HUDSON RIVER BIOLOGICAL MONITORING PROGRAM
1974-2017
FINAL REPORT

DRAFT FOR NYSDEC REVIEW
CONFIDENTIAL

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1. INTRODUCTION

> "No one knows in detail what activities of life go on in the unseen depths of the Hudson River nor what the future response to changing inputs is going to be. Under these conditions the experts are free to choose those assumptions which best fit their beliefs about what may go on, and the arguments that follow produce thousands of pages of testimony and documents without providing answers that can be agreed upon, or that give clear guidance to a Board."– Atomic Safety and Licensing Board (1973), Initial Decision on Indian Point Unit 2.

> "To those who know it, the Hudson River is the most beautiful, messed up, productive, ignored, and surprising piece of water on the face of the earth. There is no other river quite like it, and for some persons, myself included, no other river will do. The Hudson is the River." – Robert H. Boyle, The Hudson River: A Natural and Unnatural History." (1969)

The objective of this report is to summarize, in a single document, the purposes, content, and – within the limits of the current scientific understanding – the potential uses of the Hudson River Biological Monitoring Program (HRBMP) data for furthering the scientific understanding of large-scale ecological systems, particularly the Hudson River Estuary.

1.1 HISTORICAL BACKGROUND

Well before the inaugural Earth Day in 1970, which many people identify as the beginning of the modern environmental movement, the Hudson River had been a major focus of public attention and scientific study. Of particular relevance for this report, in 1963, local citizens in the Hudson Valley raised concerns about the potential environmental impacts of the Consolidated Edison Company of New York's (Con Ed) proposed Cornwall Pumped Storage facility[1] on Storm King Mountain, the operation of Indian Point, Unit 1, among the first U.S. commercial nuclear power plants, and the proposed construction of Unit 2. With respect to Unit 1, impingement, or trapping of large numbers of Striped Bass and other fish began soon after this unit began commercial operation in 1962 (Boyle 1969). Despite repeated attempts to reduce impingement through fish deterrents and intake structure modifications, major fish kill events continued to occur throughout the 1960s. Although many were concerned about the aesthetic impact of the Storm King facility, which was to be located in the Hudson Highlands, others were concerned about the impacts of the trio of facilities' significant water withdrawals on the River's most iconic fish species, Striped Bass (*Morone saxatilis*). Researchers in the 1950s (Rathjen and Miller 1957) had found that the principal spawning grounds of Hudson River Striped Bass were near Storm King, and it was feared that large numbers of eggs and larvae could be sucked into the intake, a process termed "entrainment," and killed.

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[1] Pumped storage power plants use excess energy generated during low power demand periods to pump water from a lower reservoir (such as the Hudson River) to an upper reservoir (as proposed on Storm King Mountain). During periods of peak demand, the water is allowed to pass back through the pump-turbines to the lower reservoir, generating power in the process.

The Federal Power Commission's (FPC) issuance of a license for the Cornwall project in early 1964 exacerbated the controversy, with the emphasis on understanding the magnitude and effect of the potential impacts to fisheries. In 1965, a series of studies known as the Hudson River Fisheries Investigations (HRFI), were undertaken. An essential goal of the HRFI was to characterize the spatial and temporal distribution of early life stages of Striped Bass in the vicinity of the then-proposed Cornwall facility. That key aspect of the study concluded that impacts of entrainment at Cornwall on early Striped Bass would be negligible (HRFI, Hudson River Policy Committee 1969). However, what are acknowledged as material errors in the modeling used in the Striped Bass study were identified in the contemporaneous 1972 Atomic Energy Commission licensing hearing for Indian Point Unit 2 (Christensen and Englert 1988). As a consequence, construction of the Storm, King Project was halted shortly after it began in 1974 pending resolution of the entrainment issue, with the FPC reopening hearings to consider the new information.

The modeling error was discovered because impacts of water withdrawals by large power plants had become a major issue in the licensing of Indian Point Units 2 and 3. The possibility that such withdrawals of cooling water could have adverse environmental impacts had not been considered when Indian Point Unit 1 was built. Throughout the 1960s, the Atomic Energy Commission (AEC), the agency charged with licensing nuclear power plants, had considered only radionuclide releases as potential impacts of plant operations. By 1969 the National Environmental Policy Act had been passed and in 1971 an appellate court ruled that the AEC must consider non-radiological impacts as well.[2] This meant that licensing decisions for Indian Point Units 2 and 3, then under construction, would have to address a host of environmental considerations, including the implications of water withdrawals and discharges associated with condenser cooling and system operations. By this time the regulatory functions of the AEC had been transferred to a new agency, the Nuclear Regulatory Commission (NRC). Hearings were held, decisions were made and appealed, and the NRC determined that the issue of potential impacts on Striped Bass could not be resolved using existing scientific information (Barnthouse et al. 1984).

Although not subject to the NRC's licensing requirements, the fossil-fired Bowline Point and Roseton power plants then under construction on the Hudson became subject to the 1972 Clean Water Act, which among its many and diverse provisions required power plants to minimize environmental impacts of associated with their cooling water intake structures. Although smaller with respect to water use than Storm King or the combined Indian Point units, the collective impression at the time was that new power plant operations were being deployed all along the Hudson. Not coincidentally, significant ownership interests in these fossil fuel units was held by Con Ed, a time when Charles Luce, a well-regarded environmentalist, was taking the helm at Con Ed as chief executive officer.

In short, in the early 1970's, it became clear that substantial, credible science-based investigations of the potential impacts of the multiple power plants, all advanced or substantially owned by Con Ed, would need to be established. And, to know potential impacts, it became critical to know when Striped Bass were in the Hudson, where and at what life stages, because life stage correlated to susceptibility to impacts. Since various life stages of Striped Bass utilize the entire estuary from Battery Park to the federal dam at Troy, a riverwide survey program became needed. Moreover, the program had to study not only early life stages of Striped Bass, but older fish as well, because where adult female Striped Bass spawn determines where some of the most susceptible life stages end up. This meant that multiple types of sampling gears would

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[2] Calvert Cliffs Coordinating Committee, Inc. v. United States Atomic Energy Commission

be needed to sample the habitats utilized by Striped Bass. Although federal agencies had the ultimate responsibility for assessing the potential impacts of the plants and reaching ultimate decisions on whether the projects could proceed, the utility companies proposing the variously plants, primarily Con Ed, were responsible for designing the programs and collecting the data.

The first riverwide sampling was conducted in 1973, and the three coordinated sampling programs that together constitute the core of the HRBMP were fully initiated in 1974. The data collected during the mid-1970s were used in quantitative assessments performed by both utility and the federal agencies in connection with parallel regulatory proceedings involving numerous state and federal agencies, the facility owners, and a broad range of public interest groups, most notably the Hudson River Fishermen's Association[3], the Scenic Hudson Preservation Council, and the Natural Resources Defense Council. In 1975, as the lead federal agency with respect to the Clean Water Act, the U.S. Environmental Protection Agency (EPA) issued draft National Pollutant Discharge Elimination System (NPDES) permits that echoed NRC's proposal with respect to Indian Point for reduced water withdrawals through cooling tower retrofit. Permits including the same requirements were also issued for Bowline Point and Roseton. Owners of all of these plants challenged these draft NPDES permits, precipitating a consolidated adjudicatory hearing that began in 1977 and continued for 3 years. The regulatory impasse was resolve in 1981 when all parties agreed to a milestone agreement termed the Hudson River Settlement Agreement (HRSA). The terms of the HRSA included abandoning the Storm King project, maintaining a moratorium on power plant construction beyond the proposed units, and the funding for 10 years at a minimum cost of $2.0 million per year (1981$) of a riverwide biological monitoring program. This program, among the most ambitious and progressive scientific investigations ever been proposed in the US, was the HRBMP.

The complex history of power plants on the Hudson and the scientific studies performed to support regulatory actions during the 1970s are documented in detail elsewhere (Talbot 1983, Barnthouse et al. 1984, McDowell 1986, Barnthouse et al. 1988, Young and Dey 2011). This summary is provided to facilitate an understanding of the confluence of circumstances, from new federal law to NGO pressure, that underpinned the development of the HRBMP.

