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[Article]

Juvenile Atlantic Sturgeon Habitat Use in Newburgh and Haverstraw Bays of the Hudson River: Implications for Population Monitoring

JOHN A. SWEKA,* JERRE MOHLER, MICHAEL J. MILLARD, AND THOMAS KEHLER
U.S. Fish and Wildlife Service, Northeast Fishery Center, Post Office Box 75, Lamar, Pennsylvania 16848, USA

ANDREW KAHNLE AND KATHRYN HATTALA
New York State Department of Environmental Conservation, Hudson River Fisheries Unit, 21 South Putt Corners Road, New Paltz, New York 12561, USA

GREGG KENNEY AND AMANDA HIGGS
New England Interstate Water Pollution Control Commission, Hudson River Fisheries Unit, 21 South Putt Corners Road, New Paltz, New York 12561, USA

Abstract.—Populations of Atlantic sturgeon *Acipenser oxyrinchus* are at historically low levels along the Atlantic coast of North America. Atlantic sturgeon is a long-lived species with a complex life history, making population assessment difficult. The purpose of this study was to determine seasonal habitat use by juvenile Atlantic sturgeon in the Hudson River estuary and provide recommendations for future population monitoring. Our study focused on Newburgh and Haverstraw bays in the Hudson River, as these are areas of known juvenile sturgeon concentrations. The habitat within each bay was coarsely stratified according to substrate (hard versus soft) and depth (deep versus shallow). Sampling occurred during fall 2003, spring and fall 2004, and spring and fall 2005. Fall sampling occurred from October through November and spring sampling occurred from March through April. We used anchored gill nets of 76-, 102-, and 127-mm stretch mesh fished together at a sampling site. A total of 562 individual juvenile Atlantic sturgeon were captured during the course of this study (14 were captured more than once), the majority (90%) coming from Haverstraw Bay. Soft and deep habitat comprised only 25% of the available habitat in Haverstraw Bay but yielded the greatest frequency of catches, the highest mean catch per unit effort (CPUE), and lowest variance of CPUE. Catch per unit effort was highest during spring seasons in soft–deep areas of Haverstraw Bay. These results suggest that future population monitoring should focus sampling effort in soft–deep areas of Haverstraw Bay to have the greatest statistical power in detecting population trends.

The Atlantic sturgeon *Acipenser oxyrinchus* historically supported a valuable commercial fishery in the Hudson River estuary from the late 19th century through 1996. The estuary is 246 km long, beginning at the southern tip of Manhattan Island (rkm 0) and running north to Troy Dam (rkm 246) near Albany, New York. The fishery in the estuary targeted adult sturgeon for both meat and caviar, and coastal fisheries targeted subadults for meat. The pre-1900s commercial fishery can be characterized as a period of high harvest followed by a period of minimal harvest and some limited population recovery during 1900–1979. Renewed effort in the fishery occurred between 1980 and 1992 causing the population to decline again in 1993–1996 (ASMFC 1998a; Bain et al. 1999). As data became available in the 1990s, evidence of overfishing became apparent (ASMFC 1998a) and the New York State Department of Environmental Conservation (NYSDEC) placed a moratorium on the Hudson River fishery in 1996. The Atlantic States Marine Fisheries Commission (ASMFC) followed suit in 1998 by amending the 1990 Atlantic sturgeon interstate fisheries management plan to include a moratorium on the harvest of the species for Atlantic coast states (ASMFC 1998a).

The Atlantic sturgeon is a long-lived species, males beginning to mature at age 10 and females at age 14 (Van Eenennaam et al. 1996). The population historically supported 40 year-classes in the spawning population and the ASMFC (1998b) recommended that the moratorium remain in place until evidence that at least 20 protected year-classes of spawning females exist in each stock along the Atlantic coast. Given that median age of maturity for females does not occur until age 18, the moratorium should remain in effect for a

* Corresponding author: john_sweka@fws.gov

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minimum of 38 years. For the Hudson River stock, the moratorium should remain in place until at least 2034.

The life history of Atlantic sturgeon makes monitoring population trends through time difficult (Dovel and Berggren 1983; Bain 1997; Bain et al. 1999). Male Atlantic sturgeon may spawn every year (Van Eenennaam et al. 1996), but females have an interspawning period of 3–5 years (Smith 1985). The differences between the sexes with respect to age at maturity and spawning periodicity complicate the indexing of adult abundance.

The early juvenile stages provide the best opportunity for population monitoring. Juveniles may remain in the river for as long as 6 years, but may emigrate to marine environments as early as age 2 (Dovel and Berggren 1983; Peterson et al. 2000). There have been two population estimates of age-1 Atlantic sturgeon in the Hudson River. Dovel and Berggren (1983) estimated the 1976 cohort at 25,647 individuals (95% confidence interval [CI] = 13,206–53,039) in 1977 and Peterson et al. (2000) estimated the 1994 cohort at 4,314 (95% CI = 1,916–10,473) individuals in 1995, and they suggested this was evidence of declining recruitment in the Hudson River. The large confidence intervals from Peterson et al. (2000) illustrate the difficulty in obtaining precise population estimates in a large river system such as the Hudson River.

