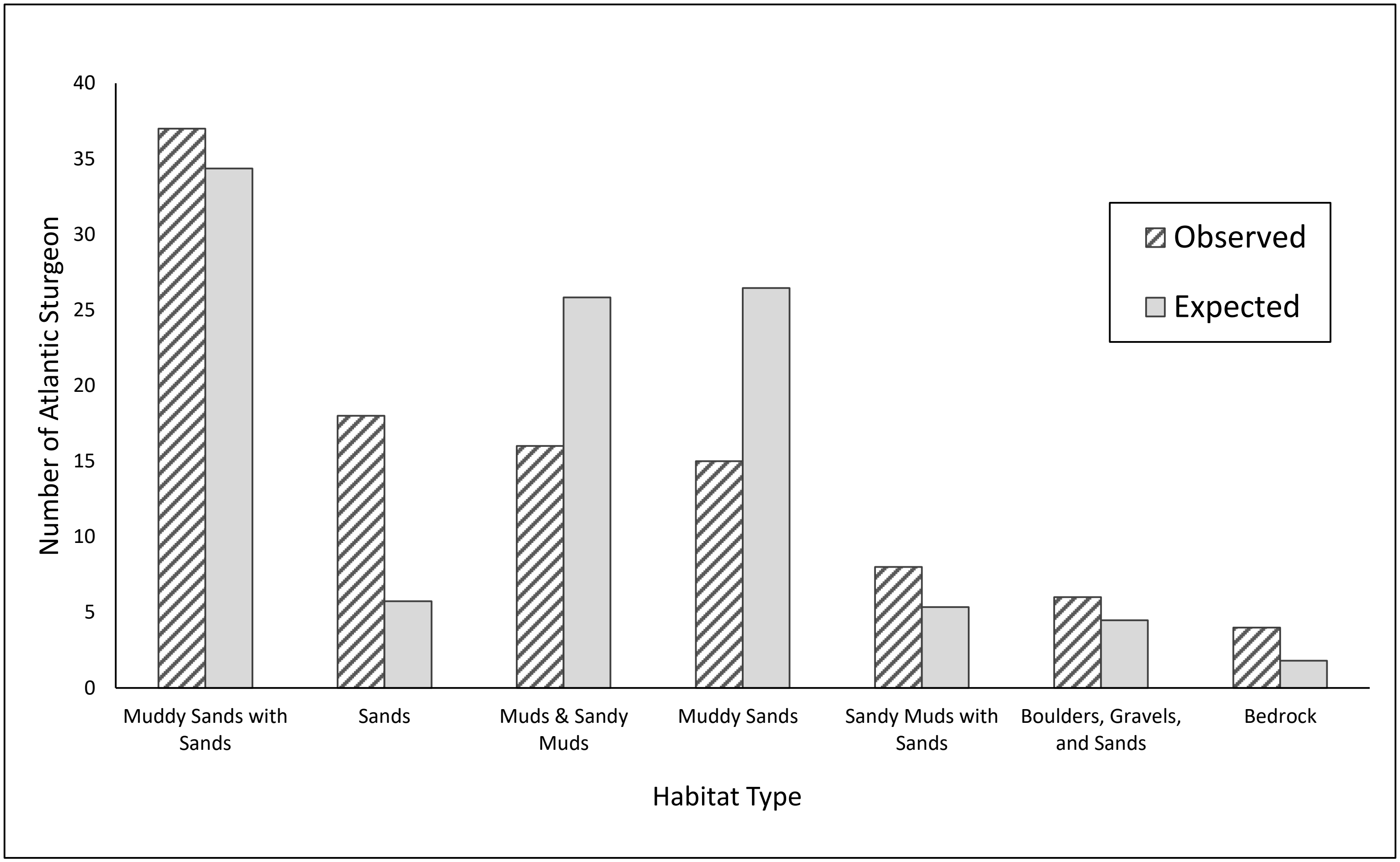

Figure 1-13. Observed and expected habitat use of adult Atlantic Sturgeon targets in 2013 from the Hyde Park Reach in the Hudson River, NY. Observed values were calculated based on the total number of targets (n) (2013 n= 104, 2014 n= 479) multiplied by the proportion (P_io) of each habitat type in the survey reach.

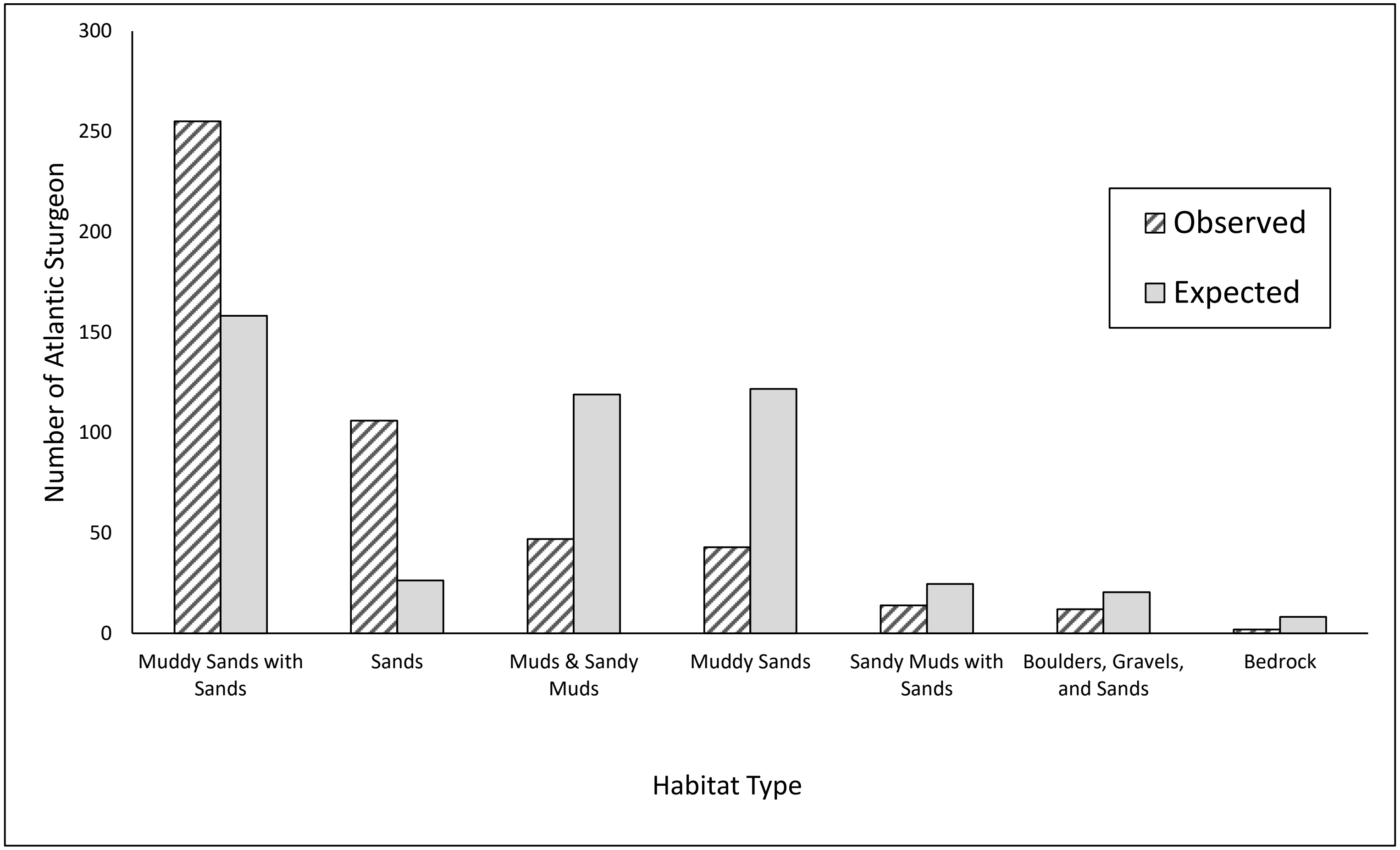

Figure 1-14. Observed and expected habitat use of mature sized Atlantic Sturgeon targets in 2014 from the Hyde Park Reach in the Hudson River, NY. Observed values were calculated based on the total number of targets (n= 479) multiplied by the proportion (P_io) of each habitat type in the survey reach.

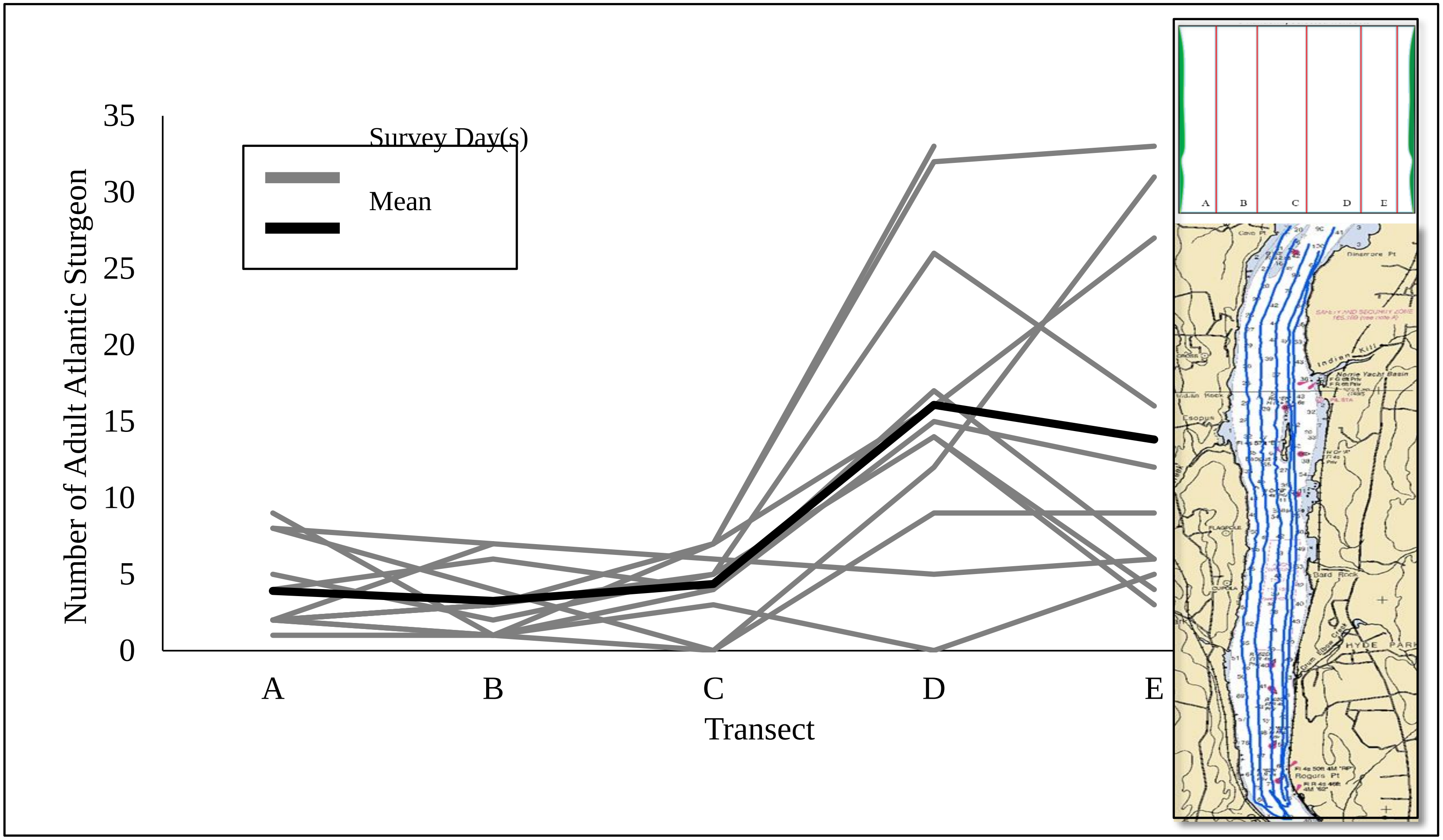

Figure 1-15. Adult Atlantic Sturgeon per transect in the Hyde Park Reach, Hudson River, NY. A total of 479 Atlantic Sturgeon were imaged on 12 sampling days from June 11 – July 02, 2014 (June 11-13, June 17-19, June 23-25, and June 30 – July 02). The grey lines indicate daily count data, and the black line indicates the mean number of sturgeon per transect.