The principal driver of concern throughout this period was potential impacts of impingement and entrainment on susceptible fish populations, and so monitoring emphasized fish.[4] The early focus on Striped Bass – at least as much related to its commercial and recreational significance, as to its susceptibility to entrainment and impingement – meant that the riverwide biological survey programs designed in the early 1970s focused disproportionately on this species' life history – when it was in the River, where, and in what life stage. Striped Bass are pelagic broadcast spawners, meaning that eggs are released directly into the water column where they drift with the tides. Striped Bass larvae are also pelagic, although as they develop they become more actively mobile and begin to concentrate in favorable habitats. Plankton nets must be used to sample these early life stages. Sampling must be performed during the late Spring and early Summer, when those life stages are present in the river, and must focus on those regions in which Striped Bass are expected to be most abundant. Once the larvae have grown and transformed into juvenile fish, they actively move up and down the river and seek out specific habitats such as shoal and shore zones. Gears such as trawls and beach seines are needed to sample these

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[3] Predecessor to the Hudson Riverkeeper organization, which was established in 1983.

[4] Macrozooplankton present in the ichthyoplankton samples collected during the HRBMP have been preserved. These samples are still available for analysis by future researchers

habitats and must be deployed during the seasons (mid-summer through fall) when juveniles are expected to be present.

Fortunately, many of the most abundant or economically important species that utilize the estuary, including White Perch, Bay Anchovy, Atlantic Tomcod, American Shad, Blueback Herring, and Alewife, also have pelagic early life stages and spatiotemporal distributions similar to Striped Bass. Marine species that utilize the saline lower estuary are also effectively sampled, to the extent that their spatiotemporal distributions overlap those of the primary species of interest[5]. More importantly, while many power plant studies that focus on a single or several fish species address only that species, the HRBMP identified every fish species obtained during its extended sampling schedule – 171 species over the term of the HRBMP's performance and most of the year when the River is not iced. This full assay, with the fact that the 152-mile Estuary was sampled throughout the River, mitigates what could other have been a myopic view based on the early focus on Striped Bass.

The 1980 HRSA required the power plant owners to conduct a long-term biological monitoring program to address 3 objectives:

1. Evaluate the effectiveness of mitigation measures included in the settlement, specifically the flow reductions and outages intended to reduce entrainment, barrier net and screening technology, and Striped Bass stocking.

2. Monitor impingement and entrainment abundance and survival at Bowline Point, Roseton, and Indian Point.

3. Monitor the status of Hudson River fish populations as ichthyoplankton, juveniles, and adults.

The second of these objectives has been addressed through site-specific studies conducted at each of the three stations. This report emphasizes the first and third objectives, which have been addressed through riverwide studies. The Long River Ichthyoplankton Survey (LRS) provides data on the abundance, stage structure, and spatiotemporal distributions of entrainable life stages of Striped Bass and other species that could be used to quantify the effects of flow reductions and outages on entrainment of these species. The LRS also provides data on long-term trends in the abundance of early life stages of these species. The Beach Seine Survey (BSS) and Fall Shoals Survey (FSS) provide data on the status and long-term trends in abundance of young-of-the-year (YOY) fish. In addition to these programs that target multiple species, a mark-recapture program quantifies the abundance and reproductive success of Atlantic Tomcod. A separate Striped Bass mark-recapture program was initiated to evaluate the contribution of hatchery-reared Striped Bass to the Hudson River spawning stock. This program continued even after the hatchery program was discontinued as a way to monitor Striped Bass reproductive success.

The HRSA also required the owners to fund the establishment of an independent institution, the Hudson River Foundation, "to sponsor scientific, economic and public policy research on matters of environmental, ecological and public health concern and to publish the results of such research." The Foundation, which began operation in 1982, continues to fund important scientific research that complements the long-term monitoring provided by the HRBMP.

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[5] Species that utilize habitats that are inaccessible to HRBMP gear (e.g., shoreline weed beds and tributary streams), or that spawn in nests, or that are present in the river primarily during late fall or winter are less effectively sampled.

As the HRSA was finalized, EPA had granted the New York State Department of Environmental Conservation (NYSDEC) the authority to administer the NPDES permit programs for New York State power plants. Consistent with the agreements made by all parties to the HRSA, NYSDEC issued discharge permits[6] for Indian Point, Bowline Point, and Roseton in 1982 and 1987, all of which included the requirement to continue the HRBMP and to address whether reduced water use, including through cooling tower retrofits, was required. When the 1987 permits were set to expire in 1992, the power plant owners agreed to continue the HRBMP until new permits were developed. The regulatory debate, and substantial associated litigation in the New York State and federal courts, also continued. Power plants changed their ownership, their operations, as the overarching law, regulatory spirit and cultural view of environmental impacts and power production evolved. It is an easy thing to focus on the battle, but the fundamental fact remains that Indian Point's final NPDES permit, the last to be issued to the trio of major, Hudson River power plants that were the subject of the HRSA, was granted in 2018. And, just as Con Ed before it, the owners of Indian Point had continued the HRBMP. What this meant is that, in late 2017, when the last full series of the HBMP studies was completed, it had operated for forty-four (44) continuous years.

As documented in Appendix 1 to this report, selected components of the HRBMP data set have been made available to Hudson River researchers over the years. However, the full suite of data sets, with documentation of data collection methods, QA/QC procedures, data dictionaries, and data management software has never before been available.

1.2 STRUCTURE OF THIS REPORT

Section 2 describes the five essential or core components of the long-term HRBMP studies. It also provides a comprehensive road map to the HRBMP design, methods, analytical systems, and database organization. The goal of this discussion is to ensure that new users of the HRBMP data understand what data were collected over the last 44 years, how the data were collected, and how they can be accessed and used. The discussion includes details concerning QA/QC procedures, database structure, and data retrieval and analysis methods. In addition to digitized data, the HRBMP archives include in excess of 12 million individual fish specimens identified and initially preserved in museum-quality condition, as well as an additional estimated 37 million individual fish contained in preserved, but unprocessed sample tows. These specimens are described in an appendix to Section 2.

Section 3 provides examples of the use of HRBMP data to answer scientific questions concerning the status of key Hudson River fish populations and the environmental and biotic factors that influence them. Major topics addressed include the influence of Climate Change-related water quality metrics on fish habitat; assessment of the frequency and magnitude of extreme weather events and of the effects of those events on select fish species; changes in the composition of the fish community over time; assessment of the impacts of changing fishery management policies on harvested species; new information on the utilization of the lower Hudson by marine fish species; and assessments of possible causes of change in populations that have undergone major changes over the duration of the HRBMP.

Section 4 provides a retrospective on the successes and failures of the HRBMP, from the perspectives of both scientists and regulators. It includes the views of current and past participants in scientific and regulatory aspects of Hudson River studies, from utility, agency, and

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[6] Termed State Pollution Discharge Elimination System (SPDES) permits

academic perspectives. It also identifies key scientific issues that remain unresolved, could not be addressed within the structure of the HRBMP, have arisen since the HRBMP was established, or could be addressed in the future with emerging technologies that did not exist during the HRBMP. Our hope is that raising these issues will inspire the next generation of Hudson River scientists to make full use of the existing data provided by the HRBMP to resolve existing issues and address new issues that will arise in the future.

2. COMPONENTS, METHODS, & ANALYTICS

2.1 INTRODUCTION

The Hudson River Biological Monitoring Program (HRBMP), in a large and fundamental sense, encompasses a set of biological, ecological and water quality studies of the Hudson River Estuary, overseen by multiple regulatory agencies and funded wholly or in part over more than four decades by companies that had planned or owned power generation facilities located on the shores of that estuary. It represented the collective, initial efforts to assess and quantify with scientific rigor the potential impacts on the ecosystem of proposed and existing power production for the largest metropolitan area in the United States. In the simplest sense, the HRBMP was an effort to understand what existed in an important major U.S. ecosystem, what was susceptible to power plant impacts, and to what degree and with what result.

Early studies related to the then existing and planned Indian Point units (including Unit 1 which began operations in 1962 and had experienced a series of impingement events), date back to the 1960s, when teams of newly deployed scientists, including from the New York University Department of Environmental Medicine (NYU), conducted a series of biological, ecological, water quality and fluid dynamic studies. These included the 1966-1968 Ecological Survey of the Hudson River, partially funded by Consolidated Edison Company of New York, Inc. (ConEdison), (NYU 1968), and the 1965-1968 study by Northeastern Biologists, Inc. of the fishes in the vicinity of the then-proposed Cornwall pumped storage facility (Carlson and McCann 1968).

To provide information necessary to evaluate the potential ecological impact of the existing and under-construction Indian Point units ConEdison began an intensive study of the Hudson River Estuary under the guidance of the Hudson River Policy Committee.[7] Raytheon Company monitored the river’s chemical and physical parameters, identified the various life forms, and compiled a list of relative abundance for the major aquatic species during 1969-1970 (Raytheon 1971). The scope of work was expanded in 1972 to permit direct empirical/experimental assessment and mathematical modeling of potential plant impact on the Hudson River Estuary from Haverstraw Bay to the Newburgh-Beacon Bridge. Three other primary contractors, Texas Instruments Incorporated (TI), New York University (NYU); and Lawler, Matusky, and Skelly Engineers (LMS), conducted the major aspects of this program. The initial study conducted by TI had two major objectives: (1) determine the ecological significance of exploiting screenable fishes on the intake screens of Indian Point Units 1, and 2, and (2) determine the effects of thermal and chemical discharges on fish and benthos.