Fishery-independent data on the relative abundance of juvenile Atlantic sturgeon before their emigration from the Hudson River estuary have been collected annually by Hudson Valley utility companies (Consolidated Edison Company of New York) and other researchers since 1974. The most extensive utility time series of data were obtained by 1-m epibenthic sled and by 3-m beam trawls in a fall shoals survey. These data suggest a slight increase in abundance in response to the fishery closure in 1996 (NYSDEC 2005). Although the utility data are extensive, the programs were not designed to sample Atlantic sturgeon specifically and thus there remains uncertainty surrounding the status of the Hudson River stock.

The present low abundance of juvenile Atlantic sturgeon in the Hudson River makes precise estimation of population size difficult (e.g., Peterson et al. 2000). Wide confidence intervals are indicative of the low probabilities of recapture associated with rare species in a large river system. A more practical approach for long-term monitoring of population trends would be generating annual indices of relative abundance, such as mean catch per unit effort (CPUE), from a standardized sampling design. A preliminary study was completed in 1998 by Cornell University (Bain et al. 1999). Their sampling occurred from April through August over a large expanse of river (river kilometer [rkm] 43–245; Figure 1) and suggested that targeted gill netting in south Newburgh Bay offered the greatest opportunity for juvenile population monitoring. Dovel and Berggren (1983) suggested the Haverstraw–Tappan Zee region of the river was an area of overwintering concentrations (Figure 1). The objective of this study was to refine juvenile Atlantic sturgeon sampling methodology by (1) assessing seasonal habitat use by juvenile Atlantic sturgeon with respect to bottom type and water depth in Newburgh and Haverstraw bays; (2) determining effective methods of fishing anchored gill nets to catch juvenile Atlantic sturgeon; (3) assessing the size selectivity of gill nets for juvenile Atlantic sturgeon; and (4) providing recommendations for future monitoring to detect population trends.

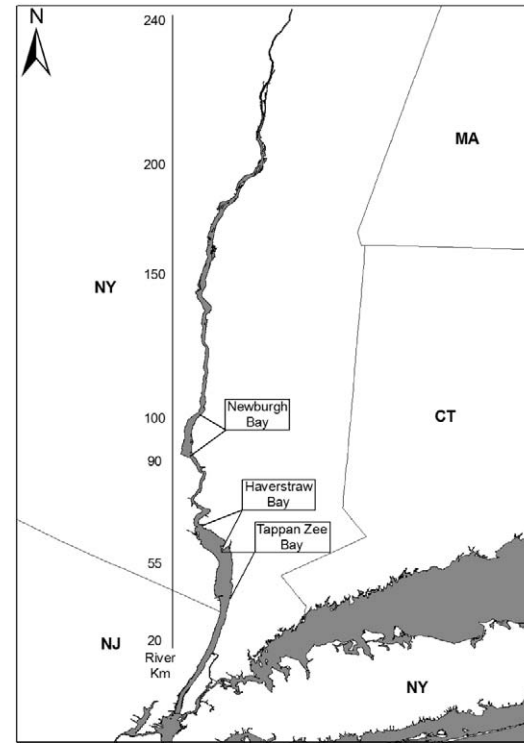

FIGURE 1.—The Hudson River estuary, New York. Sampling occurred in Newburgh and Haverstraw bays.

Methods

We assumed that substrate and depth influence Atlantic sturgeon distributions (Haley et al. 1996; Bain 1997; Haley 1999). Therefore, we used bottom type and bathymetry data from the Lamont Dougherty Earth Observatory to spatially stratify Newburgh and Haverstraw bays (Nitsche et al. 2004; Bell et al. 2006). Strata

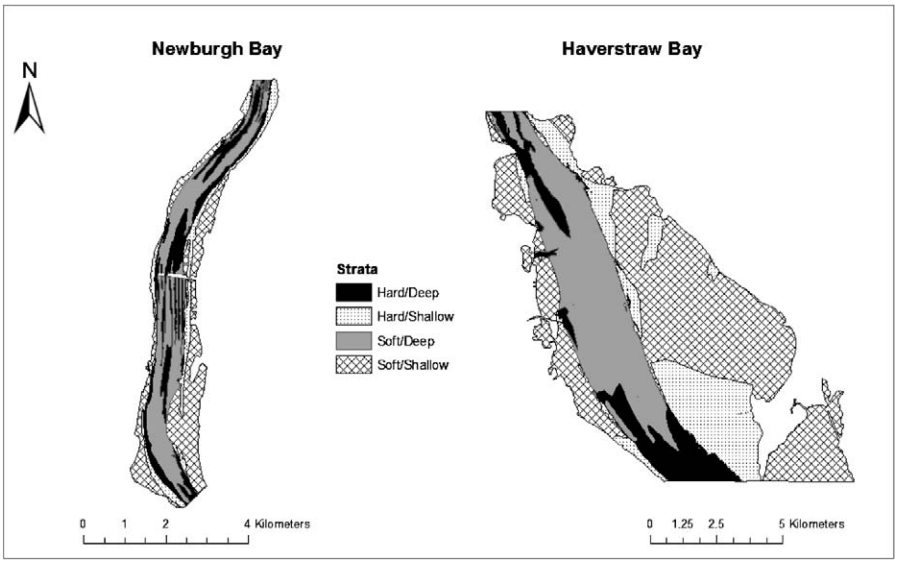

FIGURE 2.—Stratification of Newburgh and Haverstraw bays based on substrate (hard or soft) and depth (deep or shallow).

were identified as combinations of bottom type and depth: hard–deep, hard–shallow, soft–deep, and soft–shallow (Figure 2). Hard substrates typically consisted of compacted sand, rock, gravel, and remnant eastern oyster *Crassostrea virginica* beds, while soft substrates consisted of silt and mud. Deep areas in Newburgh Bay were defined as those with depths greater than 9 m. Because Haverstraw Bay is generally shallower than Newburgh Bay, deep areas were defined as those with depths greater than 6 m.