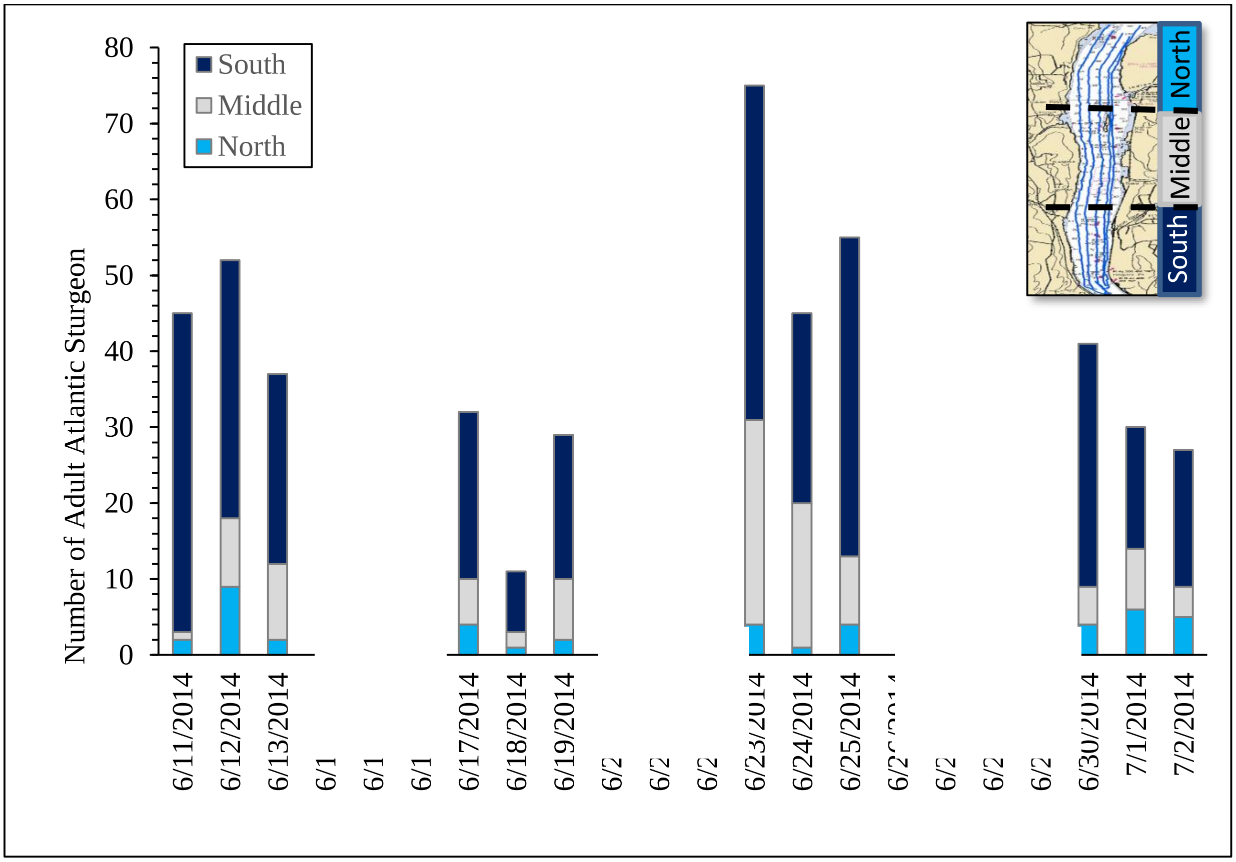

Figure 1-16. Adult Atlantic Sturgeon imaged per three equidistant regions (north, middle, and south) in the Hyde Park Reach, Hudson River, NY. A total of 479 Atlantic Sturgeon were imaged on 12 sampling days from June 11 – July 02, 2014 (June 11-13, June 17-19, June 23-25, and June 30 – July 02).

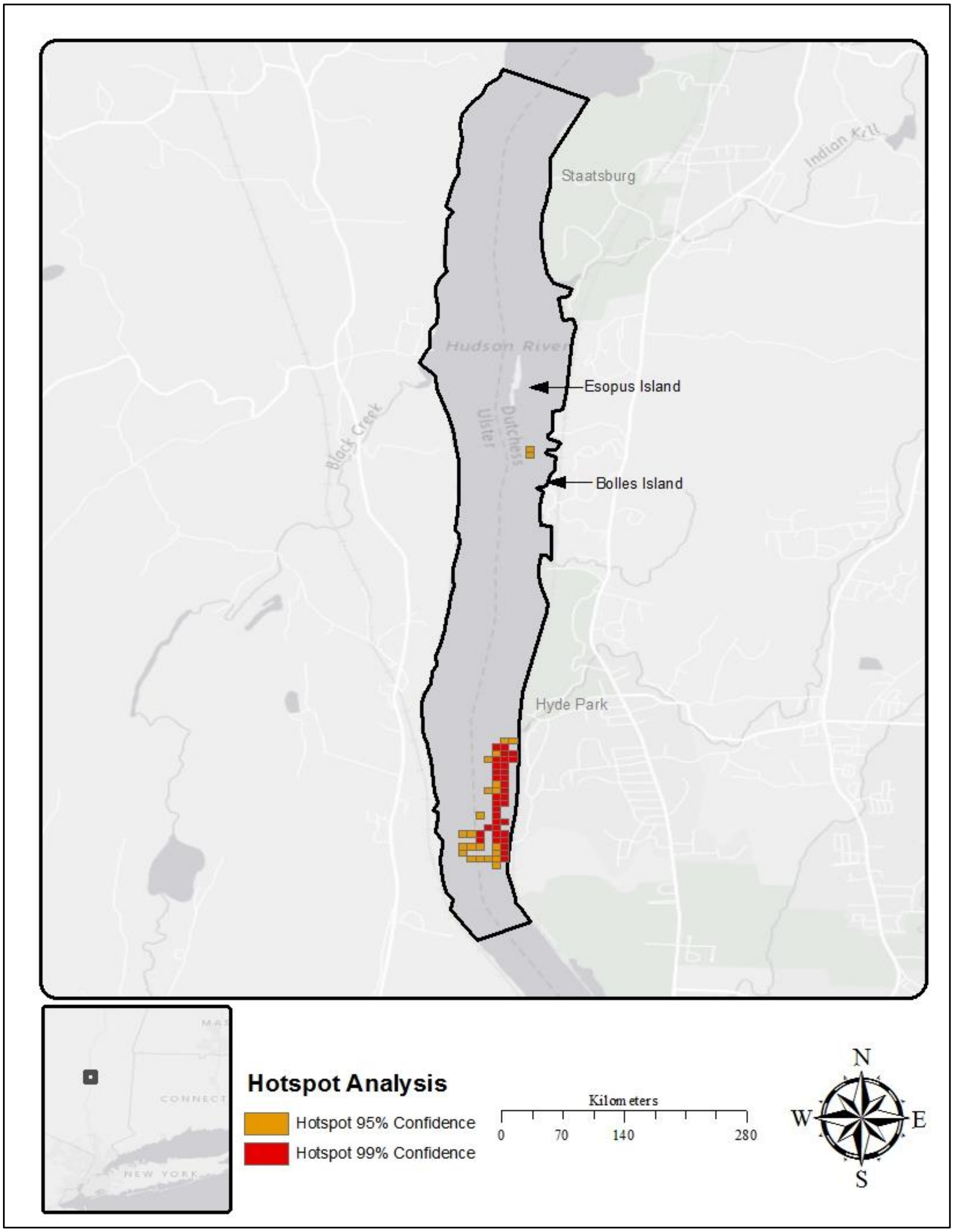

Figure 1-17. The 2014 hotspot analysis of adult Atlantic Sturgeon within the Hyde Park Reach, Hudson River Reach, NY. Hotspot analysis was done in ArcGIS. Note the presence of two statistically significant hotspots (p and z scores in Appendix A), one small one near Esopus Island and one larger hotspot near Rogers Point on the southeast side of the study site.

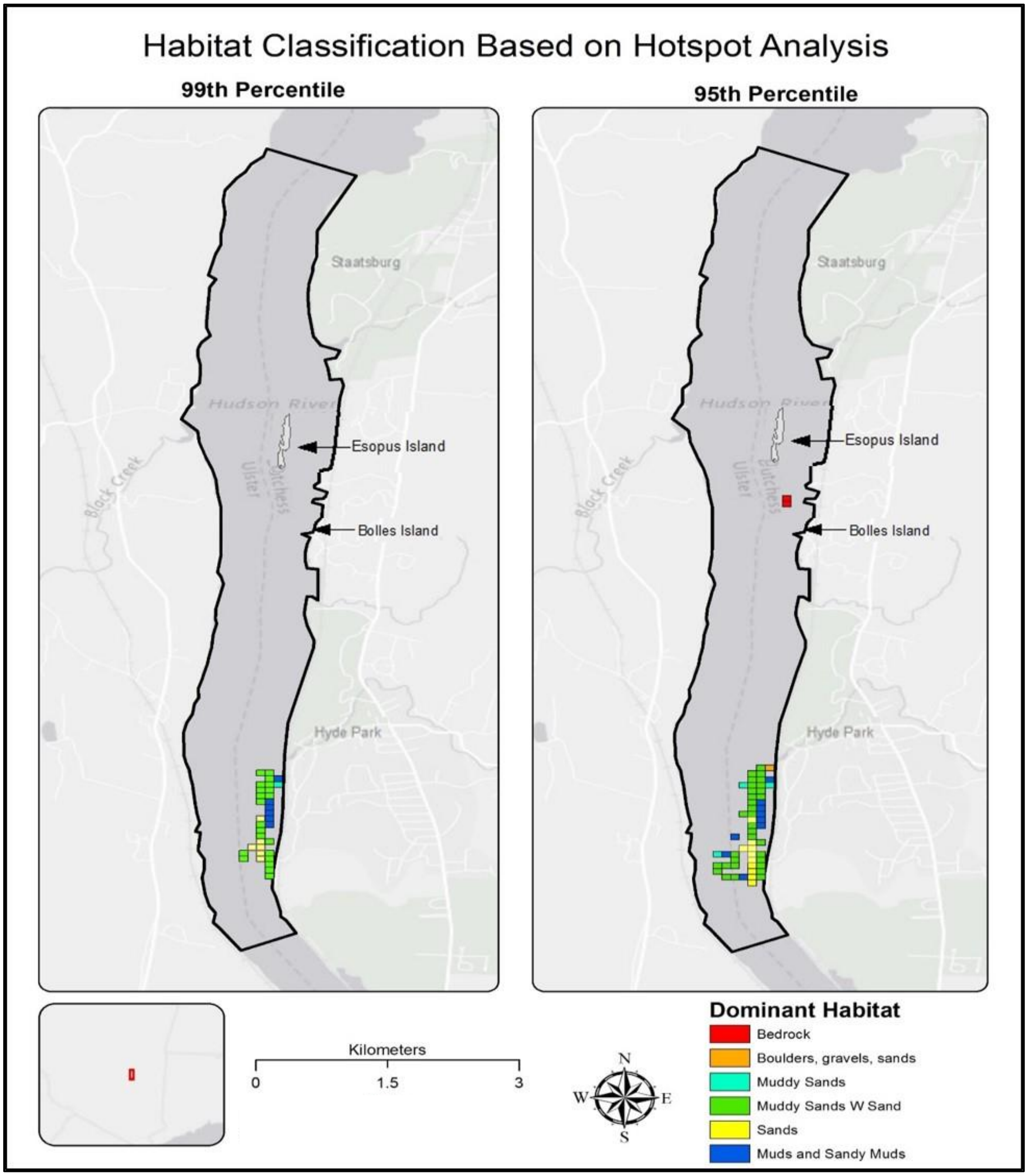

Figure 1-18. Habitat classification for each of the 2014 hotspot analysis bins, within the Hyde Park Reach, Hudson River Reach, NY. Hotspot bins were overlaid on the 2013 habitat classifications. The left inset describes 99% significance, in three habitat types: muddy sands with sands, muds and sandy muds, and sands. The right inset shows 95% significance and adds bedrock, and muddy sands. These hotspots are significant to the spatial distribution of Adult Atlantic Sturgeon in the study site.