In 1974, ConEdison’s co-owners of the Roseton and Bowline Stations, Orange and Rockland Utilities, Inc. (ORU), and Central Hudson Gas & Electric Corporation (CHGE), joined ConEdison to work as a consortium on the Hudson River studies. These facilities also needed to obtain permits for their cooling water intakes and discharges, and collectively the facilities needed to assess potential cumulative impacts. The Multiplant Program was intended to document the state of the aquatic ecosystem in the Estuary, and estimate the potential impact of entrainment and impingement at the new and existing power plants on populations of selected representative fish species, with a focus on the Indian Point, Bowline and Roseton units:

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[7] Hudson River Policy Committee was composed of representatives from the New York Conservation Department, New Jersey Department of Conservation and Economic Development, U.S. Bureau of Sport Fisheries and Wildlife, and the U.S. Bureau of Commercial Fisheries. The Committee originally guided the studies associated with the Cornwall project, and continued on with the Indian Point studies.

Life history, behavior, and population dynamics of select, representative fish species in the Estuary, from Troy Dam downstream into the western part of Long Island Sound and the lower bays, to assess both past and current ecological data to indicate significant changes that were expected to be related to the addition of power generating capacity on the Hudson River.

Synoptic analysis of Striped Bass populations comprising the Atlantic fishery using electrophoretic, meristic, morphometric, and scale-pattern characteristics to differentiate subpopulations from the major spawning rivers (Potomac, Elk, Choptank, Rappahannock, and Hudson) on the Atlantic coast. Phase II of the study was to quantify the contribution of each stock to the Atlantic fishery.

During the mid- to late-1970s, the HRBMP grew to include 11 components of the multiplant portion of the studies, plus additional near-field, entrainment, and impingement studies (Table 2-1). Most of the multiplant components were discontinued after the Hudson River Settlement Agreement (HRSA) in 1980 (Sandler and Schoenbrod 1981), but the Long River Ichthyoplankton Survey (LRS), Fall Juvenile Survey (FJS), Beach Seine Survey (BSS), Atlantic Tomcod Stock Assessment (ATSA), and Water Quality Survey (WQS) were continued in much the same form through 2017. The Striped Bass Stocking Evaluation (SBSE) was initiated in the mid-1980s to assess the success of the stocking program, and then continued after stocking ceased in 1996.

Early on, the HRBMP began using state-of-the-art quality assurance and quality control programs (Young et al 1992) to ensure that the data could withstand the scrutiny that it was sure to draw given the regulatory interest in the study results. Additional aspects of the early studies are covered by Barnthouse et al. (1988).

Table 2-1 Multiplant Components of Hudson River Biological Monitoring Program, 1971-2018.

Component	Years	Description
Long River Ichthyoplankton Survey (LRS)	1974-2017	Distribution and abundance of fish eggs and larvae in the Estuary
Beach Seine Survey (BSS)	1974-2017	Distribution and abundance of juvenile fish in the shore zone
Fall Juvenile Survey (FJS)	1974-2018	Distribution and abundance of juvenile fish in off-shore habitats
Atlantic Tomcod Stock Assessment (ATSA)	1974-2017	Spawning stock abundance and life history
Striped Bass Stocking & Evaluation (SBSE)	1984-2017	Abundance and distribution of stocked and wild sub-adults. Stocking ended in 1995.
Water Quality Survey (WQS)	1974-2018	Estuary-wide water quality parameters
White Perch Stock Assessment (WPSA)	1971-1988	Spawning stock abundance and life history
Synoptic Subpopulation Study (SSS)	1974-1975	Contribution of Hudson River stock to the coastal fishery
Interregional Trawl Survey (IRTS)	1974-1980	Distribution and abundance of juvenile fish in off-shore benthic habitats
Mark-recapture (MR)	1974-1980	Absolute abundance and movements of juvenile Striped Bass and juvenile and adult White Perch
Striped Bass Stock Assessment (SBSA)	1976-1980	Spawning stock abundance and life history

2.2 MULTIPLANT STUDIES

Sampling for the HRBMP was conducted according to a sampling design in which the Hudson River estuary from the Battery (RM 1) to the Federal Dam at Troy (RM 152) was divided into 13 regions (Figure 2-1) . Each region was further divided into "strata" on the basis of river depth. The strata are graphically presented in Figure 2-2 and defined below and in Table 2-2:

Shore—That portion of the Hudson River estuary extending from the shore to a depth of 10 ft (the stratum defined only for BSS).

Shoal— That portion of the Hudson River estuary extending from the shore to a depth of 20 ft at mean low tide.

Bottom—That portion of the Hudson River estuary extending from the bottom to 10 ft above the bottom where river depth is greater than 20 ft at mean low tide.

Channel—That portion of the Hudson River estuary not considered bottom where river depth is greater than 20 ft at mean low tide.

The relative area and configuration of the shoal, bottom, and channel strata vary over the length of the Hudson River estuary, but may be characterized using the three cross section views presented in Figure 2-2 and Table 2-2.

Although almost all of the HRBMP sampling programs used the same division of the estuary into regions and strata (Table 2-3); some programs used a stratified random sampling design, others used fixed sampling locations, and others allowed the crew leader to choose locations within a defined geographic area that best met the program objectives, i.e. free choice (Table 2-4).

Stratified random sampling was used when the catch data were intended to be representative of the entire region-stratum-week cell for purposes of estimating the relative abundance of organisms within that cell. In that case any location within the cell should have the same probability of being sampled. Random locations were chosen by a computerized sampling algorithm, but alternate locations were also chosen in case sampling issues were encountered at the original randomly chosen location, such as bottom obstructions or vessel traffic. The programs using this type of sampling were the Long River Ichthyoplankton Survey (LRS), Fall Juvenile Survey (FJS), and Beach Seine Survey (BSS).

Fixed location sampling was used when comparisons of specific locations or types of habitat across temporal strata were the primary intent of the program. For fixed location sampling, the crew leader would choose the sampling location based on fathometer reading and orientation to shoreline landmarks. Most of the fixed location sampling programs (Interregional Trawl Survey (IRTS), Indian Point Standard Stations (IPSS), and White Perch Stock Assessment (WPS), were terminated prior to availability of GPS technology.

Free choice sampling was used when the objective was to maximize the catch of particular target species. In free choice sampling, the crew leader would choose the sample location, within the geographic bounds specified by the program. Programs using free choice sampling were the Synoptic Subpopulation Study (SSS), Mark-Recapture program (MR), Striped Bass Stock Assessment (SBSA), and the Striped Bass Stocking and Evaluation (SBSE).