Sampling occurred during five time periods: fall 2003, spring 2004, fall 2004, spring 2005, and fall 2005. Fall sampling occurred from October through November and spring sampling occurred from March through April. We used 61 m (200 ft) × 2.4 m (8 ft) anchored gill nets with stretch mesh sizes of 76, 102, and 127 mm (3, 4, and 5 in). These combined mesh sizes have been shown to effectively capture juvenile-sized Atlantic sturgeon (Bain et al. 1999; NYSDEC, unpublished data). The nets were constructed of 0.40-mm clear monofilament and had a hanging ratio of 0.50, a foam-core float line, and a lead-core lead line weighing 8 kg/61 m of line. Nets were anchored on each end with a 6.8-kg navy anchor and configured so that the bottom of the net came in contact with the substrate during deployment. A net set consisted of three nets, one of each mesh size. Nets were set parallel to each other with a distance of at least 61 m between them and the group of three nets was set perpendicular to the shore. Nets were fished for a minimum of 2 h and retrieved between 2 and 4 h after deployment, depending on catches and processing time of fish captured in other nets simultaneously deployed. Net sets were made during both slack and running tides. Water quality characteristics (dissolved oxygen [DO], pH, salinity, and specific conductance) were measured at the surface and bottom in the vicinity of each net set. Tidal currents were much stronger in Newburgh Bay compared with those in Haverstraw Bay. As a result, nets set in Newburgh Bay often became fouled with debris and did not fish effectively. To determine if this problem could be overcome, we set half of net sets parallel to the shore during the spring 2005 and fall 2005 seasons to compare catches between methods of fishing. All net sets in Haverstraw Bay were made perpendicular to shore during all seasons.

Sampling effort during fall 2003 and spring 2004 was allocated among habitat types in proportion to their contribution to total available habitat within Newburgh and Haverstraw bays. Within each habitat stratum, random locations for net sets were generated in a geographic information system (GIS) before the sampling season and net sets were centered on these locations. If a randomly generated sampling location fell within the navigation channel or in an area of barge or sailboat mooring, we did not sample those locations for safety reasons and instead sampled another random location chosen a priori. The goal of the first year of study was to determine which habitat stratum was most used by juvenile Atlantic sturgeon. In subsequent seasons, we allocated half of our sampling effort in the most preferred habitat (referred to as targeted habitat)

and half in random locations outside of the preferred habitat to test the first year's results and to gain estimates of mean CPUE and associated variances.

Captured Atlantic sturgeon were inspected for tags from previous research or sampling efforts and held in a live well until processed. Atlantic sturgeon were weighed (0.01 kg), measured (1 mm; total length [TL] and fork length [FL]), tagged with both passive integrated transponder (PIT) tags and Carlin tags, and had a small section (<5 mm) removed from the leading edge of the left pectoral spine for aging purposes (T. Kehler, unpublished data). New tags were applied to recaptured fish that were missing either a PIT or Carlin tag.

Statistical analysis.—We used a chi-square test to analyze presence/absence data for juvenile Atlantic sturgeon to determine whether net sets capturing at least one sturgeon differed among habitat strata during the fall 2003 and spring 2004 seasons. Likewise, a chi-square test was used to determine whether presence/absence data differed between targeted habitat and random areas in subsequent seasons.

Catch per unit effort was calculated as the total catch of a net set (catch from all three nets) divided by the sum of the effort of all nets within the net set (100 m^2 of net deployed × hours of soak time). Summary statistics, such as mean and median CPUE and associated variances, were calculated from CPUE values from individual net sets. To test the alternative hypothesis that CPUE was greater in targeted habitat than in random areas during fall 2004, spring 2005, and fall 2005, we used a one-tailed Wilcoxon two-sample test. A two-tailed Wilcoxon two-sample test was used to compare CPUE between seasons because we had no prior assumption which season would result in greater CPUE. When comparing seasonal CPUE data, we used only those data coming from targeted habitat to eliminate the confounding effects of less preferred habitat.

The tidal effect on presence/absence and CPUE of juvenile Atlantic sturgeon was analyzed for targeted habitats. Data were pooled across years within a season (fall or spring), and each net set was classified as being on either a "slack" or a "running" tide. A net set was considered slack if the approximately 2-h deployment overlapped a slack tide. A chi-square test was used in analyzing presence/absence data, and a one-tailed Wilcoxon two-sample test was used to determine whether CPUE was higher for slack net sets than for running net sets.

Spearman rank correlation was used to examine the relationships between water quality characteristics and CPUE for each season. Because water quality variables did not differ significantly between surface and bottom readings, we used the average of the two in statistical analyses. Only data from targeted areas were used to avoid confounding differences in physical habitat preference. Correlation analysis was run separately for each season and for all seasons combined within a bay.

We plotted cumulative CPUE from targeted habitat against daily mean temperature to determine whether there was any trend to CPUE as water temperature changed through each sampling season. Cumulative CPUE was calculated for each sampling date by dividing the cumulative catch for the season by the cumulative amount of effort expended for the season up to a particular date.