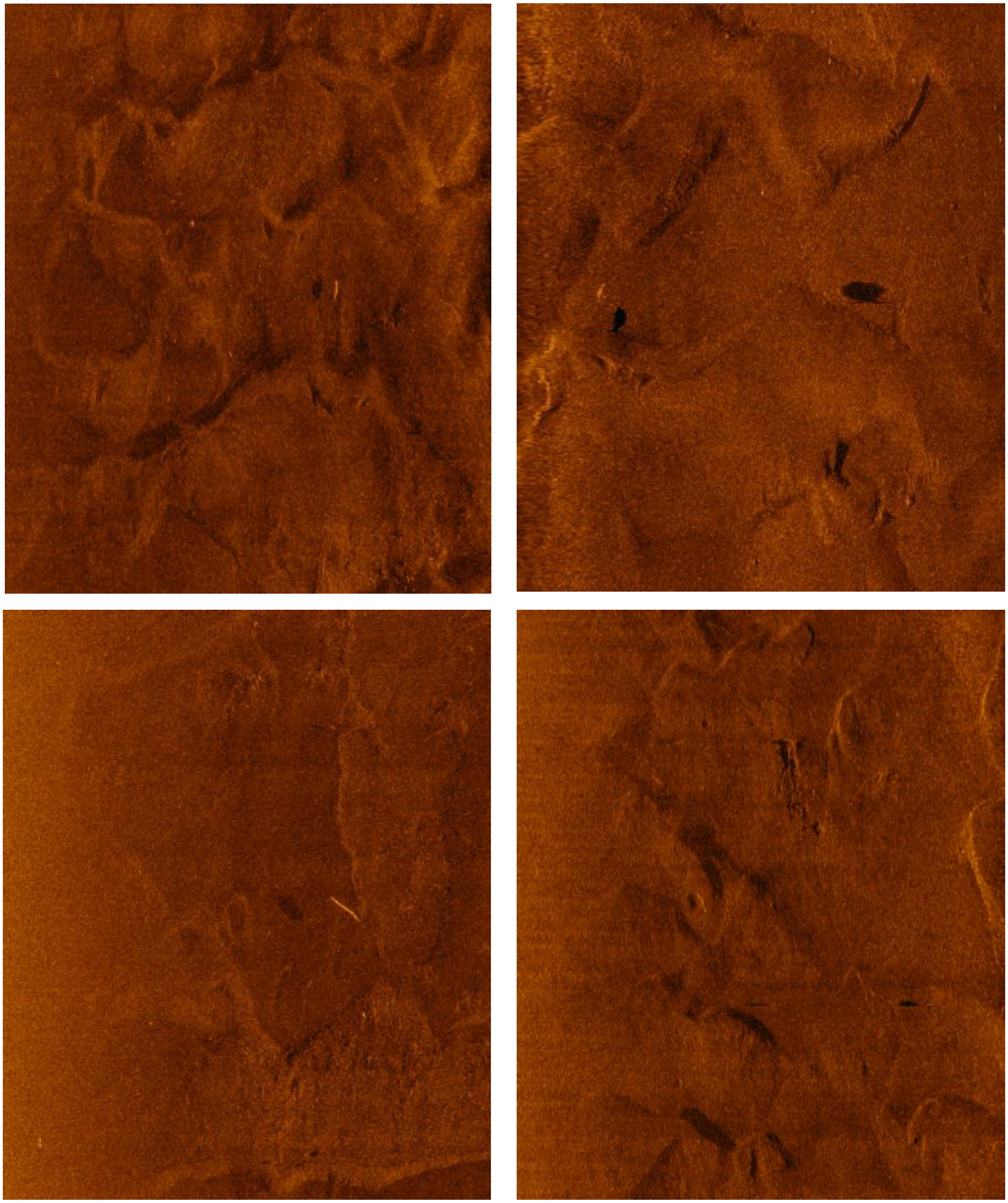

Figure 1-19. Four example images taken from side-scan sonar imagery of Atlantic Sturgeon found in muddy sand habitat dominated by sand waves. The top two example were imaged on 6/12/14 and the bottom two on 6/19/14. All images were taken in the southeastern portion of the study site, near Rogers Point Marina.

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Chapter 2

Run size estimation of reproductively mature Atlantic Sturgeon in the Hudson River Hyde Park Reach, NY during the spring spawning season.

CHAPTER 2: ABSTRACT

Historically the Hudson River supported one of the largest populations of Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*), but overfishing and other anthropogenic factors led to dramatic declines starting in the late 19th and into the 20th century. In 2012, Atlantic Sturgeon were listed under Endangered Species Act with four distinct population segments (DPSs) listed as endangered, and the fifth, the Gulf of Maine DPS listed as threatened. Central to recovery of the Atlantic Sturgeon is the monitoring of populations, including annual spawning estimated to help inform recovery goals and foster the recovery of this endangered species. The objective of this study was to develop a methodology for estimating Atlantic Sturgeon run-size. Atlantic Sturgeon were imaged using a high frequency side-scan sonar. Transect count data was used to estimate their run-size in the Hyde Park Reach (rkm 127-138), which is presumed to be the largest spawning aggregation in the Hudson River. Swept-area and N-mixture models were used in analysis to estimate population size. In 2014, an average of 40 Atlantic Sturgeon were counted per day (range: 11-75 from June 11th – July 2nd). From these data, the swept-area model estimated the Hyde Park Atlantic Sturgeon run-size at 113 – 188, (95% CI's 74-275) for each of four sampling periods while N-mixture estimates were higher at 171 – 306 Atlantic sturgeon (95% CI's 75 – 560). The high amount of daily variance decreased the detection probability estimates in N-mixture, which likely increased the positive bias in estimates for this study. Although N-mixture analysis may not have been the best model option a study design with a highly mobile species and small sites, there is plenty of application for this methodology for more sedentary species or for more and larger sites to minimize movement between sites. These methodologies (side-scan sonar, N-mixture, and swept-area) can be adapted for other systems to assess Atlantic Sturgeon and other species abundances, to help in quantifying recovery efforts.

CHAPTER 2: INTRODUCTION

The Atlantic Sturgeon *(Acipenser oxyrinchus oxyrinchus*) is an anadromous species that ranges from Hamilton Inlet, Labrador, Canada (Backus 1951) to the St. Johns River, Florida in North America (Vladykov and Greeley 1963). The history of the North American Atlantic Sturgeon fishery is similar to many other US fisheries, with commercial over-harvest as the major cause of the declines in abundance (Ryder 1888; Vladykov and Greely 1963). This overharvest was often compounded by problems associated with the outright loss (e.g. dams) and degradation of aquatic systems (NOAA 1998). Harvest records indicate that fisheries for Atlantic Sturgeon were conducted in all major coastal rivers along the Atlantic coast and concentrated on their spawning migrations (Smith 1985; NOAA 1998).

In the late 1800's, a directed Atlantic Sturgeon fishery developed along the banks of the Delaware River Estuary, where they were readily caught (Ryder 1888). This fishery rapidly expanded, quickly decimating the population in just over a decade, before shifting to neighboring systems with similar results (Borodin 1925). Atlantic Sturgeon harvest remained at approximately 1% of its peak for roughly a century (Bain et al. 2000) before a small coastal fishery that was centered in New York and New Jersey in the 1980's was established (Van Eenennaam et al. 1996). Management and enforcement of the fishery was limited in the 1980's, with overharvest occurring at double the allotted weight, and up to four times the number of individuals caught, both contributing to a second decline of Atlantic Sturgeon in the Hudson River (Bain et al. 2000).

Due to overharvest concerns, the Atlantic States Marine Fisheries Commission (ASMFC) created a Fishery Management Plan (FMP) for Atlantic Sturgeon in 1990, with a goal of restoring a population size to at least 10% of historic landings (Taub 1990). In 1998, the National

Marine Fisheries Service (NMFS) amended the FMP by implementing a coast-wide moratorium (NMFS 1998). The National Marine Fisheries Service's (NMFS) stated goals were to protect 20 year classes of spawning females and to develop a sustainable fishery at a least 10% of historic levels (ASMFC 1998). The Atlantic Sturgeon coast-wide population remained low and in 2005, the Atlantic Sturgeon Status Review Team (ASSRT) was created by NMFS in response to petitions to list the species under the provisions of the Endangered Species Act. The ASSRT identified five Distinct Population Segments (DPSs); Gulf of Maine, New York Bight (NYB), Chesapeake Bay, Carolina, and South Atlantic DPSs (ASSRT 2007). In 2009, the Natural Resources Defense Council filed another petition to list Atlantic Sturgeon and in 2012 NMFS issued a final ruling, using the five DPS model put forth by the ASSRT which listed the Gulf of Maine DPS as Threatened, whereas the New York Bight, Chesapeake, Carolinas, and South Atlantic DPSs were listed as Endangered (NOAA 2012a, 2012b). Today, one of the largest U.S. populations of Atlantic Sturgeon is thought to occur in the Hudson River (Kahnle et al. 2007), which combined with the Delaware Bay and the Connecticut River stock, comprises the NYB DPS.

Atlantic Sturgeon spawning is thought to occur in multiple sites within the Hudson River (Dovel and Berggren 1983; Van Eenennaam et al. 1996; Kahnle et al. 2007, 1998; Bain et al. 2000), although exact location information is lacking. Spawning is believed to take place in the spring or early summer, near the freshwater/saltwater interface early in the spawning season, and may move progressively upstream as the season progresses (Bain et al. 2000). Telemetry studies in several southern systems have suggested that a fall spawn may occur (Collins et al. 2000; Balazik et al. 2012; Smith et al. 2015), which could be possible in the Hudson River, but no research has identified this yet. Regardless of timing, Atlantic Sturgeon spawn in regions characterized by freshwater, high flows, (Ryder 1888; Smith and Clugston 1997), and hard-bottom habitat (Smith 1985). Atlantic Sturgeon practice skip spawning which means they don't spawn every year, and they exhibit slow maturation with males maturing between 11-20 years, and females at 15-30 years of age (Dovel 1979; Dovel and Berggren 1983; Van Eenennaam et al. 1996). Juvenile Atlantic Sturgeon remain in the riverine environment until ages 2-6, and migrate to marine waters to forage and grow for the rest of their life history. Atlantic Sturgeon can grow in excess of 4.3 m Total Length (TL) (Gilbert 1989), and when they reach reproductive maturity (approximately 1.5 m TL), they will return to their natal rivers to spawn (Dovel and Berggren 1983).

When an anadromous species such as Atlantic Sturgeon return to their natal rivers to spawn, the species is concentrated in higher densities during spawning runs, which make directed collections relatively easier (Moser and Ross 1995). More specifically, migration routes, timing, and seasonal concentration areas highlight the vulnerability of many species, including Atlantic Sturgeon to overharvest. Although Atlantic Sturgeon are handled while concentrating near spawning grounds in the spring or early summer, handling during high water temperatures or low dissolved oxygen can be lethal if handled improperly or for extended lengths of time (Moser and Ross 1995; Moser et al. 2000; Damon-Randall et. al. 2010). There is also evidence that the stress from capture during spawning runs, have caused individuals to abort and return to the ocean without a successful spawn (Kahn and Mohead 2010). Due to these factors, traditional sampling techniques such as gillnets, set trammel, drift nets, and seine nets may not be the most appropriate methodology for sampling these imperiled species during warm month's in-riverine periods and spawning migrations. Advances in technology may provide non-invasive alternatives to the traditional sampling methodologies, especially when considering imperiled species, such as the Atlantic Sturgeon.

The Hudson River Atlantic Sturgeon population is at a fraction of its peak in the late 1800's, and is estimated to have the second largest extant population of Atlantic Sturgeon in North America, which is estimated at 10% of its historic population size (Kahnle et al. 2007). Given the endangered status of Atlantic Sturgeon in the New York Bight DPS (NOAA 2012a), it is important to assess and monitor the population and gain a benchmark of spawning run sizes. Gaining these insights will allow managers to track recovery and possibly set run size recovery goals. Finally, gaining insights into future recruitment is a much needed and often missing part of the equation.

Historic estimates of Atlantic Sturgeon focused on mature females, with an estimated 6,000 females as the maximum spawning stock abundance in the late 1800's (Secor 2002). Over a century later this population has decreased over 95% and is likely comprised of a few hundred spawning females (267 females: 596 males, 863 total population size; Kahnle et al. 2007). A recovery plan for Atlantic Sturgeon is mandated under the ESA and fisheries managers are to set recovery goals, emphasizing the need to develop robust tools to track population abundance to inform management and recovery actions.

Reliable run-size abundance estimates are a necessity for proper management, species planning, and recovery strategies. Most commonly, mark-recapture studies are used to estimate abundances in fish, however, these studies require direct handling which can result in mortality, lead to harassment of spawning adults, and they often require extreme efforts to develop the necessary sample sizes required to develop both accurate and precise results (Nelson et al. 2013).

The employment of side-scan sonar may offer a non-intrusive and less intense methodology for abundance estimations of target species like Atlantic Sturgeon.

There are several ways to use side-scan sonar data to estimate relative abundance, but possibly the most direct approach is to use swept area methodology (Gunderson 1993). In fisheries, the swept area methodology is most commonly associated with trawl surveys (Gunderson 1993). Using the swept area method, one assumes that the area swept by the trawl, or in this case the side-scan sonar, is representative for the entire area over which the fishes are distributed. The trawl (side-scan sonar) would therefore sweep a well-defined path, the area of which is the length of the path, times the width of the trawl/sonar swath and is called "swept area." Users then take the count data, standardize it as catch per unit area (CPUA) thereby developing a measure of abundance. As such, the use of side-scan sonars in lieu of trawls may provide a non-invasive way to estimate abundance using the swept-area method.

A secondary abundance estimation is N-mixture modeling, and can be accomplished by assessing presence/absence per site (Royle and Nichols 2003). These surveys entail repeat visits to a given number of sites (x) where target species presence is noted as "1" with absence as a "0". At each repeat visit, a binary detection matrix was built, based on detection or non-detection of the target species. These matrices are an important component in modeling abundance estimates, as they account for detection probabilities during analysis (Royle et al. 2004). Detection probabilities are a crucial component when estimating abundances, as observations of "0" individuals can occur because either the species was not present, or because it was present but not detected. Side-scan sonar data also yields count information which can be used when coupled with the length and width of the survey transects (Flowers and Hightower 2013). These counts are analyzed with N-mixture modeling (Royle 2004), which use detection probabilities and distribution to simulate abundance.