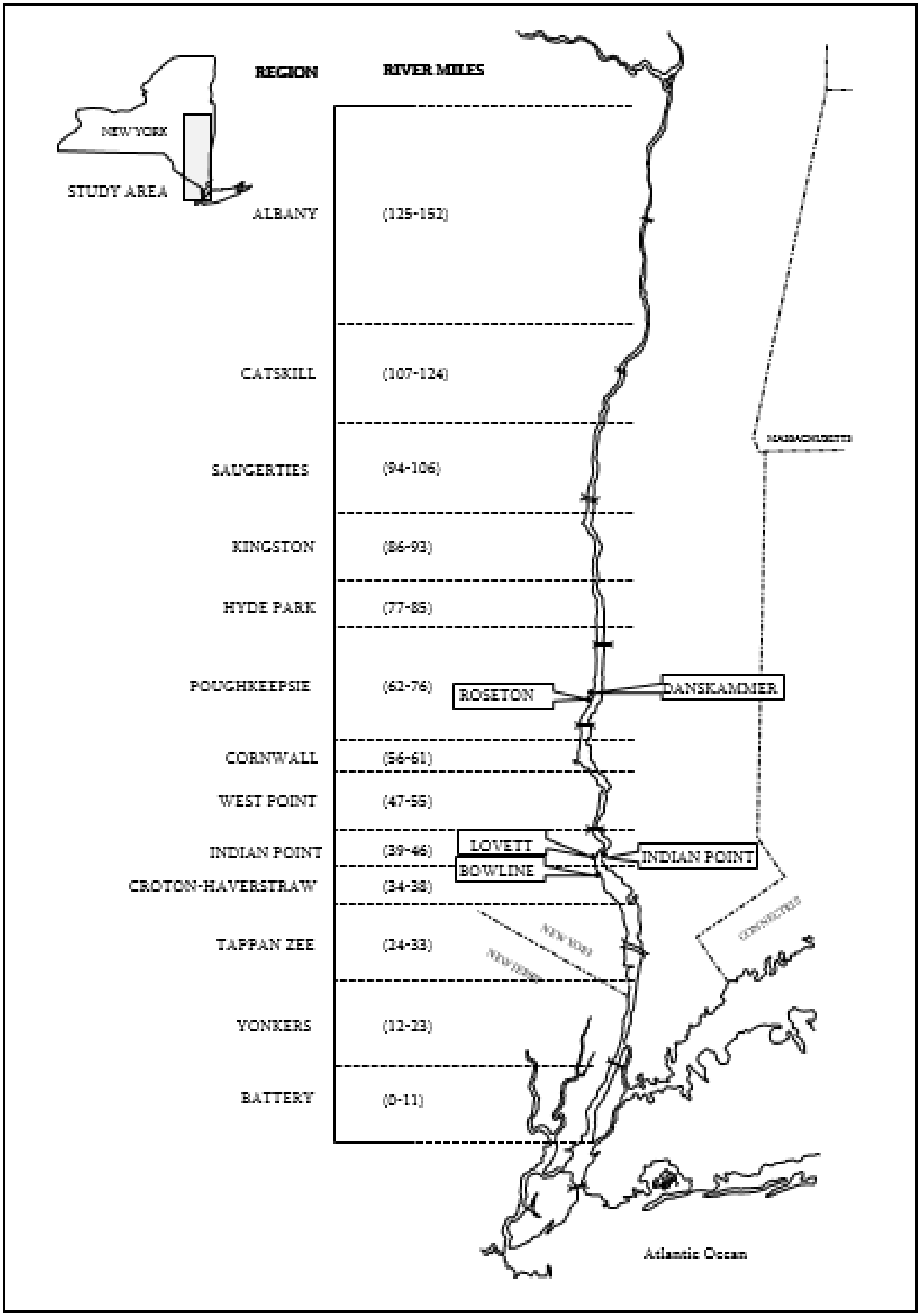
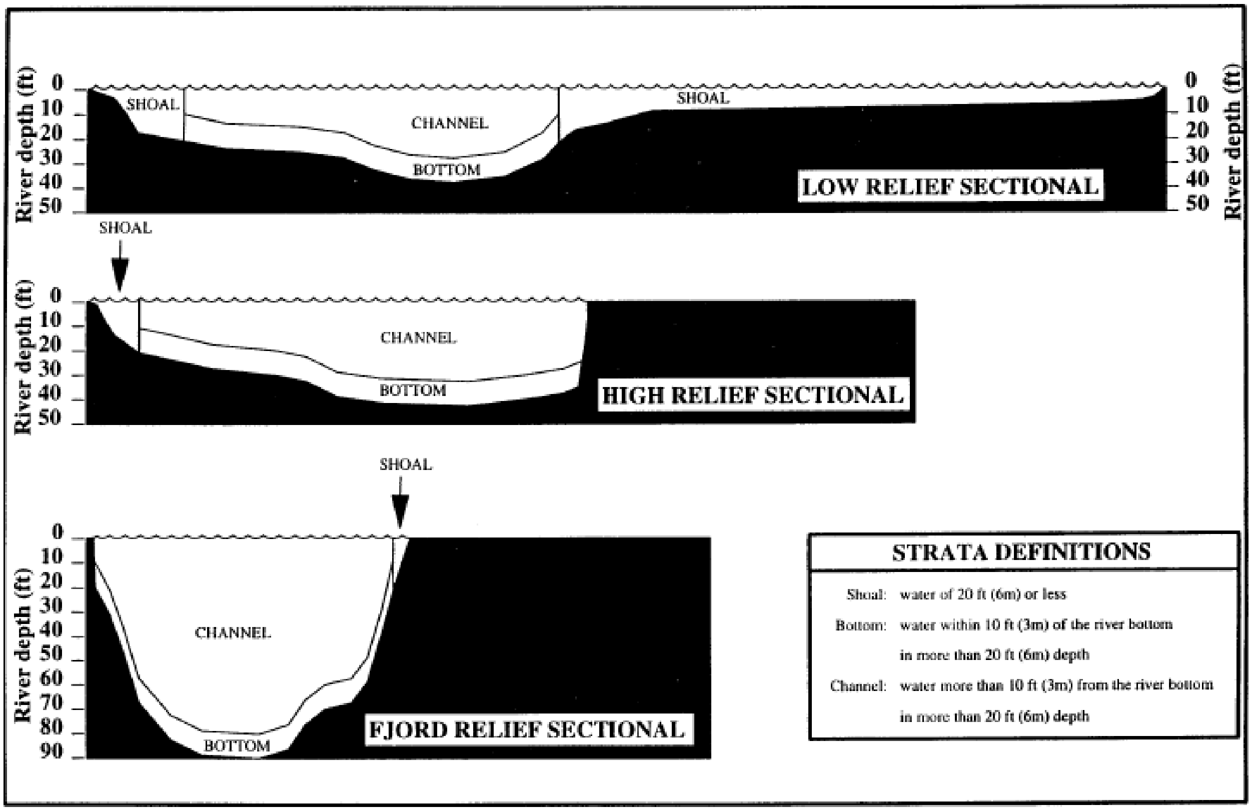


Figure 2-1 Location of 13 geographic regions sampled during the Hudson River Biological Monitoring Program.



STRATA DEFINITIONS

Shoal:	water of 20 ft (6m) or less
Bottom:	water within 10 ft (3m) of the river bottom in more than 20 ft (6m) depth
Channel:	water more than 10 ft (3m) from the river bottom in more than 20 ft (6m) depth

Figure 2-2 Cross sections of the Hudson River estuary showing locations and typical proportional relationships of the shoal, bottom, and channel strata. Vertical and horizontal scales are not the same.

Table 2-2 Strata Sampled within the 13 Geographic Regions of the Hudson River Estuary River.

Region	Abbreviation	River Miles	Kilometers	Shore	Shoal	Channel	Bottom
Battery	BT	1-11	1-19	--	--	B	B
Yonkers	YK	12-23	19-39	A	A	A	A
Tappan Zee	TZ	24-33	39-55	A	A	A	A
Croton-Haverstraw	CH	34-38	55-63	A	A	A	A
Indian Point	IP	39-46	63-76	A	A	A	A
West Point	WP	47-55	76-90	A	--	A	A
Cornwall	CW	56-61	90-100	A	A	A	A
Poughkeepsie	PK	62-76	100-124	A	--	A	A
Hyde Park	HP	77-85	124-138	A	--	A	A
Kingston	KG	86-93	138-151	A	--	A	A
Saugerties	SG	94-106	151-172	A	--	A	A
Catskill	CS	107-124	172-201	A	--	A	A
Albany	AL	125-152	201-246	A	--	A	A

NOTE:
A indicates sampled in all years of the program
B indicates sampled in 1985 and later years
-- indicates not sampled

Table 2-3 Stratum and Region Volumes (m3) and Surface Areas (m2) Used in Analysis of Hudson River Estuary Data.

Geographic Region	Channel Volume	Bottom Volume	Shoal Volume	Region Volume	Shorezone Surface Area
Battery	141,809,822	48,455,129	18,747,833	209,012,784	(a)
Yonkers	143,452,543	59,312,978	26,654,767	229,420,288	3,389,000
Tappan Zee	138,000,768	62,125,705	121,684,992	321,811,465	20,446,000
Croton-Haverstraw	61,309,016	32,517,633	53,910,105	147,736,754	12,101,000
Indian Point	162,269,471	33,418,632	12,648,163	208,336,266	4,147,000
West Point	178,830,022	25,977,862	2,647,885	207,455,769	1,186,000
Cornwall	94,882,267	36,768,629	8,140,123	139,791,019	4,793,000
Poughkeepsie	228,975,052	63,168,132	5,990,260	298,133,444	3,193,000
Hyde Park	131,165,041	32,012,000	2,307,625	165,484,666	558,000
Kingston	93,657,021	35,479,990	12,332,868	141,469,879	3,874,000
Saugerties	113,143,296	42,845,077	20,307,338	176,295,711	7,900,000
Catskill	83,924,081	42,281,206	34,526,456	160,731,743	8,854,000
Albany	32,025,080	13,517,183	25,606,842	71,149,105	6,114,000
Total	1,603,443,480	527,880,156	345,505,257	2,476,828,893	76,555,000

a. Shorezone surface area is unknown and not used in data analysis as no beach seine sampling is performed in the Battery region.