We assessed gill-net size selectivity in two ways. First, we compared the size distributions of juvenile Atlantic sturgeon between gill-net mesh sizes directly with a nonparametric median test. Second, we used nonlinear response surface regression (see Helser et al. 1998 for details) to estimate size selectivity curves for each mesh size. This method simultaneously solves for type A and type B selectivity curves (Regier and Robson 1966). We used the normal model from Helser et al. (1998),

$$E(\Pi_{ij}) = \exp\left[-\frac{m_i - (\mu_0 + \mu_1 l_j)^2}{2(\sigma_0 + \sigma_1 l_j)}\right],$$

where $E(\Pi_{ij})$ is the expected standardized gill-net selectivity, m_i is the size of mesh i, l_j is the mean size of the fish in size-class j, $\hat{\mu}_j = \mu_0 + \mu_1 l_j$, which is the estimated optimum mesh size for size-class j, and $\hat{\sigma}_j = \sigma_0 + \sigma_1 l_j$, which is the estimated standard deviation (SD) of the optimum mesh size for size-class j. Nonlinear regression using the PROC NLIN procedure in SAS version 9.1 was used to obtain estimates for μ_0, μ_1, σ_0, and σ_1 and to evaluate the fit of the model to the data.

In all hypothesis tests, we used $\alpha = 0.10$ rather than the conventional $\alpha = 0.05$. Given the sporadic catch rates, generally low numbers of juvenile Atlantic sturgeon caught in a single net set, and finite sampling resources in a large river system, we erred on the side of finding differences in an effort to focus future monitoring. Using an α of 0.10 reduced the chance of making a type II error and missing important biological effects.

Results

A total of 562 wild juvenile Atlantic sturgeon were tagged and released. The mean FL was 563 mm (range = 320–1,012 mm). Fourteen individuals were captured a second time, and we recaptured two individuals from experimental stockings in 1994 and 2004 by NYSDEC

TABLE 1.—Distributions of juvenile Atlantic sturgeon in two Hudson River bays, by habitat type (October 2003–November 2005).

Season	Bay	Substrate[a]	Habitat area		Net sets			Fish caught	% of nets with fish	χ^2	P
			ha	%	With fish	Without fish	Total				
Fall 2003	Haverstraw	Hard–deep	372	10	1	3	4	3	25	6.65	0.08
		Hard–shallow	716	18	3	8	11	60	27		
		Soft/deep	962	25	9	5	14	23	64		
		Soft–shallow	1,849	47	7	20	27	22	26		
	Newburgh	Hard–deep	617	22	2	15	17	2	12	6.60	0.09
		Hard–shallow	349	12	0	6	6	0	0		
		Soft–deep	958	34	5	13	18	12	28		
		Soft–shallow	888	32	0	14	14	0	0		
Spring 2004	Haverstraw	Hard–deep	372	10	4	4	8	8	50	5.74	0.12
		Hard–shallow	716	18	5	8	13	5	38		
		Soft–deep	962	25	14	9	23	55	61		
		Soft–shallow	1,849	47	9	22	31	26	29		
	Newburgh	Hard–deep	617	22	0	4	4	0	0		
		Hard–shallow	349	12	0	1	1	0	0		
		Soft–deep	958	34	0	3	3	0	0		
		Soft-shallow	888	32	0	4	4	0	0		
Fall 2004	Haverstraw	Random	2,937	75	9	23	32	51	28	9.04	0.00
		Soft–deep	962	25	21	11	32	56	66		
	Newburgh	Random	1,237	44	0	26	26	0	0	5.53	0.02
		Deep	1,575	56	5	21	26	7	19		
Spring 2005	Haverstraw	Random	2,937	75	14	22	36	65	39	11.20	0.00
		Soft–deep	962	25	28	8	36	104	78		
	Newburgh	Parallel			0	5	5	0	0		
		Perpendicular			0	5	5	0	0		
Fall 2005	Haverstraw	Random	2,937	75	7	16	23	34	30	2.04	0.15
		Soft–deep	962	25	3	20	23	10	13		
	Newburgh	Parallel			7	12	19	14	37	0.49	0.49
		Perpendicular			5	14	19	22	26		

[a] The terms "parallel" and "perpendicular" refer to the orientation of the nets with respect to the shore in deepwater habitats. See text for other substrate descriptions.

and the U.S. Fish and Wildlife Service (USFWS). The majority of our catches (90%) occurred in Haverstraw Bay during all seasons. No juvenile Atlantic sturgeon were caught in Newburgh Bay during spring seasons.

Effect of Habitat on Presence/Absence

There were significant differences in the occurrence of juvenile Atlantic sturgeon among habitat strata in Haverstraw and Newburgh bays (Table 1). Atlantic sturgeon showed a preference for soft–deep areas of Haverstraw Bay ($\chi^2 = 6.65$, $P = 0.08$) in 2003, with 64% of the net sets in this stratum capturing at least one Atlantic sturgeon. Presence in other strata ranged from 25% to 27%. In Newburgh Bay, Atlantic sturgeon were only caught in deep areas regardless of substrate type. During the spring 2004 season, Atlantic sturgeon again tended to be caught more frequently in soft–deep areas of Haverstraw Bay (61% of net sets), but these results were not significant ($\chi^2 = 5.74$, $P = 0.12$) and hard–deep areas also had a relatively high occurrence of Atlantic sturgeon, 50% of net sets catching at least one individual. When fall 2003 and spring 2004 data were combined, juvenile Atlantic sturgeon showed a preference for soft–deep areas in Haverstraw Bay ($\chi^2 = 11.78$, $P = 0.01$) with 62% of net sets catching fish. Owing to extreme problems with gear fouling in Newburgh Bay during spring 2004 sampling, no Atlantic sturgeon were caught and effort was greatly reduced in this area. Juvenile Atlantic sturgeon were only captured from deep areas in Newburgh Bay, and there was no difference between substrate types within deep areas ($\chi^2 = 1.54$, $P = 0.21$). In the above chi-square tests some of the expected frequencies fell below commonly accepted minimum criteria (e.g., $E_j \geq 5$; Conover [1999]), which may have inflated the chi-square statistic. However, we chose to proceed with the results from these data and err on the side of finding biological differences among habitat strata.