Occupancy and N-mixture modeling are becoming more commonplace in fisheries as means to estimate abundance (Royle and Nichols 2003), however these models rely on a set of assumptions, which may not be met in all studies, although important to understand how they may effect results. These include assumptions that the population is closed to immigration, emigration, and death during sampling periods (Wenger and Freeman 2008). A second assumption is that individuals are equally available for sampling. Admittedly, these assumptions are difficult for highly mobile species such as Atlantic Sturgeon, and may be violated to some degree resulting in subsequent decrease/increase of abundance estimates due to a reduction in detection probabilities (Wenger and Freeman 2008). For instance, if there is both immigration and emigration during the sampling period, with a net immigration of 10%, the model would inflate estimates of abundance.

Central to the recovery of an imperiled species, and mandated by the Endangered Species Act (ESA), managers must develop recovery plans. Developing a methodology to help derive population estimates in long-lived species like Atlantic Sturgeon, and to estimate the number of spawners contributing to the population could be key to the management and subsequent recovery of this population. Providing this information gives managers a benchmark to track changes in population levels and may help set recovery goals. Through this study, I estimated the number of spawning Atlantic Sturgeon (i.e. run size) in the Hyde Park Reach, which is presumed to be the largest spawning aggregation in the Hudson River (Bain et al. 2000).

CHAPTER 2: METHODS

Study Site

My study was conducted in the Hyde Park Reach of the Hudson River, which covers approximately 11 km stretch between Rogers Point and Staatsburg, NY (rkm 127 – 138) which is hypothesized as the river's largest Atlantic Sturgeon spawning site (Van Eenennaam et al. 1996; Bain et al. 2000) (Figure 1-1). The Hudson River is fairly deep with a mean depth of 10 m, maximum depth of 53 m, and tidal amplitude of 0.8 to 1.4 m. The river from Troy Dam (rkm 246) to West Point, NY (rkm 82) marks the freshwater portion of the Hudson River, and below West Point (rkm 82) marks the transition between fresh and estuarine portions of the Hudson River (Cooper et al. 1988; Limburg et al. 1989; Figure 1-1). In the Hyde Park Reach (rkm 127-138), depths average 18 m (6.1 m – 38.1 m) and the bottom habitat consists of mud and sand (NYSDEC 2004; NYS DOS OPD 2012; Figure 1-1).

Study Timing

A total of four sampling periods, consisting of three consecutive days of sampling, yielded twelve (12) sampling events between June 11, 2014 and July 02, 2014. Sampling occurred over three consecutive days to get an idea of detection probability on the site. For analyses purposes, dates were analyzed individually, by sampling period, and finally across all sampling events. Sampling periods were as follows: 1: 6/11-6/13, 2: 6/17-6/19, 3: 6/23-6/25, 4: 6/30-7/02. Finally, 'All' covers all sampling days, which is assumed to encompass the overall Hyde Park Reach spawning-run from June 11 – July 02, 2014.

Side-Scan Sonar Data Acquisition

Side-scan sonar surveys were conducted using an Edgetech 4125-P sonar system consisting of a towfish with 600/1600 kilohertz (kHz) dual frequencies transducer (Figure 1-4).

The sonar was towed behind a small vessel at speeds of 4.5 km/h – 10.0 km/h and at depths of between 5 – 10 m above bottom until depths reached deeper than the capabilities of the towfish cable (~25 m). Surveys were conducted during daylight hours, using five parallel transects (A-E; Figure 1-3) traveling with the tide and each sonar transect covered 70 m of the river bottom (coverage = 41% of survey site). Full details on side-scan sonar data acquisition are provided in Chapter 1 methods.

Side-Scan Sonar Target Identification

Post-processing of side-scan sonar data were conducted using SonarWiz5 software, (Chesapeake Technology, Mountain View, CA) which allows the user to mark potential targets, generate size estimates, and measure distance off-bottom in a geo-referenced file format. All targets were classified as “yes”, “no”, or “suspected” Atlantic Sturgeon (Figure 1-6), and information such as target length and height off bottom was collected for each target. Data analysis were completed using targets classified as “yes” Atlantic Sturgeon, and filtered for adult Atlantic Sturgeon at >1.5 m total length. A full description of side-scan sonar post-processing and target identification can be found in Chapter 1.

Classification as Atlantic Sturgeon can be subjective and could vary based on observer experience, habitat complexity, and or based on the size and shape of targets (Flowers and Hightower 2013). To account for this, a second reviewer independently processed a subset (25%) of the side-scan sonar files and classified targets. An observer based identification probability was generated and was calculated as the proportion of sturgeon detected by the primary reviewer relative to a second, independent review. See chapter I for details.

Swept-Area Modeling

Generally speaking, swept area estimates are calculated as

$$\mathrm{CPUA} = \mathrm{C}/\mathrm{A} \qquad \text{Equation 1}$$

where CPUA= Catch Per Unit Area, C=Count, and A=Area Swept (Equation 1). This concept has been the basis of the “swept-area” method largely employed in assessment programs worldwide (Gunderson 1993; Pezzuto et al. 2008). Ideally, all individuals within the swept area would be detected, however, that is rarely the case and it is common for a correction factor (E) to be applied to compensate for the loss of a certain percent of the fish (Equation 2)

$$\mathrm{CPUA} = \left(\frac{\mathrm{C}}{\mathrm{A}}\right) * \mathrm{E} \qquad \text{Equation 2}$$

The stated length of the Hyde Park Reach is 11 rkm (rkm 127 – 138), however, the measured transect distance is 14 km. This discrepancy is likely due to different measuring techniques between ArcGIS and real time data collection. Using the 14 km transects, the Hyde Park Reach was divided into one km ‘survey units’ (n=14) using ArcGIS 10.1, where each adult Atlantic Sturgeon “yes >1.5 m target” was assigned to a survey unit. The one km length of the survey units was chosen to maximize the number of sites available for estimation purposes, while weighing the likelihood of immigration or emigration from the units. All target data were then exported into Microsoft Excel where each target had an associated date, transect ID (A-D), and one km survey unit. For each sampling day, sampling period, and for the duration of the sampling season, the mean sturgeon density per survey unit was calculated. The mean sturgeon density was then resampled at 1,000,000 iterations using R (R Core Team 2017), to produce bootstrapped confidence interval distributions of total abundance (Appendix B). The bootstrapping approach assumes that the observations (i.e. one km units) were independent. Bootstrapping these data helped characterize the uncertainty of the abundance estimates. Mean estimates and bootstrap estimates were then multiplied by the correction factor to yield the run-size estimate. Two key sources of uncertainty contributed to the observed variation in the proportion of spawners (1) lack of a closed population for estimation (i.e. open population) (2) the identification probability at < 1.0. In practice, these two sources of uncertainty are compounded and serve as the (E) correction factor. The uncertainty surrounding an open population, leads to biases in the counts of Atlantic Sturgeon on a given day or sampling period. The standard deviation of the bootstrapped estimates for each date was considered to represent measurement uncertainty ($\sigma_{\epsilon,i}$). When I estimated swept area run-size by day, the correction factor (E) was the identification probability (0.8695). When I estimated the swept area run-size by survey period (1-4) and by the sampling season "All", the identification probability (0.8695) and the movement index (see below) were multiplied to provide the correction factor (E). Mean sturgeon density estimates were then scaled to the full transect area by multiplying by the number of survey units per day (transects were 14km long = 14 (1km) survey units per transect * 5 transects per day = 70 survey units per day). The data were then extrapolated to the entire survey reach based on the proportion of the reach scanned (41%), to yield run-size estimate. It was assumed that abundance estimates were independent among dates.

N-Mixture Modeling

For the N-mixture analysis, I used the same yes > 1.5 m Total Length (TL) data (e.g. adult Atlantic Sturgeon), and split the site into one km survey units as explained above. Sturgeon data were then compiled into a binary detection history matrix within each survey unit. Count data were then analyzed using the program unmarked (Fiske and Chandler 2011) which was developed using the N-mixture framework within the program R. It was assumed that all targets were correctly identified as adult Atlantic Sturgeon. Count data were analyzed in unmarked using the pcount procedure, based on the N-mixture framework proposed by Royle (2004). Sites (e.g. fourteen, one km bins) were assumed to be closed for the duration of the experiment and probability of detecting an individual animal was assumed to be constant (Royle 2004). This method also uses repeated counts on a temporal scale to estimate the abundance of a closed population. The framework of N-mixture uses a combination of two different processes, detection probability and abundance. The general form of the N-mixture model for site abundance is:

$$N_i \sim f\ (\lambda, \theta) \text{ for } i = 1, 2, \ldots, M \qquad \text{Equation 3}$$

and for the detection process is:

$$y_{ij} \,\middle|\, N_i \sim \text{Binomial } (N_i, p) \text{ for } j = 1, 2, \ldots, J_i \qquad \text{Equation 4}$$

where N_i is the abundance at $_I$ time, λ is the mean abundance per site, and p is the detection probability. A discrete distribution, such as the Poisson or negative-binomial, is used for f (function), with support restricted to $Ni \geq 0$ (Fiske and Chandler 2011). The θ are additional parameters of f other than the abundance rate for distributions such as the negative binomial (Fiske and Chandler 2011). Detection probability is modeled using a binomial distribution, while abundance is modeled using a Poisson, negative binomial, or zero-inflated Poisson distribution. Run-size estimates were modeled using the N-Mixture framework using repeated counts to estimate the abundance of a closed population (Royle 2004). I assessed the models by their statistical fit and the ecological realism of the parameter estimates. Specifically, I assessed the statistical fit with Akaike's information criterion (AIC) and assessed the ecological realism by comparing the parameter estimates with the swept area parameter estimates. The most appropriate model was selected and estimates of abundance and 95% confidence intervals were calculated using the predict function in unmarked. My R-code can be found in Appendix C.

Biotelemetry

A collaborative (DSU, New York State Department of Environmental Conservation (NYSDEC), Stony Brook University) array of passive acoustic receivers (VEMCO Ltd. VR2W) was deployed to monitor the presence of telemetered sturgeons in the Hudson and East Rivers, as well as New York Harbor (Figure 2-1). Receivers were affixed, with permission, to United States Coast Guard Aids to Navigation. The DSU portion of the array was deployed on June 9 -10th, 2014 – October 13th, 2014, and comprised the majority (25/43) of receiver's present.

Collaborative research efforts have been undertaken along the species range, to implant acoustic transmitters in Atlantic Sturgeon in order to track movements, learn about mortality, and more. As a part of research at Delaware State University (D. Fox Lab), Atlantic Sturgeon are intercepted during their migration near Delaware waters. Upon capture of an Atlantic Sturgeon, they are placed in a live well (≈ 1,100L), with water pumped directly from the ocean to maintain ambient conditions. All individuals are measured to fork length (FL), total length (TL), weighed (kg), and scanned for the presence of passive integrated transponder (PIT) tag, using an AVID Power Tracker VIII or Biomark FST2001FT PIT tag reader. Individuals are also monitored for the presence of a VEMCO Ltd. Acoustic transmitter using a VEMCO Ltd. VR-100 receiver and VH165 hydrophone. In instances where no PIT tag was present, one (Biomark model IMI 1000, 400 kHz) PIT tag was inserted at the base of the left dorsal fin. A small tissue sample then gets collected from the caudal fin and placed in 95% ethanol for genetic analysis. A United States Fish and Wildlife Service (USFWS) plastic T-bar tag would then be inserted on the left side of the fish at the base of the dorsal fin following established protocols (Damon-Randal et al. 2010). Atlantic Sturgeon large enough to be considered mature (>1.3 m FL; Van Eenennaam et al.

1996) would then be implanted with acoustic transmitters. A full description of methodologies can be found in Breece 2012.

To independently assess the distribution of telemetered Atlantic Sturgeon in the study region, I simultaneously scanned for telemetered individuals using a mobile tracking receiver (VEMCO Ltd. VR-100 ultrasonic receiver) equipped with an omni-directional hydrophone (VEMCO VH165-5m) secured 5 m above the towfish. The VR100 was operated at a standardized gain of 36 or 48, depending on environmental conditions. When a transmitter was detected, the mobile receiver logged the transmitter number, receiver location via internal GPS, and time/date for later examination. The passive telemetry data was plotted against the mobile telemetry data, in an effort to identify whether using only one form of telemetry is enough, or whether a combination of the two is needed.

I used a combination of biotelemetry data and individual sturgeon sizes to assess the likelihood that telemetered individuals spawned during 2014. Sturgeon that were greater than 1.5 m TL which moved upriver beyond Con Hook, NY (rkm 79) were considered likely spawners. Con Hook, NY (rkm 79) was designated as "in-river" as it encompasses the southernmost hypothesized spawning location. These data were then used to assess Atlantic Sturgeon occupancy, within the Hudson River and within the Hyde Park study site.