Table 2-4 Sampling design type used for each of the HRBMP multiplant components.

HRBMP Component	Sampling Design
Long River Ichthyoplankton Survey	Stratified Random
Beach Seine Survey	Stratified Random
Fall Juvenile Survey	Stratified Random
Atlantic Tomcod Stock Assessment	Fixed Location
Striped Bass Stocking & Evaluation	Free Choice
Water Quality	Stratified Random / Fixed Location
White Perch Stock Assessment	Fixed Location
Synoptic Subpopulation	Free Choice
Interregional Trawl Survey	Fixed Location
Mark-recapture	Free Choice
Striped Bass Adult Stock Assessment	Free Choice

2.3 POST-HRSA COMPONENTS OF THE HRBMP

After the 1980 HRSA, certain HRBMP components were continued, while others were eliminated, and a single new component was added.

2.3.1 Long River Ichthyoplankton Survey (LRS)

2.3.1.1 Field Methods

Sampling encompassed the entire length of the Hudson River estuary, initially from the George Washington Bridge (RM 12) to RM 140, but after 1987 covered the entire estuary from RM 1 to RM 152 at the Federal Dam in Troy. The LRS yielded ichthyoplankton data to support calculations of standing crop, temporal and geographic indices, and growth rates for selected Hudson River fish species. The primary species were Atlantic Tomcod (*Microgadus tomcod*), American Shad (*Alosa sapidissima*), Striped Bass (*Morone saxatilis*), White Perch (*M. americana*) and Bay Anchovy (*Anchoa mitchilli*). LRS sampling was concentrated during the spring, summer, and early fall when eggs and larvae of the primary species have historically been abundant.

Sample locations are determined from a stratified random design. Sample number each week varies from approximately 100 to 200, depending seasonally on whether the entire estuary is being sampled. Sampling is done in the shoal and bottom habitat using a 1-m^2 epibenthic sled (Figure 2-3), and in the shoal and channel strata using a 1-m^2 Tucker trawl (Figure 2-4). Both gears are fitted with 0.5 mm mesh plankton nets. The nets are equipped with flowmeters to record volume sampled. Early in the season, sampling was typically done in daylight, but once fish larvae are present, sampling was conducted between sundown and sunrise.

Larger fish, if any are removed from the sample upon retrieval, and the remaining net contents are washed into a sample jar and preserved with 10% formalin. Samples are analyzed in the laboratory for identification to species (if possible), count, life stage, and a subsample are measured.

Two distinct gear types were used for field collections during the LRS:

- 1-m^2 epibenthic sled (Figure 2-5 and Table 2-5) to sample the bottom-only shoal and channel strata.
- 1-m^2 Tucker trawl (Figure 2-6 and Table 2-5) to sample the shoal and channel strata (non-bottom), and

Both gear types were towed against the prevailing current for 5 minutes. The tow started with the remote opening of the net and terminated with its remote closing. If the river depth was 20 ft or less, an open set and retrieval of the net was performed. The tow speed for the Tucker trawl was adjusted to maintain a towing wire angle of approximately 45º averaging approximately 0.9 m/second. The tow speed for the epibenthic sled-mounted net was maintained at approximately 1.0 m/second. An electronic flowmeter mounted along the side of the research vessel and equipped with an on-deck readout display was used to establish and maintain tow speed. A calibrated digital flowmeter mounted in the center of the net mouth was used to calculate the volume of water filtered for each sample.

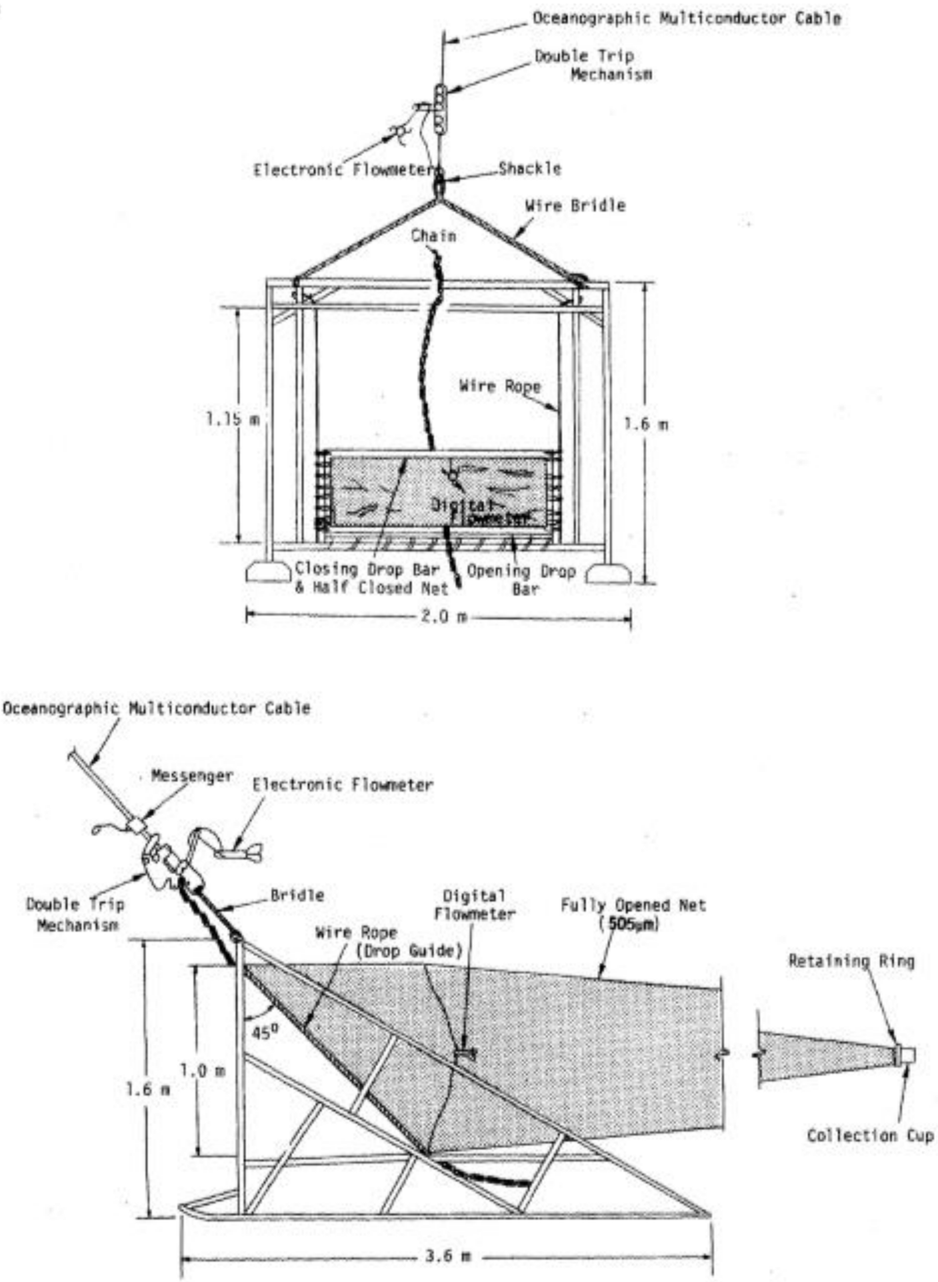


Figure 2-3 1-m^2 (mouth opening) Epibenthic sled used in LRS sampling program, 1974-2017.