Effect of Habitat on Catch per Unit Effort

After redistributing our sampling effort among habitat strata based on the first year's results, we found that catch per unit effort (CPUE) tended to be highest in the soft–deep areas of Haverstraw Bay (Table 2). When each sampling season was analyzed separately, soft–deep areas had the highest CPUE during both the fall 2004 and spring 2005 seasons (one-tailed Wilcoxon two-sample test: $P = 0.02$ and $P < 0.01$, respectively). However, the CPUE in soft–deep areas was not greater than that in random areas

TABLE 2.—Effect of habitat on CPUE (number• 100 m^{-2}• h^{-1}) of juvenile Atlantic sturgeon in Haverstraw Bay. *P*-values are from a one-tailed Wilcoxon two-sample test; CV = coefficient of variation.

Season	Substrate	*N*	Mean	Median	SD	CV	Minimum	Maximum	*P*
Fall 2004	Random	32	0.156	0.000	0.326	2.090	0.000	1.342	0.02
	Soft–deep	32	0.172	0.109	0.214	1.246	0.000	0.824	
Spring 2005	Random	36	0.156	0.000	0.360	2.332	0.000	1.831	<0.01
	Soft–deep	36	0.280	0.197	0.310	1.108	0.000	1.470	
Fall 2005	Random	21	0.130	0.000	0.307	2.366	0.000	1.074	0.95
	Soft–deep	25	0.042	0.000	0.114	2.722	0.000	0.412	

during fall 2005 (one-tailed Wilcoxon two-sample test: $P = 0.10$).

Pooling the CPUE data from the soft–deep areas of Haverstraw Bay over all years showed that spring seasons had a higher CPUE than fall seasons (two-tailed Wilcoxon two-sample test: $P < 0.01$). The CPUE for the soft–deep areas of Haverstraw Bay during spring seasons was 0.255 ± 0.307 fish• 100 m^{-2}• h^{-1}, whereas during fall seasons it was 0.125 ± 0.191 fish• 100 m^{-2}• h^{-1}. Spring seasons in soft–deep areas also had lower coefficients of variation (SD/mean) in CPUE compared with those in fall seasons.

The low catches of juvenile Atlantic sturgeon in Newburgh Bay negated the analysis of CPUE data in this region. Atlantic sturgeon were only captured in deep areas during all seasons. Spring 2005 and fall 2005 sampling directed all effort in deep areas of Newburgh Bay to determine whether there was a difference in catches between perpendicular and parallel net sets. No juvenile Atlantic sturgeon were caught during spring 2005, and presence/absence data for fall 2005 indicated no difference in the occurrence of fish between perpendicular and parallel net sets.

Tidal Influence on Juvenile Atlantic Sturgeon Catches

There was no significant difference in the presence of Atlantic sturgeon between net sets occurring on a running versus a slack tide in either Haverstraw Bay or Newburgh Bay (Table 3). Even in Newburgh Bay, where we experienced problems with gear fouling during running tides, we could not show significantly greater catches from net sets that overlapped slack tides.

Influence of Water Quality on Catch per Unit Effort

Catch per unit effort was inconsistently correlated with water quality (Table 4). Significant correlations were either restricted to a single season, or were inconsistent between Newburgh and Haverstraw bays. For example, salinity was negatively correlated with CPUE in Haverstraw Bay during fall 2003 ($r = -0.60$, $P = 0.03$) and fall 2005 ($r = -0.37$, $P = 0.09$) but was positively correlated with CPUE in Newburgh Bay during fall 2005 ($r = 0.56$, $P < 0.01$). Likewise, temperature was positively correlated with CPUE in Newburgh Bay during fall 2005 ($r = 0.61$, $P < 0.01$) but showed no correlation with CPUE in Haverstraw Bay during fall 2005 ($r = -0.08$, $P = 0.71$). Fall 2005 correlations for Newburgh Bay showed positive relationships with specific conductance ($r = 0.58$, $P < 0.01$) and salinity ($r = 0.56$, P 0.01) and a negative correlation with dissolved oxygen ($r = -0.50$, $P < 0.01$). Fall 2005 yielded the greatest catches of Atlantic sturgeon in Newburgh Bay and this period also corresponded to when the highest values of temperature, specific conductance, and salinity and the lowest values of dissolved oxygen were recorded in Newburgh Bay during this study. Significant correlations

TABLE 3.—Distribution of juvenile Atlantic sturgeon in the Hudson River, by tidal stage (October 2003–November 2005). Only soft–deep areas in Haverstraw Bay and deep areas in Newburgh Bay were used in this analysis to avoid confounding factors of habitat. Data were pooled across years within seasons.