Occupancy based models generally require the population to be closed to immigration and emigration (i.e. no net population change). For the purposes of this study, a 'movement index', was developed by focusing on the three acoustic receivers within the study site (Rogers Point Marina Warning Buoy (rkm 128), Esopus Island N Shoal Lighted Buoy (LB) EN (rkm 135), and Staatsburg LB 63 (rkm 138)), as well as three receivers that bracketed the study boundaries (south: Poughkeepsie LB 60 (rkm 122); north: Esopus Meadows LB 67 (rkm 143), Sturgeon Point LB 70 (rkm 140); Figures 2-1). To examine the assumption of site closure in the study reach, I combined the mobile telemetry data with the three receivers in the Hyde Park Reach (Figure 2-1). If a telemetered individual was detected less than five times over the three consecutive day period, it was excluded from further analyses. I assumed that if a fish was detected less than five times, it likely migrated through the study site and wasn't accessible to detection by the side-scan sonar, or was a spurious detection(s). A total count of detections per transmitter were evaluated, on the three receivers within the study site and the three receivers bracketing the study site. If a transmitter was detected both within and outside of the study site, whichever had the larger summed detections would yield the area occupied. All telemetered individuals were evaluated and given a -1, 0, or +1. Net movement, or a "movement index" of -1 identified an individual that emigrated out of the site, a 0 identified an individual that remained in the site, and a +1 identified an individual that immigrated into the site during the three-consecutive day sampling period. These data were aggregated per sampling period to come up with a movement index. The movement index was then divided by total telemetered adult Atlantic Sturgeon detected per sampling period to come up with a proportion of individuals immigrating or emigrating from the Hyde Park Reach, which was used as the correction factor (E) in the swept area model (above).

To estimate the proportion of telemetered spawners ($\hat{\tau}_i$;) in the Hyde Park Reach, the total number of unique acoustic telemetry tags, from the mobile and passive telemetry ($N_{t,i}$), was divided by reach-wide abundance estimate ($\widehat{N}_{ss,i}$) (Equation 5) for each sampling period (i). To come up with a sampling period estimate of the proportion of spawning Atlantic Sturgeon, I calculated the mean from the daily proportion of spawners.

$$\hat{\tau}_i = \frac{N_{t,i}}{\hat{N}_{ss,i}} \qquad \text{Equation 5}$$

CHAPTER 2: RESULTS

Side-Scan Sonar

Side-scan surveys were conducted on 12 dates between June 11th, 2014 and July 2nd, 2014. In that time, 58 total transects covering 812 km were completed, and a total of 609 sturgeon were identified, of which 479 (78.7%) met the > 1.5 m size threshold for adult Atlantic Sturgeon (mean= 40/day; range: 11 – 75 Atlantic Sturgeon). Those adult targets measured a mean length of 1.9 m (range 1.5 m – 4.6 m) (Figure 1-8), and were positioned at a height of 1.8 m above bottom (range 0.1 m – 14.5 m) (Figure 1-9).

Swept-Area Run-Size Estimation

The 2014 Atlantic Sturgeon Hyde Park run-size were first analyzed by individual day, then by sampling period, and finally across all sampling dates from June 11 – July 02 ("all"). Daily estimates yielded a swept area run size of $\hat{N}$ = 31 – 210 depending on the day (95% CI: 14 – 379), with a mean daily estimate of 116 Atlantic Sturgeon (Table 2-1, Figure 2-2). The estimated run-size per three-consecutive day sampling period was estimated to be $\hat{N}$ =176 (95% CI=116 – 250) in period 1, $\hat{N}$ =150 (95% CI= 51-196) in 2, $\hat{N}$ =188 (95% CI = 115 – 275) in 3, and $\hat{N}$ =113 (95% CI = 74 – 159) in period 4 (Figure 2-2). The overall run-size for the sampling season (June 11 to July 02) was $\hat{N}$ =188 (95% CI = 115-275) adult Atlantic Sturgeon and was the maximum estimate over the 4 sampling periods (Figure 2-3).

N-Mixture Run-Size Estimation

The negative binomial model yielded the lowest AIC value, which suggested it was the best supported model. Although the negative binomial was chosen as the lowest AIC, both it and the zero inflated poisson model, produced ecologically unrealistic estimates and or would increase when increasing *k* (*k*=upper index of integration for N-mixture models). Due to this, the models would not converge and could not be considered viable model run options. N-mixture analysis was run again using the poisson model, which generated reasonable parameter estimates, so was used for the analysis.

N-Mixture analysis of the 2014 Hyde Park run-size could only be estimated on a sampling period basis, and the entire month basis, due to how the model estimates abundance (Table 2-2). During sampling period 1, abundance was estimated at $\widehat{N}$=171 (95% CI=94 - 332), in period 2 at $\widehat{N}$=241 (95% CI=64 - 490), in period 3 at $\widehat{N}$=306 (95% CI=133 - 560), in period 4, at $\widehat{N}$=228 (95% CI=75 - 453), and finally across sampling periods, the total run-size estimate of $\widehat{N}$= 440 (95% CI=262 – 678) individuals.

Biotelemetry

The amount of unique telemetered adult Atlantic Sturgeon in the Hyde Park reach decreased over the sampling periods. Period one detected 26 Atlantic Sturgeon and by sampling period four, only 14 were present (Table 2-2). Although the amount of unique transmitters decreased over the sampling periods, the Hyde Park Reach recorded more adult Atlantic Sturgeon detections then all other receiver locations combined (Figure 2-4). A total of 32 Atlantic Sturgeon contributed to the total number of detections. Another area of interest that telemetry data highlights in the Catskills (rkm 179 – 182), which detected six adult Atlantic Sturgeon for a longer duration then the receivers bracketing it (Figure 2-4).

In an effort to understand how the mobile and passive telemetry gears performed, the amount of unique transmitters was examined (i.e. passive and mobile telemetry; Figure 2-5). Overall, the mobile telemetry surveys observed more telemetered individuals than the passive array the vast majority of sampling events (10 / 12; Figures 2-3, 2-6). On one of the remaining days both gear types detected the same number of tags, and on the remaining day, the passive array detected one transmitter that was not detected during the mobile surveys. Finally, throughout the entire sampling period from June 11 – July 02, 2014, approximately 13% (10 - 16%) of the Atlantic Sturgeon participating in the Hyde Park 2014 spawning run, were telemetered individuals (Table 2-2, Figure 2-6).

CHAPTER 2: DISCUSSION

The second chapter of my thesis represents an approach to generating run size estimates of sturgeon abundance, and provides a proof of concept for other researchers to expand and develop river wide spawning run size estimates. Side-scan sonar was able to effectively census the number of adult Atlantic Sturgeon within the Hyde Park reach on each of the twelve survey days, and a combination of the acoustic receiver array and mobile telemetry detected tagged spawners. These measures were combined to estimate the proportion of the spawning population fitted with acoustic tags, that may be helpful in future estimates of run-size in the Hudson River.

Biotelemetry

On 10 of the 12 total sampling days, mobile telemetry detected more transmitters than passive telemetry. This was expected, as the mobile reciever was attached to the towfish, and the towfish was making multiple transects at different locations throughout the river, thus increasing the opportunity to observe tag codes. Passive telemetry might be less successful in a study like this where species are mobile, the river is fairly wide, and due to the sheer number of telemetered sturgeon in the area. With up to 26 telemetered sturgeon at the site and at one time (Table 2-2), code collision could be occuring which could be the reason why passive telemetry rarely detected the same or more transmitters than mobile telemetry. Alternatively, tagged Atlantic Sturgeon may be out of range of the passive reciever stations, but close enough during the mobile telemetry transects. Interestingly, only on one occasion did passive telemetry observe more tags than mobile telemetry (6/17/14). It is likely that on this day, the fish that was picked up on passive telemetry was either out of the survey reach, but close enough to the reach to be observed by the passive reciever, but far enough away that it was not detectable by the mobile telemetry reciever.

Based on the results of this study, it would be assumed safe to use both passive and mobile telemetry, as neither gear type picked up all sturgeon on all days. In the future, it may be worthwhile to increase the number of recievers with placement in the west, middle, and east side of the river. Increasing the number of recievers would likely increase the likelihood of passive telemetry tag detections in the Hyde Park Reach. It is therefore suggested that future studies continue to use a combination of telemetry data, or increase the number of recievers in the Hyde Park Reach.

Through this study, I estimated the proportion tagged sturgeon that were participating in the 2014 spawning run in Hyde Park. Over the course of the entire sampling period approximately 13% of presumed spawning Atlantic Sturgeon were telemetered. Interestingly, on one occasion, 6/18/14, the run-size estimate was extremely low (n=31), while the count of transmitters remained consistent (n=17) which means they were in or near the Hyde Park Reach. This is interesting, as one would've expected to see a drop in the number of transmitters on days where run-size estimates are low. Unforuntely, there is no way to know why the run-size was low on 6/18, however it could be hypothesized that Atlantic Sturgeon were in other reaches of the Hyde Park Reach where I did not side-scan. If Atlantic Sturgeon were still in the Hyde Park Reach but not detectable by the side-scan sonar, it could explain why the transmitter count stayed consistent over the sampling days (6/17/14 – 6/19/14). Another explanation could be that Atlantic Sturgeon were located in an area of the river just outside the study area. Either situation could explain the low number of sturgeon detected by side-scan sonar, with seemingly consistent number of telemetered sturgeon in the area.

The percentage of individuals, amount of time, and total detections of Atlantic Sturgeon in Hyde Park Reach emphasizes its importance for the conservation and recovery of this species. A total of 32 Atlantic Sturgeon were observed by passive telemetry in 2014. Interestingly, none of the five telemetry stations south of Hyde Park (rkm 99-131) detected all 32 Atlantic Sturgeon, which suggests individuals either migrated quickly up-river to Hyde Park, they migrated far enough away from the receivers to not be detected, or were simple not picked up by the receivers while migrating through. Furthermore, the total number of detections in the Hyde Park Reach were more than any other site in the Hudson River. Males tend to migrate to the spawning grounds earlier than females, stage in river until females arrive, and tend to spend a longer period of time in the river than females (Van Eenennaam 1996). If males are staging in the Hyde Park Reach while waiting for females to migrate into the river, this could be the reason why the Hyde Park Reach has as an extensive amount of detections compared to other sites in river.

The passive telemetry data also suggests that Atlantic Sturgeon are spending an increased amount of time in the Catskills rkm 179-183, compared to adjacent regions (Figure 2-4). Although only six Atlantic Sturgeon were detected in the Catskills by acoustic telemetry, the total detections in that reach suggests the sturgeon used the area for a longer time period. These data suggest that the Catskills could be another spawning site, which corresponds with other literature (Van Eenennaam et al. 1996). Clinton Point is the other hypothesized spawning site in the Hudson River (Bain et al. 2000), and although 39 Atlantic Sturgeon were detected there in 2014, the number of detections were low which suggests fish did not spend a lot of time at that site or that fish were not being detected by the receivers.

Run-size

Historically large population sizes suggest that the Hudson River has the capabilities to provide excellent conditions for Atlantic Sturgeon reproduction. Although I imaged a total of 479 adult Atlantic Sturgeon over the survey period, it does not represent the total number of Atlantic Sturgeon as it's likely individual fish were imaged and counted on multiple days. The Hyde Park Reach day to day run-size estimates were widely variable using the swept-area methodology. When estimating the run-size per day, as few as thirty-one (31) fish were estimated on 6/18, while 210 fish were estimated in the site on 6/23.

The Hyde Park swept area run-size was also estimated for each sampling period, to (1) make it comparable to the N-mixture estimates, and (2) to help reduce bias associated with the daily count variability. Swept area estimates of run-size by sampling period yielded between 113 and 188 Atlantic Sturgeon. The sampling period estimates yielded run-size that were similar to the day to day data, but helped average out the large day to day variations.

Based on the spatial design and over dispersion of the sturgeon data, I expected the negative binomial model to run better than the other two models, and the AIC value confirmed such an assumption. However, although the negative binomial performed the best according to AIC, the negative binomial and zero-inflated poisson produced ecologically unrealistic estimates that would increase when increasing *k*. When this occurs, the model(s) were not converging and could not be considered viable option(s). These data might work in a different modeling framework, but since Unmarked is a canned package, there wasn't enough ability to make changes to accommodate this data and assumptions. The next best option was to run the Poisson model, as it generated reasonable parameter estimates. Similar findings have been reported, where the best performing model according to AIC did not yield the most accurate estimations (Joseph et al. 2009). In fact, it has been suggested that to obtain ecologically realistic estimates of abundance, occupancy, and detection probabilities, one is required to understand the source of the variation to improve model selection (Joseph et al. 2009). For this study, the main source of variation was the fluctuations in the three consecutive days' count data. The fluctuations could have been due to several factors including poor detection probability or migration in and out of the study site. Unfortunately, this study's variation was likely the product of both ecological processes (true variation) and sampling error (false variation; Martin et al. 2005a). Simulations have showed that the N-mixture models provide unstable estimations for species with detection probabilities <0.5, and empirically seemed to estimate abundance at about twice the true abundance (Couturier et al 2013). If this were true, and the N-mixture abundance estimates were halved, sampling period 2-4 would be much closer to the swept-area estimates.

It is beyond the scope of this study to evaluate whether the swept area or N-mixture model is preforming better than the other. However, several things should be evaluated when considering using these models for future studies. First, the swept area methodology is fairly simplistic and its only assumption is that if the target species is there, it is sampled. The N-mixture methodology on the other hand has several assumptions, which need to be closely evaluated before choosing this modeling option. The assumption that was most violated in this study design was that the sites were closed to migration. The telemetry data were able to provide insights into the movement in and out of the Hyde Park reach, but not within the smaller scale one km sites that were used for the N-mixture analysis. The likely movement in and out of the one km sites allowed for large variation in the day to day site specific counts, which led the detection probability to be low. Low detection probabilities in N-mixture analysis can produce inflated N-mixture estimations (Royle 2004). Several things can be done to prevent this in the future or for other studies including increasing the amount of sites, or for this study in particular, to increase the size of the site to encompass three consecutive days of movement.