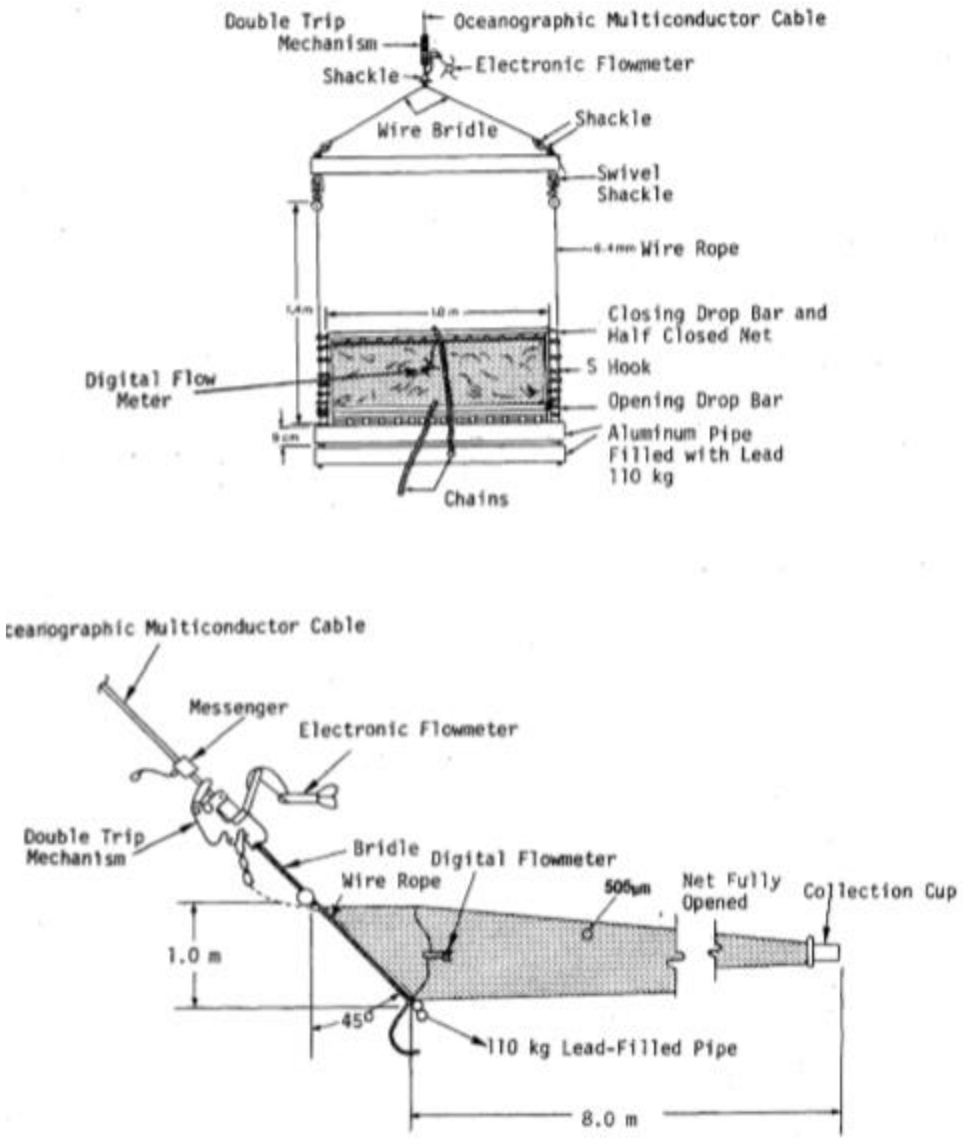


Figure 2-4 1-m^2 (effective mouth opening) Tucker trawl used in LRS program, 1974-2017.

Figure 2-5 Epibenthic sled on stern of Sametta Too during LRS sampling in the 1970s.

Table 2-5 Characteristics of sampling net and collection cup used on 1-m^2 Tucker trawl and 1-m^2 epibenthic sled used in LRS program.

Characteristic	Description
Sampling Net	
Length	8.0 m
Mouth (width)	1.0 m
Mouth (height)	1.4 m
Mesh size	500 μm
Net material	Nytex (monofilament nylon)
Collection cup	
Length	30 cm
Length with net-retaining ring	37 cm
Mesh size	500 μm
Net material	Nytex (monofilament nylon)

Figure 2-6 1-m^2 Tucker trawl employed to sample shoal and channel strata during LRS program.

Following deployment and retrieval of the sampling gear, net washing was performed to concentrate the sample into the cod end bucket. The samples were then examined for yearling and older fish which were identified, enumerated, measured to determine length class (1: total length ≤ d1; 2: d1 < total length ≤ d2; 3: d2 < total length ≤ 250mm; 4: total length > 250mm; where d1 is the species-specific upper length limit for YOY, and d2 is the upper length limit for yearlings of key species and 150 mm for others) and returned to the Hudson River estuary. Special care was taken to observe Sturgeon species for physical condition and for the presence of marks and/or tags. All yearling and older Sturgeon were measured to the nearest millimeter, weighed to the nearest gram, and, if alive, returned to the river or, if dead, frozen and saved for the NYSDEC. After yearling and older fish were removed, the remaining sample was placed in container(s) so that the sample occupied no more than 25 percent of the container volume. The containers were filled with a 10 percent aqueous formalin solution.

From 1974-1981, in situ measurements of water temperature (°C), dissolved oxygen (mg/L), and specific conductance (microsiemans/cm at 25°C) were taken with calibrated meters in conjunction with each biological sample. From 1982-2017, water quality measurements were taken at fixed river mile and strata stations (Table 2-6). Physical/chemical measurements were recorded from surface, mid-depth, and bottom water depth at channel stations and from the surface and bottom water depth at shoal stations. During the 23 collection weeks of the 2016 LRS, 3520 physical/chemical measurements were scheduled.

Table 2-6 Location of water quality stations used from 1982-2017 in HRBMP.

River Region	RM of Channel Station	RM of Shoals
Battery	1, 3, 6, 9	--
Yonkers	12, 14, 17, 19, 22	19
Tappan Zee	25, 27, 29, 32	29
Croton-Haverstraw	35, 36, 37, 38	36
Indian Point	40, 42, 43, 46	43
West Point	49, 51, 53, 55	--
Cornwall	56, 57, 59, 61	59
Poughkeepsie	63, 67, 71, 75	--
Hyde Park	78, 80, 82, 84	--
Kingston	87, 89, 91, 93	--
Saugerties	96, 99, 102, 105	--
Catskill	109, 114, 118, 122	--
Albany	126, 131, 135, 138, 142	--
Total Stations	54	5

2.3.1.2 Gear Studies

A series of studies, described in Appendix 12, were conducted during the 1970s and early 1980s to optimize deployment techniques and estimate capture efficiency (the fraction of organisms in the path of the net that are actually collected) of the epibenthic sled and Tucker trawl. These studies examined different types and sizes of net, mesh sizes, tow speeds, and deployment protocols. The studies confirmed that the nets and deployment methods used in the LRS were sufficiently optimized to continue their use throughout the HRBMP.

2.3.1.3 Laboratory Methods

Since the late 1970s, approximately 2/3 of the LRS samples have been analyzed, with the other 1/3 held back in case additional samples were needed to provide additional precision to density estimates. Selection of samples for laboratory analysis began with the grouping of samples according to river run (i.e., sampling week), region, and strata. Based on these groupings, samples were selected based on one of the following criteria:

If there were less than 6 samples in the group, then all were selected for analysis.

If there were between 6 and 12 samples in the group, then 50 percent of the samples were randomly selected for analysis.

If there were more than 12 samples in the group, then 20 percent of the samples were randomly selected for analysis.

Splitting (or subsampling) was permitted. A trained technician first determined, by visual inspection, if the sample needed splitting. Samples containing large numbers of eggs may have been split so that eggs were only sorted from one or more aliquots containing a total of at least 250 eggs (all species combined).

Figure 2-7 Ichthyoplankton laboratory in Verplank, NY, during early days of the LRS program.

Two different sets of criteria were used for subsampling of larval stages, depending on the river run. Beginning with the river run in which Striped Bass PYSL first appeared, and for the next 8 river runs (a total of 9 consecutive river runs), a minimum of 500 *Morone* larvae (i.e., the combined total of YSL, PYSL, and YOY of Striped Bass, White Perch, and unidentified *Morone*) was sorted from the entire sample and a minimum of 50 non-*Morone* larvae was also sorted. Because some of the more difficult distinctions between species (e.g., Striped Bass versus White Perch) or between life stages could not be made reliably during sorting, samples from these 9 river runs were typically sorted in their entirety for larvae (i.e., YSL, PYSL, and YOY combined) of all species combined. An exception to this may have been made, at the discretion of the laboratory supervisor, under the following circumstances: when extremely large numbers of non-*Morone* larvae occurred in the sample and a qualified identifier had verified that sufficient numbers of both *Morone* larvae and non-*Morone* larvae were sorted to meet their respective subsampling quotas. The purpose of this exception was to allow splitting before sorting of taxa such as clupeids which could readily be distinguished from *Morone* by sorters.

The second set of criteria for subsampling larvae applied to the 13 other river runs not covered in the previous paragraph (before and after the period of Striped Bass abundance). Any sample from these river runs may have been subsampled so that larvae were sorted from one or more splits containing at least 100 larvae (i.e., YSL, PYSL, and YOY combined) of all species combined.

To eliminate bias, some steps in the splitting procedure were performed by an assistant so that the sorter had no prior knowledge of which splits were to be used for the analysis. Randomness of the splitting procedure was monitored and demonstrated by testing selected samples to determine whether splits from the same sample differed by more than random variation. Samples were selected to test for randomness by a continuous sampling plan, (CSP-V from MIL-STD-1235, AOQL = 10 percent).