			Net sets						
Season	Bay	Tide	With fish	Without fish	Total	Fish caught	% of nets with fish	χ^2	*P*
Fall	Haverstraw	Running	20	26	46	46	43	1.05	0.31
		Slack	13	10	23	43	57		
	Newburgh	Running	10	36	46	17	22	0.29	0.59
		Slack	14	39	53	43	26		
Spring	Haverstraw	Running	8	21	29	59	28	2.30	0.13
		Slack	14	16	30	73	47		
	Newburgh	Running	0	11	11	0	0		
		Slack	0	6	6	0	0		

TABLE 4.—Summary statistics from water quality data recorded at net sets in the Hudson River (October 2003–November 2005).

Season	Bay	Statistic	Temperature (°C)	pH	DO (mg/L)	Salinity (‰)	Conductivity (μS/cm)
Fall 2003	Haverstraw	*n*	52	46	45	47	44
		Range	6–20.2	6.3–7.3	5.7–10.2	0.0–2.0	79–2,758
		Mean	13.7	6.8	8.8	0.3	621
	Newburgh	*n*	50	48	48	48	47
		Range	9.5–18.4	6.3–7.2	5.2–9.5	0.0–0.2	105–309
Spring 2004	Haverstraw	*n*	73	9	55	65	61
		Range	3.1–12.7	7.5–7.81	6.8–13.0	0.1–1.8	228–3,450
		Mean	7.1	7.6	11.0	0.5	938
	Newburgh	*n*	11	2	7	9	9
		Range	0.8–7.4	6.8–7.0	9.9–13.0	0.1–0.1	117–309
		Mean	4.1	6.9	11.7	0.1	266
Fall 2004	Haverstraw	*n*	61	64	64	64	63
		Range	10.1–19.9	6.8–7.7	7.1–10.6	0.3–6.3	665–10,975
		Mean	14.6	7.3	8.9	3.6	6,357
	Newburgh	*n*	52	52	51	48	48
		Range	9.4–18.3	6.9–8.1	6.4–12.5	0.1–1.0	211–1,890
		Mean	13.7	7.7	9.7	0.2	365
Spring 2005	Haverstraw	*n*	71	61	61	61	61
		Range	1.4–12.4	6.6–7.9	9.02–13.1	0.1–4.0	184–7,187
		Mean	7.4	7.6	11.1	0.8	1,528
	Newburgh	*n*	9	8	8	8	8
		Range	1.2–8.8	7.1–7.8	12.4–13.3	0.1–0.2	296–325
		Mean	4.1	7.6	12.6	0.1	312
Fall 2005	Haverstraw	*n*	46	46	46	46	46
		Range	8.1–23.5	7.3–7.8	5.5–10.1	0.1–7.1	213–12,429
		Mean	15.2	7.5	7.9	1.8	3,208
	Newburgh	*n*	37	37	37	37	37
		Range	9.0–22.9	7.3–7.8	6.1–11.6	0.1–0.9	191–1,855
		Mean	12.9	7.6	9.0	0.2	391

with dissolved oxygen are probably spurious because at no time did dissolved oxygen drop below 5 mg/L.

Although the correlations the CPUE of individual net sets and water quality were not consistent, plots of cumulative CPUE on temperature showed a distinct pattern during the spring seasons as temperatures warmed (Figure 3). Cumulative CPUE increased sharply in Haverstraw Bay when water temperatures reached 4°C in both spring 2004 and spring 2005. This occurred at approximately March 20 in both years. No discernable pattern in CPUE was seen during fall seasons in Haverstraw or Newburgh bays.

Mesh-Size Selectivity

All mesh sizes caught a wide range of juvenile Atlantic sturgeon. More fish were caught in 102-mm ($n = 229$) and 127-mm ($n = 211$) stretch mesh nets than in the 76-mm net ($n = 137$). Although the size distributions of Atlantic sturgeon caught in each mesh size overlapped to a large degree, there was an overall significant difference in size distributions (median test: $P = 0.02$). The size distributions in 76- and 102-mm stretch mesh nets were equivalent (median test: $P = 0.19$), but the 127-mm stretch mesh captured larger Atlantic sturgeon than both the 76-mm stretch mesh (median test: $P = 0.02$) and 102-mm stretch mesh (median test: $P < 0.01$). The median fork lengths of the fish caught in the 76-, 102-, and 127-mm stretch meshes were 568, 552, and 584 mm, respectively.

There was little difference between the gill-net selectivity curves for the three mesh sizes (Figure 4). The four-parameter selectivity model performed rather poorly, with an r^2 of 0.44 and a mean square error (MSE) of 0.09. Reducing the model to three parameters (μ_0, μ_1, and σ_0) improved the fit ($r^2 = 0.76$; MSE = 0.03), but the 95% confidence intervals of all the parameter estimates included zero. Thus, there was no measurable difference in the size selectivity of the gill-net mesh sizes used in this study.