After running the Atlantic Sturgeon count data through the N-mixture models, I would suggest other researchers think about different study designs including (1) one pass/transect to get a better estimate on detection probability while (2) increasing the site size to account for daily immigration and emigration between sites (3) use a less transient species which would reduce day to day variability in count (4) image sturgeon during a less transient life stage (5) considering a distance sampling approach (Flowers and Hightower 2015).

Detection probability in the N-mixture framework is defined as the probability that an Atlantic Sturgeon would be seen, if the Atlantic Sturgeon was present. There are several reasons why an Atlantic Sturgeon wouldn't be observed in this study, but N-mixture assumptions that should not be violated are that: (1) if a sturgeon is present in the environment, it will be seen by the gear (e.g. side-scan sonar) (2) assuming the sturgeon is imaged by the side-scan, the observer will identify the target. The second factor should be teased out by having multiple independent observers. Although I used prior identification probability information for the model run, the variance of the day to day data was too high for the model to have precision in the estimates. The use of N-mixture for analyses may be better fit for a less mobile or transient species or with a different study design as mentioned above. As an example, if I were to recreate a proper N-mixture study on Atlantic Sturgeon run-size in the Hudson River, I would use telemetry to evaluate the median or maximum sturgeon movement per day (e.g. 5 km), which would be used as the site size. All spawning and staging sites in the Hudson River would be binned into the site size (e.g. 5 km). Each sampling day I would then make one pass through each site. These data would likely increase the detection probability and decrease the opportunity for double counting between sites, thus increasing the accurateness of estimates using N-mixture.

In my study design, the swept-area methodology provided a more conservative approach compared to the N-mixture model. Due to less violations in model assumptions compared to N-mixture, I feel comfortable saying that the minimum number of spawning adults in 2014, in the Hyde Park Reach of the Hudson River was 188 Atlantic Sturgeon. Although these data are relevant for Hyde Park, there are several other spawning sites that were not assessed which wouldn't make this estimate relevant river wide. It was beyond the scope of this thesis to expand the swept area estimates to include all spawning sites in the Hudson River. However, this framework could easily be used to estimate the full spawning run in the Hudson River. Those data could then be compared to Kahnle et al. (2007), and historic estimates (Secor et al. 2002) of total spawning adults, to evaluate how the spawning population may be changing or recovering over-time. This information is an important piece of the puzzle for managers to help predict and protect Atlantic Sturgeon recovery. The 1985 – 1995 run-size estimation totaled 863 spawning adults (596 males, 267 females) in the Hudson River (Kahnle et al. 2007). Although not comparable because Kahnle estimates were river wide, by making the assumption that the telemetry data is representative of the total population, the Hyde Park Reach data can be evaluated. For instance, a total of 35 Atlantic Sturgeon entered the Hudson River in 2014. Of those, 69% were males, 9% were females, and 23% were unknown (Table 1-6). It could be gleaned that if 188 Atlantic Sturgeon participated in the 2014 spawning run in the Hyde Park Reach, that 129 of those fish were males, 16 were females, and 43 are of unknown sex. Future studies could expand upon these methodologies, by estimating the run-size for all the spawning sites in the Hudson River. Expanding to a river-wide estimate of run-size could help managers track the total run size year to year, can be compared to previous estimates (Kahnle et al. 2007), and may even be used to help managers predict recruitment.

This chapter provided further refinement of side-scan sonar technology, swept area modeling, and N-mixture modeling to fisheries managers. My study was able to integrate side-scan sonar and acoustic telemetry as an effective approach for estimating run-size abundance of in the Hyde Park Reach of the Hudson River. The approach presented here appears to be a viable option and can be fitted for Atlantic Sturgeon or other large species in other river systems. Furthermore, after initial cost, the methodologies presented here are fairly easy to carry out, are low cost, and are non-intrusive and could be done year after year to create an index of river wide spawning size. These data could eventually be linked to recruitment, and help to estimate recruitment sizes of Atlantic Sturgeon in the Hudson River, which would aid in the restoration of this endangered species.

Table 2-1. The count of unique transmitters (mobile and passive), the count of side-scan detected Atlantic Sturgeon, by the swept-area run-size estimates, with 95% confidence intervals per day. This data was gathered using a side-scan sonar and telemetry on adult Atlantic Sturgeon that participated in the 2014 Hyde Park spawning run.

Date	Count of Transmitters	Count of Atlantic Sturgeon from Side-scan	Swept-Area Run-Size Estimate
06/11	18	45	158 (46 – 316)
06/12	20	52	146 (79 – 227)
06/13	17	37	104 (53 – 163)
06/17	17	32	90 (53 – 129)
06/18	17	11	31 (14 – 53)
06/19	19	29	81 (45 – 123)
06/23	18	75	210 (81 – 379)
06/24	13	45	126 (39 – 241)
06/25	13	55	154 (70 – 272)
06/30	11	41	115 (45 – 208)
07/01	11	30	84 (48 – 123)
07/02	11	27	95 (39 – 168)
ALL	32	479	210 (81 – 379)

Table 2-2. Abundance estimates and 95% confidence intervals in parentheses for riverine Atlantic Sturgeon >1.5 m TL within the Hyde Park reach, Hudson River, NY. Maximum counts (per sampling period) and number of survey sites for each river system are listed for comparison (14 km transects x five transects/day = 70 one km sites). The percentage of telemetered sturgeons refers to the mean of the swept-area and N-mixture estimates divided by the number of telemetered sturgeon per sampling period. All refers, not to a mean, but an individual run of swept-area and N-mixture models.

Sampling Period	*N* Sites	Unique Sturgeon (Telemetry)	Side-Scan Maximum Counts	Swept Area Estimate	N-Mixture Estimate	Percentage of telemetered Sturgeons
1	70	26	52	176 (116 - 250)	171 (94 - 332)	15%
2	70	25	32	150 (51 - 196)	241 (64 - 490)	16%
3	70	18	75	188 (115 - 275)	306 (133 - 560)	10%
4	70	14	41	113 (74 - 159)	228 (75 - 453)	12%
ALL	-	32	-	188 (115 - 275)	440 (262 – 678)	

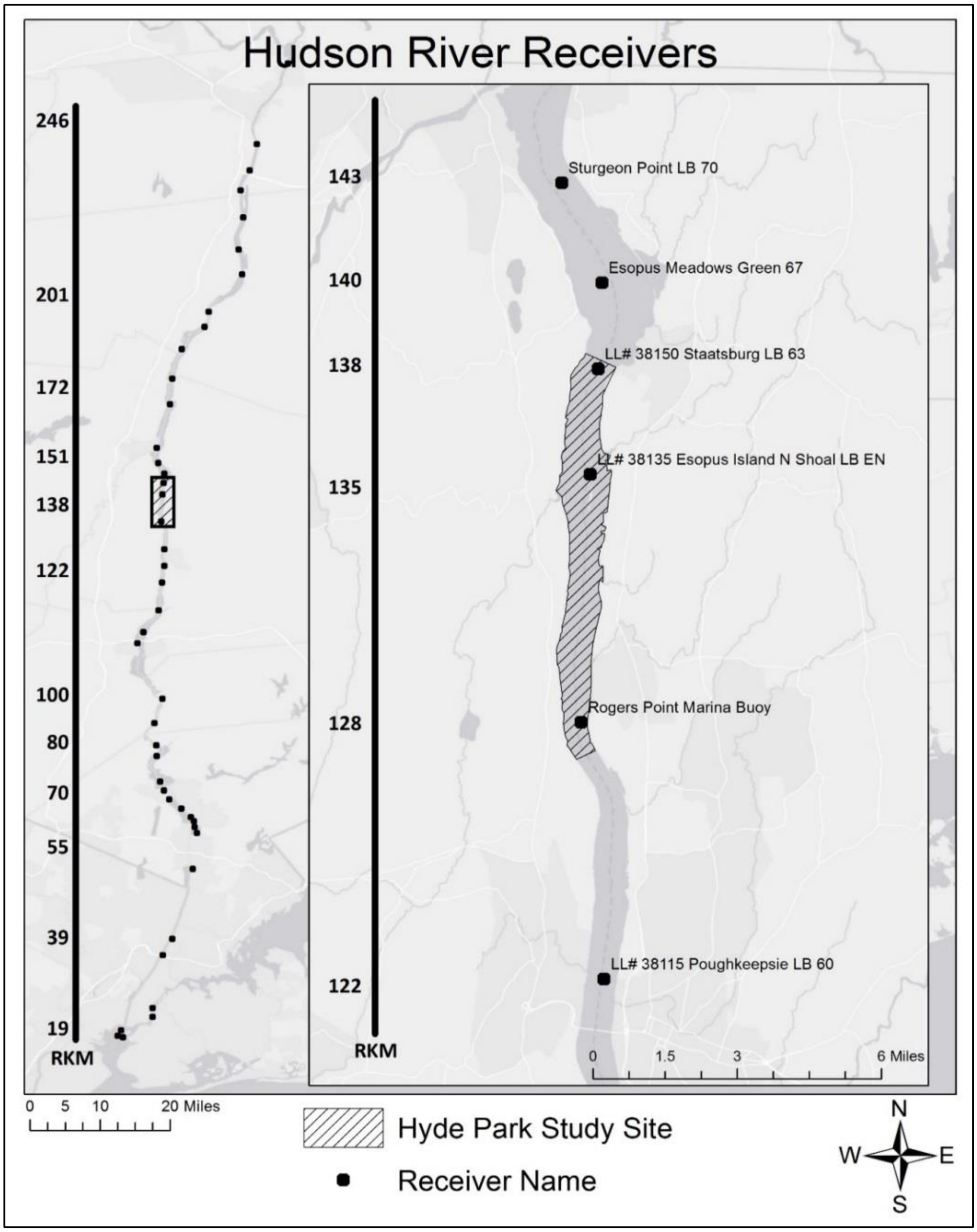

Figure 2-1. Hudson River receiver locations with inset of the Hyde Park Reach study site. Note the inset shows the three receivers located within the study site, and the three receivers outside of or bracketing the study site.

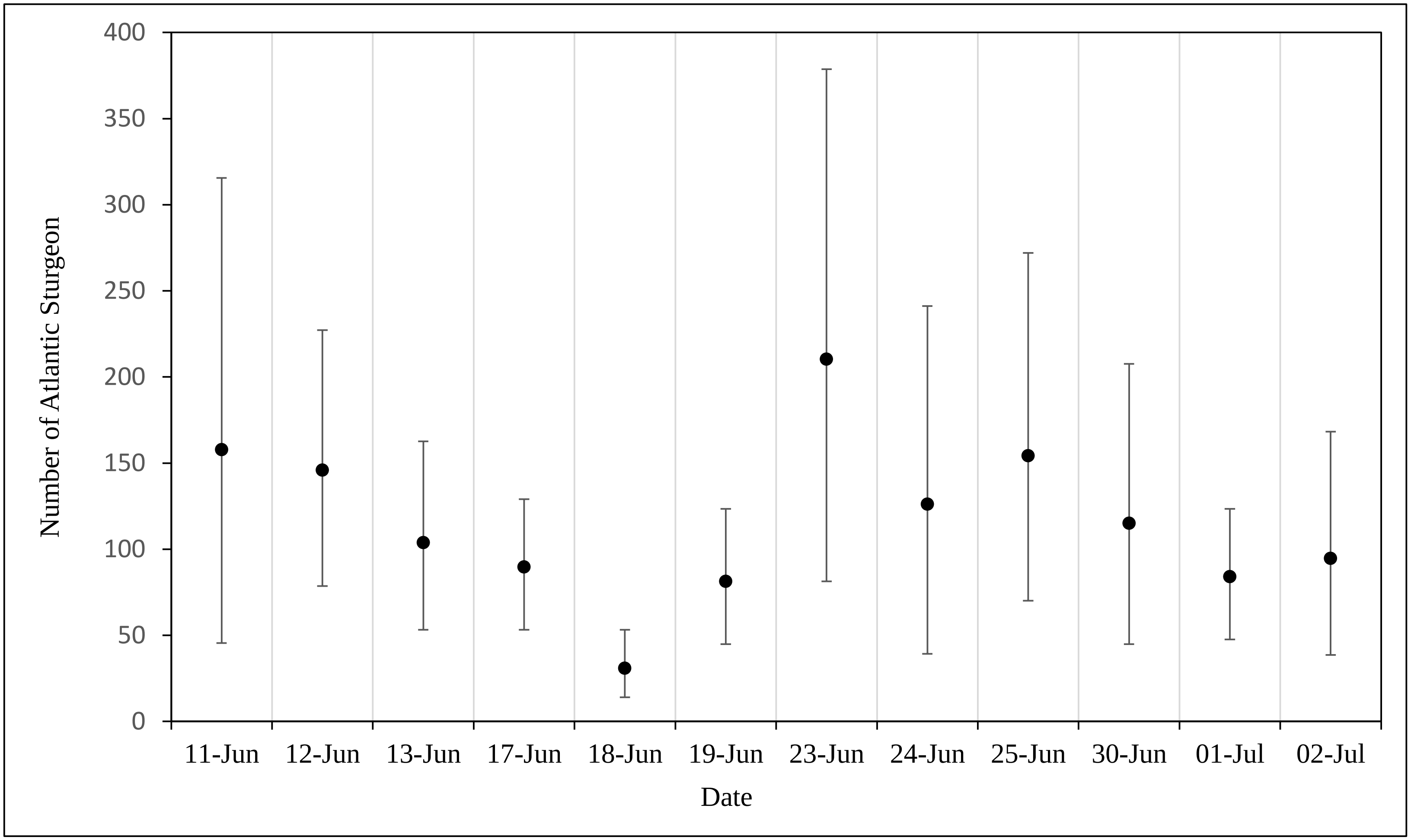

Figure 2-2. Daily run-size estimates including 95% confidence intervals for presumed spawning Atlantic Sturgeon in the Hyde Park Reach, Hudson River, NY in 2014. Estimates are from swept-area modeling. Note, x axis portrays sampling dates in order of occurrence and is not proportional.