For each split sample evaluated, three fractions of the same aliquot size were sorted and compared by the chi square test according to the following procedure. The counts of the three splits (including any quality control [QC] finds) were averaged to obtain the expected value for the sample. Chi-square was calculated as:

$$chi\,square = \frac{(O_1 - E)^2}{E} + \frac{(O_2 - E)^2}{E} + \frac{(O_3 - E)^2}{E}$$

where O_1, O_2, and O_3 = Observed counts for splits 1, 2, and 3.

E = Expected value for the sample (average of O_1, O_2, and O_3).

If the calculated value for chi-square was less than 5.99, then the splits of that sample were considered random, and the sample passed the split QC (5.99 was the critical value of chi square with two degrees of freedom at an alpha level of 0.05). If a sample was split for both eggs and larvae, then both stages were tested separately. The sample passed the split QC only if chi-square was below the critical value for both life stages.

Eggs and larvae were separated from detrital material, sorted by major taxonomic group and life stage, counted, and placed in vials containing 5 percent formalin or in ethyl alcohol. Sorted samples were evaluated by a trained technician under magnification and all organisms were identified and enumerated. The following life stage designations were used in identification:

Life Stage	Description
Egg	Embryonic stage from spawning to hatching,
YSL	From hatching to development of a complete and functional digestive system,
PYSL	From complete development of digestive system to transformation to juvenile form,
YOY	From completed transformation to Age 1.

Whenever possible, a maximum of 30 Striped Bass, 30 White Perch, 30 American shad, 30 Atlantic Tomcod, and 30 bay anchovy per sample were measured. Organisms were chosen at random from each taxon regardless of life stage until the required numbers were obtained; life stages to be included were YSL, PYSL, and YOY. The total length of YSL and PYSL was measured to the nearest 0.1 mm and to the nearest 1 mm for YOY. Measurements were recorded on the laboratory data sheet. Selection of specimens for measuring was randomized by spreading them uniformly in a gridded container, selecting a starting point in the grid by means of a random number table, and then measuring the first 30 measurable specimens encountered in a predetermined pattern commencing at the starting point. Every grid space had an equal probability of being selected as the starting point, so every specimen had an equal probability of being included in the subsample.

Continuous sampling inspection was employed during the sort and identification procedures to ensure an average outgoing quality limit of 10 percent or better. Two sampling modes were required in the continuous sampling plan (CSP-1):

Mode 1—The first eight samples sorted or analyzed for larval identification by an individual are subject to 100 percent QC reanalysis. If all eight pass the reanalysis, i.e., if <10 percent of the ichthyoplankton are missed or misidentified per sample, the individual is placed in CSP Mode 2. If any sample fails during Mode 1, then Mode 1 is continued until eight consecutive samples pass. For example, if a sample with QC No. 7 fails, then samples with QC Nos. 8 through 15 are subject to QC resorting.

Mode 2—Lots of seven consecutive samples per individual are assigned for identification QC and per laboratory facility for sort QC. One sample from each lot is randomly chosen for QC analysis. If a sample fails (>10 percent of organisms missed or misidentified) during Mode 2, the individual is placed back into Mode 1. For example, if a sample with QC No. 6 fails in a lot of seven samples, then samples with QC Nos. 7 through 14 are subject to QC reanalysis. If samples 7 through 14 pass, the individual is again placed in Mode 2.

Key contractors: TI, NAI, LMS, EA

Representative Publications: ASA 2015

2.3.2 Fall Juvenile Survey (FJS)

2.3.2.1 Field Methods

Samples were collected every other week from the Yonkers region through the Poughkeepsie region initially (1974-1978), Yonkers to the Albany region (1979-1995), and the Battery region to Albany region (1996-2017) in mid-summer and fall. The objective was to provide data on YOY fish to support calculation of standing crop and temporal and geographic indices for selected Hudson River fish species. From 1974 to 1978, all sampling was done in the shoal and bottom strata using a 1 m^2 epibenthic sled; beginning in 1979 the channel stratum was sampled with a 1-m^2 Tucker trawl, and beginning in 1985 a 3-m beam trawl replaced the epibenthic sled (Table 2-7). The target species were Atlantic Tomcod, American shad, Striped Bass, and White Perch.

Table 2-7 Specifications of Sampling Gear Used During the FJS.

Gear	Characteristic	Dimensions
1-m^2 Tucker Trawl And 1-m^2 Epibenthic Sled	Net	
	Length	8.0 m
	Mouth (width)	1.0 m
	Mesh size	3.0 mm
	Collection cage	
	Length	81 cm
	Diameter	41 cm
	Mesh size	3.0 mm
3-m Beam Trawl	Net	Dimensions
	Length	7.6 m
	Beam width	3.0 m
	Net body	3.8-cm mesh (stretch)
	Codend	3.2-cm mesh (stretch) net with 1.3-cm mesh (stretch)
	Hood	3.8-cm mesh (stretch)
	Footrope	Equipped with 5.1-cm rollers
	Headrope	Equipped with three floats
	Mouth area	2.7 m^2

Each sample week, 200 samples are taken. Sample locations are selected with a stratified random design. Catches are typically analyzed at time of collection and fish are released. All species are identified, separated into the four standard length groups, and counted. Some samples are returned for laboratory analysis when required to fill quotas for more detailed analysis.

Both gear types were towed against the prevailing current for approximately 5 minutes. For the Tucker trawl, vessel speed was adjusted as necessary to achieve and maintain a 45° wire angle; the resultant tow speed was recorded. The beam trawl was towed at a speed of approximately 1.5 m/second. Tow speed was established and maintained by use of an electronic flowmeter mounted along the side of the research vessel and equipped with an on-deck readout display. Tucker trawl samples taken in greater than 20 ft of river depth were remotely opened and closed at sampling depth. A calibrated digital flowmeter mounted in the center of the net mouth was used to calculate the volume of water filtered for each sample.

Calibrated water quality instruments were used to measure water temperature (°C), dissolved oxygen (mg/L), and specific conductance (microsieman/cm at 25°C) at fixed river mile and strata stations in conjunction with field sampling from 1974-1981, and from 1982-2017 at the same fixed locations measured during the LRS program (Table 2-6). Measurements of physical/chemical parameters were recorded from surface, mid-, and bottom water depths at channel stations and from surface and bottom water depths at shoal stations.

Because of the difficulty in differentiating some species, especially YOY *Morone* (Striped Bass, White Perch) and *Alosa* (Alewife, Blueback Herring), samples collected during the first three sampling periods (River Runs 1 through 3) were typically preserved with 10 percent formalin at the time of collection and returned to the laboratory for analysis. Before preservation, samples were examined for fish determined to be yearling or older, based on length categorization; live fish were returned to the river after count data were determined.

Beginning with the fourth biweekly sampling period, samples were evaluated in the field; only fish required to fill length measurement and food habit quotas were returned to the laboratory. The quota was to be 20 specimens of a selected species from each river region per river run; because of the necessity of returning fish to the river alive, the first 20 specimens of a selected species were brought to the laboratory for length measurements. The Hyde Park through Albany regions were considered one region for the purpose of filling length measurement quotas during the entire FJS and during River Runs 4 through 10 of the BSS. Also for the BSS during River Runs 1 through 3, the Yonkers through West Point regions were considered as one region for the same purpose. In river regions where fewer than 10 samples were collected per survey, no more than 10 specimens of each selected species from an individual sample were used to fill the length measurement quota. This criterion was used in the following surveys for the specified river regions:

Sampling Program	Region
BSS	YK, IP, WP, CW, PK
FJS	WP, PK

In all other regions, when the sample schedule resulted in 10 or more samples per survey, no more than 5 specimens per species in a sample were used to fill the length measurement quotas.

If more specimens of a species were collected than needed, the individuals used to fill the quotas were randomly selected.

All fish not returned to the laboratory were identified and enumerated into length classes as described in the following section. All Atlantic Sturgeon, Shortnose Sturgeon, and Striped Bass were examined for external and internal magnetic tags. All sturgeon were measured to the nearest millimeter, weighed to the nearest gram, and, if alive, returned to the river or, if dead, frozen and saved for the NYSDEC. All Striped Bass with external streamer tags were measured and a scale sample was taken.

2.3.2.2 Gear Studies

A series of studies, described in Appendix 12, were conducted during the 1970s and early 1980s to optimize deployment techniques and estimate capture efficiency (the fraction of organisms in the path of the net that are actually collected) of the epibenthic sled and Tucker trawl. These studies examined different types and sizes of net, mesh sizes, tow speeds, and deployment protocols. The studies confirmed that capture efficiency was low for target species, and resulted in the substitution of the 3-m beam trawl for the epibenthic sled beginning in 1985.