Discussion

Juvenile Atlantic sturgeon appear to exhibit seasonal movements within the Hudson River. Dovel and Berggren (1983) suggested a downstream fall migration of juvenile Atlantic sturgeon once water temperature drops below 20°C and that the Haverstraw–Tappan Zee region of the river was an area of overwintering concentrations. Once water temperatures warm in the spring, juvenile fish that have not yet outmigrated may move upriver from overwintering areas (Dovel and Berggren 1983). Our fall and spring sampling periods probably bracketed the time at which

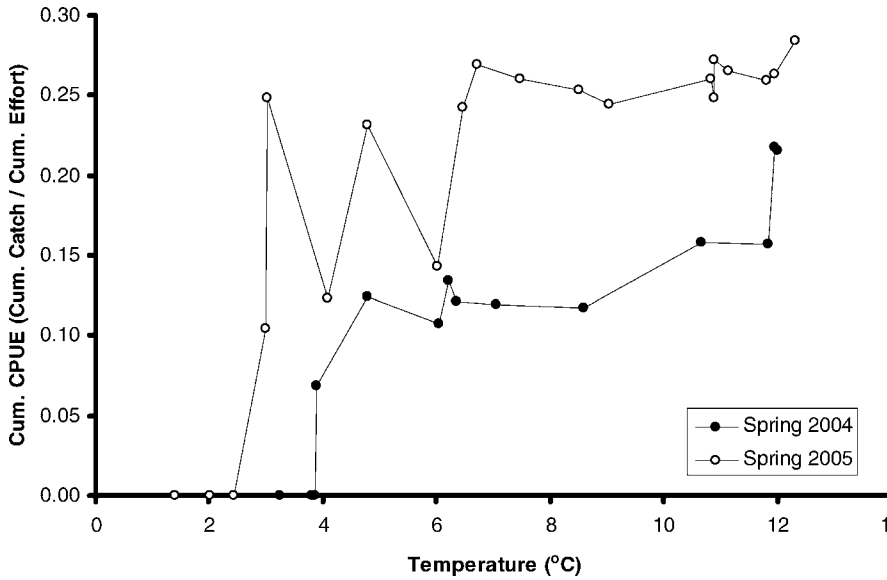

FIGURE 3.—Cumulative CPUE and mean daily water temperature in soft–deep areas of Haverstraw Bay during spring 2004 and 2005. When water temperature exceeded 4°C (on approximately March 20), CPUE increased sharply.

juvenile Atlantic sturgeon were entering and leaving this overwintering habitat. Bain et al. (1999) suggested south Newburgh Bay was an area of concentration for age-1 Atlantic sturgeon during the summer months. If this is true, any fish congregated in south Newburgh Bay during the summer months may have moved downstream by the time of our sampling in October–November because we tended to catch fewer fish in this area during the fall 2003 and fall 2004 sampling periods than in Haverstraw Bay.

Our results from fall 2005 differed from those of either fall 2003 or 2004. Summer 2005 experienced drought conditions. Temperature and salinity were at their highest recorded levels during this study in both bays at the beginning of the fall 2005 season. Our greatest catches of juvenile Atlantic sturgeon in Newburgh Bay occurred at the beginning of fall 2005 sampling, where we recorded water temperatures greater than 20°C and salinity values of approximately 0.6‰. Our catch rate declined as water temperatures dropped in this area. Conversely, catches in Haverstraw Bay during early fall 2005 were much lower than in previous years, and we recorded salinities greater than 6.0‰ and water temperatures greater than 20°C. We did not capture any Atlantic sturgeon in typically preferred soft–deep areas of Haverstraw Bay until October 24. We hypothesize that the drought conditions of 2005 probably delayed the downstream fall migration described by Dovel and Berggren (1983) and was responsible for the resulting fall 2005 catches in Newburgh and Haverstraw Bays.

Juvenile Atlantic sturgeon were most consistently caught in the soft–deep areas of Haverstraw Bay. Haley (1999) also showed a strong preference by juvenile Atlantic sturgeon for deep water and they also preferred areas of mixed silt substrates, which would correspond to our "soft" classification. These areas may be associated with higher abundance of preferred food of juvenile Atlantic sturgeon (Haley 1999) and make up 25% of the available habitat in Haverstraw Bay. Although the soft–deep areas were those most frequently used, some of the largest catches in a single net set came from areas with hard bottoms and shallow depths (<6 m [<20 ft]). Catches outside soft–deep areas were much more variable than those in soft–deep areas, and it is possible that relatively large catches in hard–deep areas were a result of fish migrating through such areas as opposed to using them as preferred habitat.

Yearly variation in the downriver migration of early juveniles may complicate population monitoring efforts. Bain et al. (1999) also found concentrations of juvenile Atlantic sturgeon in Haverstraw Bay, but concluded that these were largely age-2 and older fish that had not yet emigrated from the river. Thus, they recommended that relative abundance of fish in Haverstraw Bay not be used as an index of population trends and that sampling should concentrate on age-1 fish during the summer in southern Newburgh Bay.