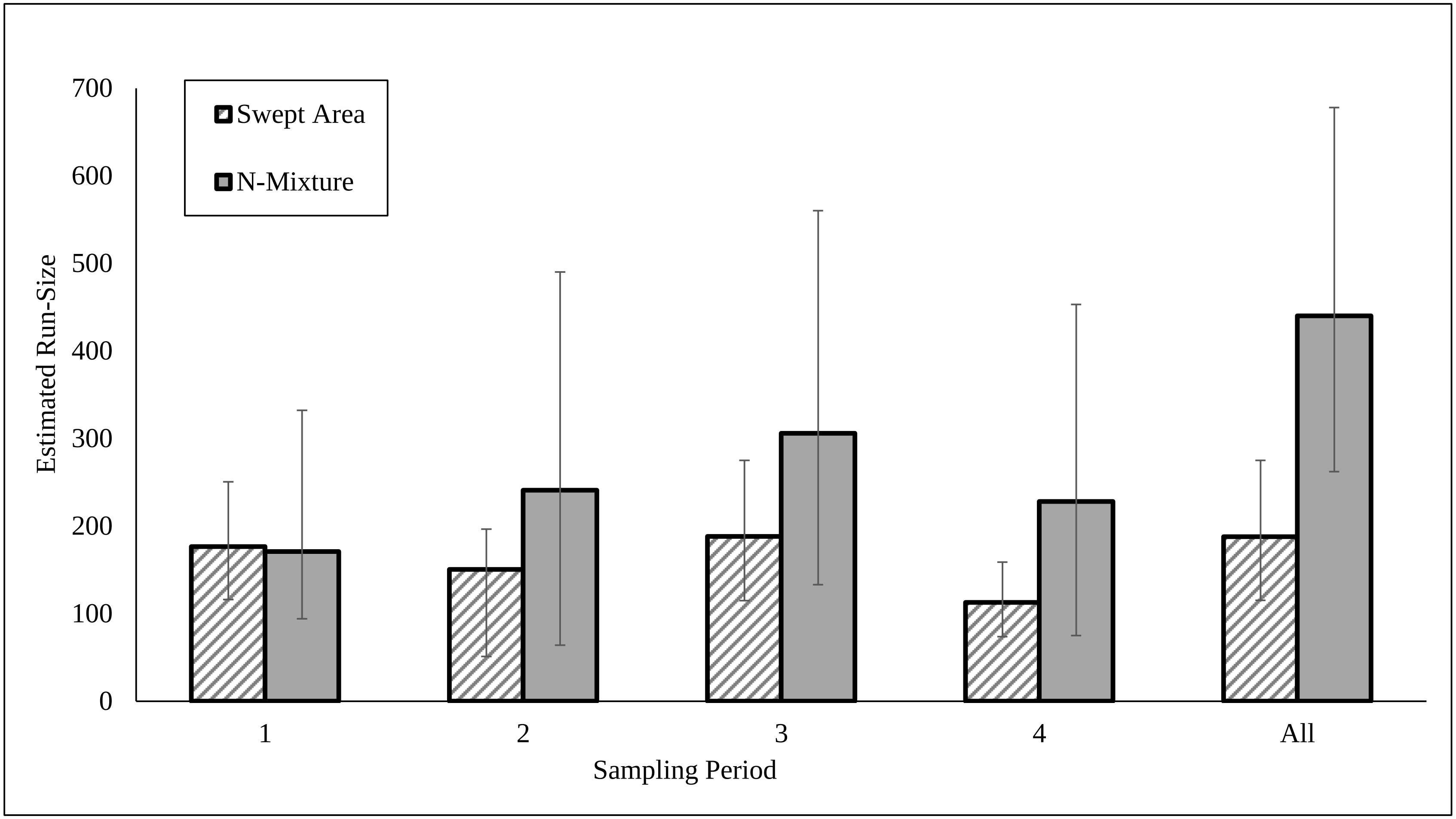

Figure 2-3. The 2014 Atlantic Sturgeon spawning run-size estimates in the Hyde Park Reach, Hudson River, NY using two methodologies, swept-area and N-Mixture. Sampling dates are as follows: period 1 was June 11-13, 2014, period 2 was June 17-19, 2014, period 3 was June 23-25, 2014, period 4 was June 30- July 2, 2014, and All included all data from sampling periods 1-4.

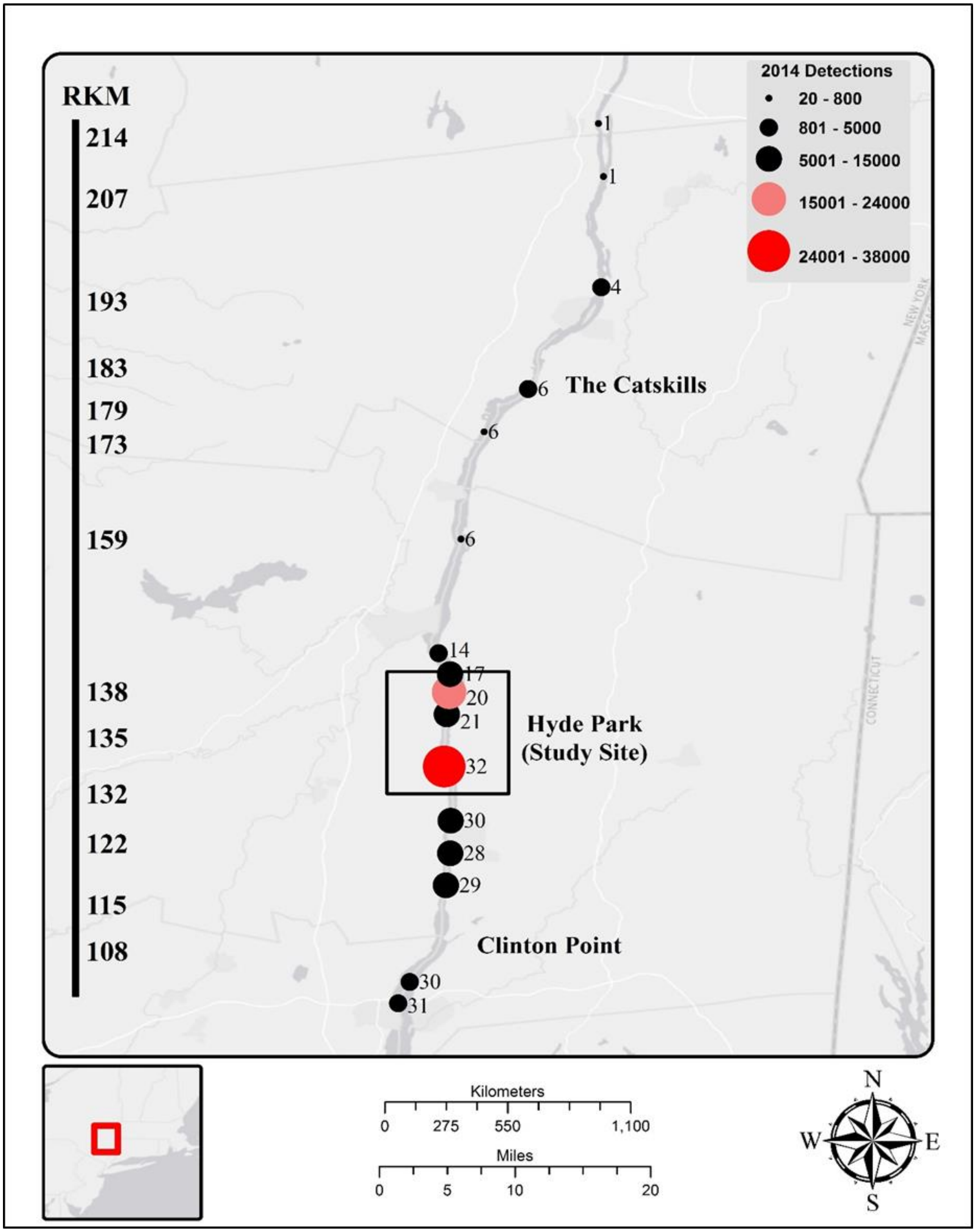

Figure 2-4. Site importance based upon number of detections of telemetered adult Atlantic Sturgeon in 2014 in Hyde Park, Hudson River, New York. The size of the circle indicates total number of detections on VEMCO VR-2W passive acoustic receivers. The numbers next to the detections indicates the number of Atlantic Sturgeon contributing to the total detections. .

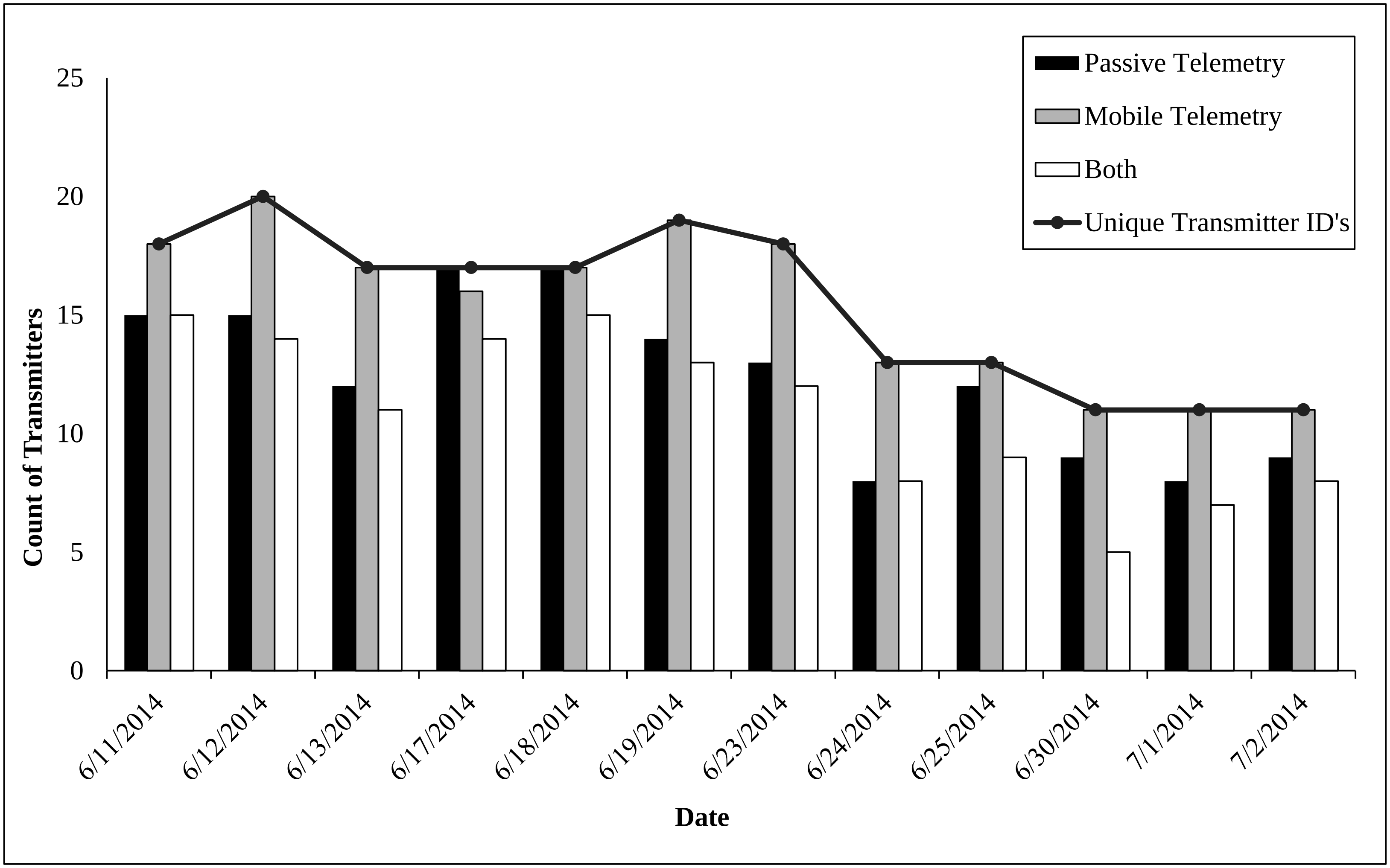

Figure 2-5. Mobile and passive telemetry data of Atlantic Sturgeon in the Hudson River, Hyde Park, NY. Sampling dates were June 11-13, June 17-19, June 23-25, and June 30- July 2, 2014. The ‘both’ column refers to the count of tags that were seen in both the mobile and passive telemetry. Note, x axis portrays sampling dates in order of occurrence and is not proportional.