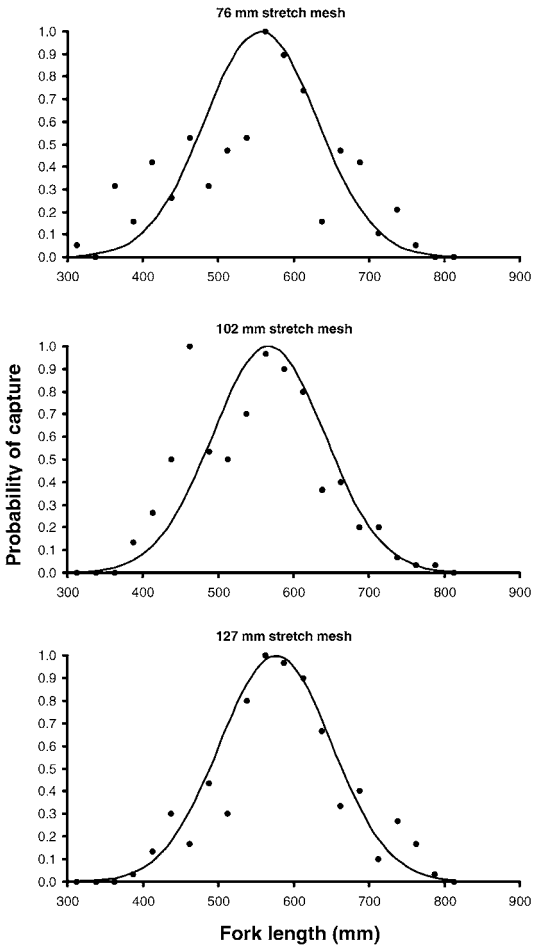

FIGURE 4.—Size selectivity of gill nets for juvenile Atlantic sturgeon in the Hudson River. The curves correspond to the three-parameter model $E(\Pi_{ij}) = \exp\{-[m_i - (\mu_0 + \mu_1 \cdot l_j)^2]/2(\sigma_0 + \sigma_1 \cdot l_j)\}$, where m_i is the mesh size, l_j is the mean size of the fish in size-class j, and the point estimates for the parameters were as follows: $\mu_0 = -1{,}378.9$, $\mu_1 = 2.6123$, and $\sigma_0 = 195.10$. As the 95% confidence intervals for these parameters all included zero, the selectivity curves may be considered equivalent.

The fish that we captured in Haverstraw Bay ranged in age from 1 to 8 years, the majority being 3 and 4 years old (T.K., unpublished data). Concentrating on age-1 fish would show year-to-year variability in recruitment, but our data suggest that sampling only in Newburgh Bay would result in greater variability in CPUE data and a lower chance of being able to detect population trends though time. Using relative abundance as an index of abundance in Haverstraw Bay requires the assumptions that the proportion of juvenile Atlantic sturgeon within a cohort immigrating to Haverstraw Bay is constant each year, and that the proportion of juveniles from a cohort emigrating from the river is constant each year. An advantage of looking at several year classes in a population monitoring effort is that yearly variation in relative abundance due to variability in recruitment of age-1 fish may be dampened and enhance the probability of detecting trends for the population as a whole.

Subadult Atlantic sturgeon are known to migrate along the coast and enter other river systems (Kieffer and Kynard 1993; Bain 1997). There is the possibility that some of the fish sampled in Haverstraw Bay could have come from other systems. However, this possibility seems remote. Tagging data from the Atlantic Coast Sturgeon Tagging Database show greater emigration from the Hudson River to other systems than for immigration to the Hudson River. Between 1995 and 2005, 1,060 sturgeon have been tagged and released in the Hudson River, 13 of which have been recaptured in other systems along the coast. During the same time period, 1,752 sturgeon have been tagged in other systems, but only 1 of these individuals has been recaptured in the Hudson River (S. Eyler, USFWS , Maryland Field Office, personal communication). Also, analysis of mitochondrial DNA by Waldman et al. (1996) showed that 97% of the Atlantic sturgeon captured in the New York Bight fishery in 1993 and 1994 were from the Hudson River population.

The size distributions of juvenile Atlantic sturgeon varied somewhat with gill-net mesh size, although there was a large degree of overlap between mesh sizes. Statistical analysis found that 127 mm stretch mesh captured significantly larger fish than the 76 and 102 mm stretch mesh, but the greatest difference between median fork lengths of each mesh size was only 32 mm. The size selectivity model failed to show differences among mesh sizes as parameter estimates were not significantly different from zero. However, the smallest fish (<375 mm FL) were only caught in 76-mm stretch mesh. The morphology of juvenile Atlantic sturgeon (sharply pointed rostrums, large pectoral fins, and jagged scutes) often resulted in fish being entangled in the net rather than being caught by the gill opercula. This type of morphology is responsible for the high degree of overlap in size distributions and the failure to clearly observe meaningful differences in size selectivity among the mesh sizes used in this study.

Management Implications

Our results can serve as a baseline for future population monitoring of the juvenile Atlantic sturgeon in the Hudson River. Future sampling effort should be focused in soft–deep areas of Haverstraw Bay during the spring when water temperatures rise above 4°C.

Our initial estimates of mean CPUE and the associated variance from soft–deep areas after March 20 in spring 2005 (0.309 ± 0.315 fish$\cdot$m$^{-2}\cdot$h^{-1}) can be used in a power analysis to determine the sample sizes required to detect a given degree of trend over a given time period. For example, if a 10% change in CPUE per year is the minimum desired change to be detected in 10 years of monitoring with 95% power, then a minimum of 24 net sets should be made each year (see Gerrodette [1987] for sample size calculations).

Atlantic sturgeon populations appear to be at all-time low levels throughout their range, and the ASMFC recommends that states with significant spawning populations explore options for monitoring the relative abundance of juveniles (ASMFC 1998a). The methodology employed by our study, whereby available habitat was stratified to identify which habitat provides the most consistent catches to minimize the variance of relative abundance measures, may serve as a model for other agencies in designing population monitoring programs. Expenditure of a relatively large amount of effort during the design of a population monitoring program will save effort in the future and ensure statistically meaningful results from the monitoring program.

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