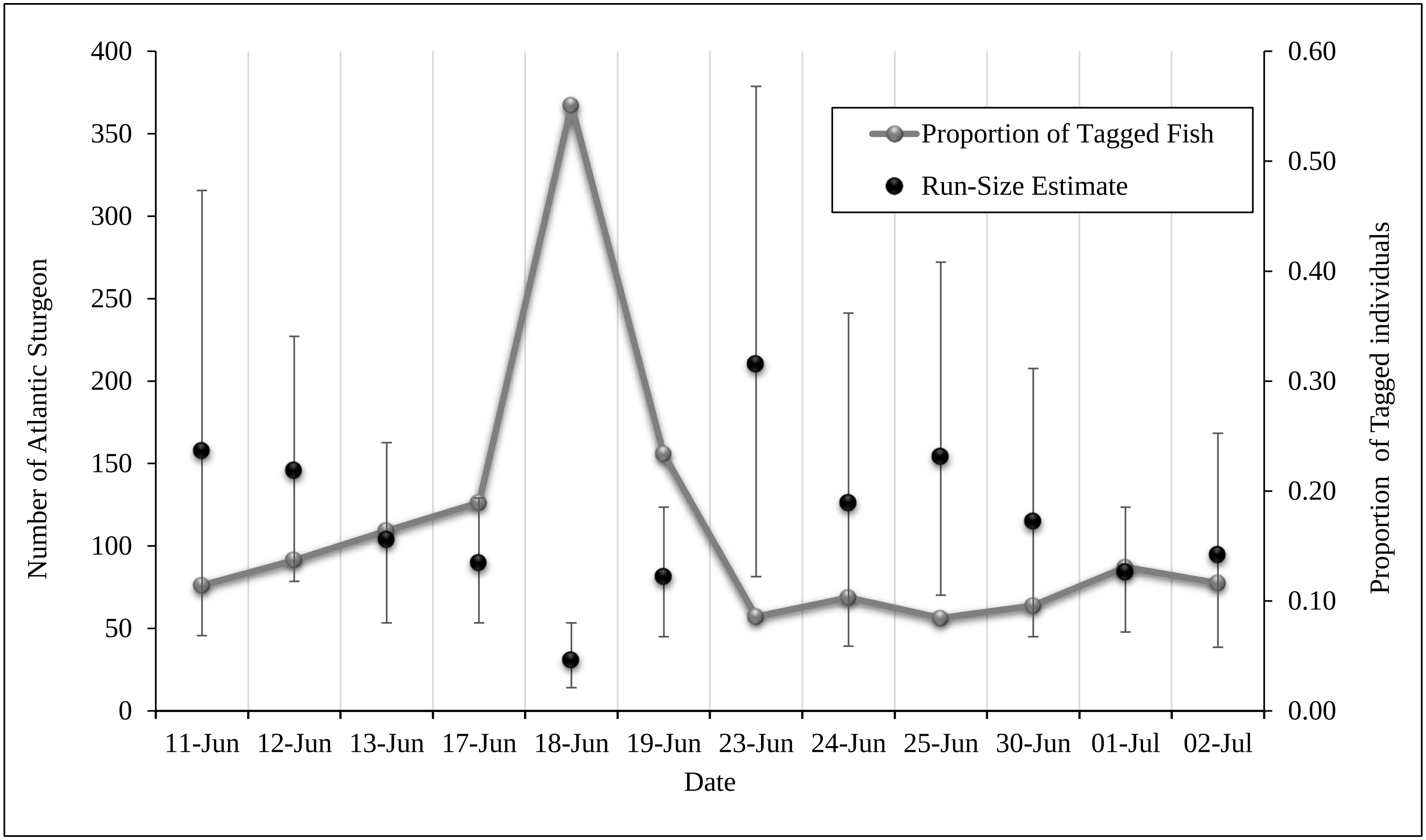

Figure 2-6. The 2014 Hyde Park run size estimates with corresponding 95% confidence intervals, with the proportion of tagged individuals overlaid per day. Total number of tagged individuals per day, was divided by the run-size estimate to yield a proportion of tagged individuals per day.

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APPENDICES

Appendix A: P-value and Z-value output from Hotspot Analysis in ArcGIS. The 2014 Atlantic Sturgeon data was collected using a side-scan sonar. Each GIS ID corresponds to one of the hotspot polygons in Figures 1-17 and 1-18. Hotspot grids go in order from north to south and west to east, by significance. Statistical significance is shown on the GI_Bin column **(**GI stands for the Getis-Ord GI* statistic which is used in the hotspot analysis).

GIS ID	Gi Z-Score	Gi P-Value	Gi_Bin
1	2.551065794	0.010739405	95% Significance
2	2.691220356	0.007119115	95% Significance
3	2.911874294	0.003592672	95% Significance
4	2.911874294	0.003592672	95% Significance
5	3.143271201	0.00167071	95% Significance
6	2.804868111	0.005033717	95% Significance
7	2.994686219	0.002747273	95% Significance
8	3.077498143	0.002087461	95% Significance
9	2.854876999	0.00430535	95% Significance
10	3.069340112	0.002145322	95% Significance
11	3.160310068	0.001576013	95% Significance
12	3.077498143	0.002087461	95% Significance
13	3.179563875	0.001474969	95% Significance
14	2.663438521	0.007734654	95% Significance
15	2.782511357	0.005393998	95% Significance
16	3.10881518	0.001878392	95% Significance
17	3.017725491	0.002546795	95% Significance
18	2.750665958	0.005947426	95% Significance
19	3.02839681	0.00245855	95% Significance
20	3.010715975	0.002606325	95% Significance
21	3.010715975	0.002606325	95% Significance
22	2.65825255	0.007854701	95% Significance
23	2.65825255	0.007854701	95% Significance
24	3.471955479	0.000516682	99% Significance
25	3.560667213	0.000369914	99% Significance
26	3.966279208	7.30033E-05	99% Significance
27	3.551751131	0.000382677	99% Significance
28	4.030205348	5.57281E-05	99% Significance
29	4.566250205	4.96526E-06	99% Significance
30	3.632152968	0.000281066	99% Significance
31	4.073879699	4.62364E-05	99% Significance
32	4.415631082	1.00716E-05	99% Significance

33	3.666594188	0.000245802	99% Significance
34	3.862832224	0.00011208	99% Significance
35	3.862910358	0.000112044	99% Significance
36	4.325760708	1.52006E-05	99% Significance
37	3.826802414	0.000129819	99% Significance
38	3.826802414	0.000129819	99% Significance
39	3.199904869	0.00137473	99% Significance
40	3.844137886	0.000120977	99% Significance
41	3.337035222	0.000846772	99% Significance
42	3.710706948	0.000206681	99% Significance
43	3.549254094	0.000386324	99% Significance
44	3.745843289	0.000179789	99% Significance
45	3.385639744	0.000710125	99% Significance
46	3.844137886	0.000120977	99% Significance
47	3.43703476	0.00058812	99% Significance
48	3.745843289	0.000179789	99% Significance
49	3.479370686	0.000502593	99% Significance
50	3.781526097	0.00015587	99% Significance
51	3.564263625	0.000364879	99% Significance
52	4.008023461	6.1229E-05	99% Significance
53	4.237316277	2.26207E-05	99% Significance
54	3.573101629	0.000352778	99% Significance
55	3.878209411	0.000105228	99% Significance
56	3.205820278	0.001346781	99% Significance
57	3.760563513	0.000169531	99% Significance

Appendix B: Swept Area Estimation with Bootstrap R Code (n=1,000,000)

#This is code to generate run-size estimates with bootstrapped confidence intervals around swept area abundance estimates in the Hyde Park area of the Hudson River, NY

```
###LIBRARIES
library(boot)
library(bootstrap)
library(reshape2)
###USER INPUTS
counts <- read.csv("G:/Hudson_Bain/2014Sturgeon_1kmbins_transects.csv", header = TRUE)
n_bootstraps <- 1000000 # number of replicate samples in bootstrap procedure
###DATA EXPLORATION AND FORMATTING
str(counts)
summary(counts)
levels(counts$Date)
counts_clean <- subset(counts, Count != "NA") #need to remove any values with NAs
summary(counts_clean)
hist(counts_clean$Count, breaks = seq(from = -0.5, to = 25.5, by = 1), col = "gray", xlab =
"Count of Adult Sturgeon", main = "Histogram of counts across all surveys")
with(counts_clean, table(Date, Count))
#Create separate data frames for each date
June11 <- subset(counts_clean, Date == "11-Jun")
June12 <- subset(counts_clean, Date == "12-Jun")
June13 <- subset(counts_clean, Date == "13-Jun")
June17 <- subset(counts_clean, Date == "17-Jun")
June18 <- subset(counts_clean, Date == "18-Jun")
June19 <- subset(counts_clean, Date == "19-Jun")
June23 <- subset(counts_clean, Date == "23-Jun")
June24 <- subset(counts_clean, Date == "24-Jun")
June25 <- subset(counts_clean, Date == "25-Jun")
June30 <- subset(counts_clean, Date == "30-Jun")
July1  <- subset(counts_clean, Date == "1-Jul")
July2  <- subset(counts_clean, Date == "2-Jul")
#create histograms for each date
hist(June11$Count)
hist(June12$Count)
hist(June13$Count)
hist(June17$Count)
hist(June18$Count)
hist(June19$Count)
hist(June23$Count)
hist(June24$Count)
hist(June25$Count)
hist(June30$Count)
hist(July1$Count)
```

```
hist(July2$Count)
###CALCULATE BOOTSTRAPPED CONFIDENCE INTERVALS ABOUT THE MEAN
samplemean <- function(x, d) {
  return(mean(x[d]))
}
boot_estimates <- boot(counts_clean$Count, samplemean, R = 100000, sim = "ordinary", stype
= "i")
 boot_CI <- boot.ci(boot_estimates, conf = c(0.5, 0.8, 0.9, 0.95,0.99), type = "perc")
 boot_CI
datelist <- list(June11, June12, June13, June17, June18, June19, June23, June24, June25, June30,
July1, July2)
for (j in 1:12){
  boot_estimates <- boot(datelist[[j]][,4], samplemean, R = n_bootstraps, sim = "ordinary", stype
= "i")
  boot_CI <- boot.ci(boot_estimates, conf = c(0.5, 0.8, 0.9, 0.95,0.99), type = "perc")
  print(paste0("#####STARTING ANALYSIS FOR ", datelist[[j]][1,1], "#####"))
  #print(datelist[[j]][,2:4])
  print(paste("NUMBER SURVEYED TRANSECTS ON", datelist[[j]][1,1],  "=",
length(unique(datelist[[j]][,3]))))
  print(paste("MEAN COUNT PER SECTION =", mean(datelist[[j]][,4])))
  print(boot_CI)}
sum(counts_clean$Count)
```

Appendix C: N-Mixture model R Code

```
#This is code to generate run-size abundance estimates using the N-Mixture framework,
#Unmarked, in R.
#N-Mixture code

library(unmarked)

SSdat<-read.csv("2014Sturg1km.csv",header=T) #read data
dat<-SSdat[,1:3]        #Re-run for each sampling period 1-4 #Sampling Period1=1:3,
Period2=4-6,Period3=7-9,Period4=10-12

SSumf<-unmarkedFramePCount(dat) #format data for unmarked

summary(SSumf) #summary of formatted data

Ab1<-pcount(~1 ~1, SSumf, K=1200, mixture="P")    #Model using Poisson dist. for abundance
Ab2<-pcount(~1 ~1, SSumf, K=1200, mixture="NB")   #Model using negative binom.
Ab3<-pcount(~1 ~1, SSumf, K=1200, mixture="ZIP")  # Zero-inflated Poisson

#AbRN.R<-occuRN(~1 ~River, SSumf)

RNfitlist<- fitList(Ab1,Ab2,Ab3)  #Organize results
modSel(RNfitlist)                 #Select best model (AIC)

#Manually choose which model Ab1, Ab2, or Ab3 to use for the rest of the code
# I used Ab1, i.e. poisson distribution for the rest of the code
backTransform(Ab1,type="state")   #Estimate density for mean abundance
backTransform(Ab1,type="det")     #Estimate detection probability

HD <- ranef(Ab1,K=3000)   #Estimate N per site
sum(bup(HD) )             #Estimate N
plot(HD)
HD

HDCI<-(confint(HD))       # 95% CI per site
sum(HDCI[,1])             #lower CI
sum(HDCI[,2])             #upper CI
```