2.3.2.3 Laboratory Methods

Fish from the FJS in both the field and laboratory were identified and enumerated into the following length classes:

Length Class 1—Less than or equal to the YOY length limit ("Division 1"), which was determined by the field contractor on a weekly basis for each species.

Length Class 2—Greater than Division 1 and less than or equal to the yearling length limit ("Division 2"); set at 150 mm for most species, also determined weekly by the field contractor. From 1 January through 31 May, Division 2 represents the upper length limit for yearling fish for all species. From 1 June through 31 December, Division 2 is assigned a static value of 150 mm total length for all species except Alewife, American Shad, Blueback Herring, Striped Bass, Atlantic Tomcod, and White Perch. For these species, Division 2 is maintained as a dynamic upper length limit for yearling fish throughout the year.

Length Class 3—Greater than Division 2 and less than or equal to 250 mm.

Length Class 4—Greater than 250 mm.

Twenty specimens of the following selected species (species to be measured evolved over the course of the HRBMP) collected in each river region per river run were measured for total length (nearest millimeter) in the laboratory (except for sturgeon species which were measured in the field):

Alewife
American Shad
Atlantic Sturgeon
Atlantic Tomcod
Bay Anchovy
Blueback Herring
Shortnose Sturgeon
Spottail Shiner
Striped Bass
Weakfish
White Catfish
White Perch.

Key contractors: TI, NAI, LMS, EA

Representative Publications: ASA 2015

2.3.3 Beach Seine Survey (BSS)

2.3.3.1 Field Methods

Beach seine samples were collected in alternate weeks relative to the Fall Juvenile Survey at stations ranging from the George Washington Bridge (RM 12) to the Troy Dam. The objective was to obtain distribution and relative abundance information on YOY American Shad, Atlantic Tomcod, Striped Bass, and White Perch during periods when these species were concentrated primarily in the shallow, near-shore areas. The survey was conducted from mid-June through October, when YOY of these species were typically abundant in the shore zone nursery areas.

Each week of the effort, 100 samples are collected at beaches randomly selected for each region with a 100-ft beach seine (Figure 2-8). The net is set perpendicular to the shore until fully extended, then the offshore end is towed to shore by boat. Area swept average 450 m^2. Some night sampling was conducted in 1974, but after that all samples were taken in daylight. Catches are typically analyzed at time of collection and fish are released. All species are identified, separated into the four standard length groups, and counted. Some samples are returned for laboratory analysis when required to fill quotas for more detailed analysis.

The BSS utilized a nominal 100-ft (30.5-m) total length beach seine to collect YOY fish in the shorezone of each region, except the Battery region. Table 2-8 presents specifications for the beach seine. One end of the net was held on shore and the other end was towed perpendicularly away from the shore by boat. The seine was then hauled, clockwise if possible, in a semicircular path toward shore. The complete beach seine deployment swept an area of approximately 450 m^2 (TI 1980).

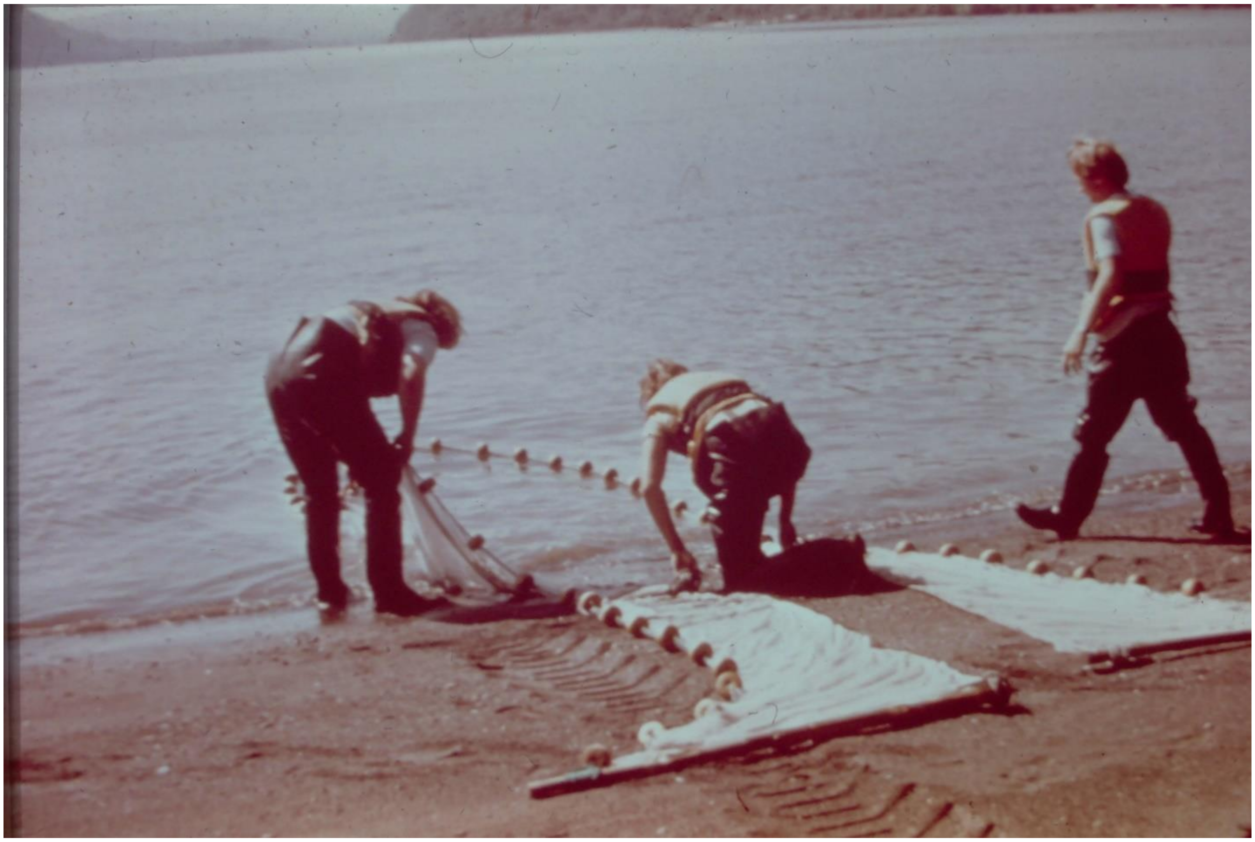


Figure 2-8 Texas Instruments field crew retrieving 100' beach seine during 1970s.

All BSS samples were collected on a during daytime (except some night samples were collected in 1974) during alternate weeks of the FJS, beginning in mid- to late-June and continues for 10 weeks of sampling. The 2016 BSS biweekly sampling program was conducted from 13 June through 23 October. Ten of the 19 weeks in this time period were collection weeks with 100 beach seine samples per week scheduled for collection.

Table 2-8 Dimensions of beach seine used in BSS program.

Characteristics	Dimension
Number of wings	2
Length of wings	12 m
Depth of wings	2.4 m
Wing mesh (bar)	1 cm
Length of bag	6.1 m
Depth of bag	3 m
Bag mesh (bar)	0.5 cm
Sampling area	450 m^2

Measurements of water temperature (°C), dissolved oxygen (mg/L), and specific conductance (microsieman/cm at 25°C) were taken with each beach seine sample using in-situ water quality instrumentation. Physical/chemical measurements were taken 1 ft below the water surface and approximately 50 ft from the shoreline.

YOY fishes collected during the first three beach seine river runs typically were processed in the laboratory because of the difficulty in distinguishing species at the YOY life stage. Older fish were processed in the field. Beginning with River Run 4, all samples were field processed; 20 specimens of the selected species from each region per run were collected (as described in Section 2.3.1) for length determination in the laboratory. Samples maintained for laboratory analysis were preserved using 10 percent formalin. Fish from the BSS in both the field and laboratory were identified and enumerated into length classes. Any Sturgeon collected during the BSS were measured to the nearest mm and weighed to the nearest g. Sturgeon that remained alive were returned to the Hudson River estuary; dead fish were frozen and held for NYSDEC. All Sturgeon and Striped Bass were examined for external and internal magnetic tags. Striped Bass with external tags were measured and a scale sample was taken.

2.3.3.2 Gear Studies

A series of studies, described in Appendix 12, were conducted during the 1970s to estimate the capture efficiency of the 100-ft seine, and to develop an adjustment that would allow the daytime sampling results in the BSS to accurately represent actual nighttime densities, to correspond with nighttime sampling in the FJS. The studies estimated adjustments for juvenile Striped Bass (10.1), juvenile White Perch (2.1) and yearling and older White Perch (3.4).

2.3.3.3 Laboratory Methods

All fish returned to the laboratory were measured for total length to the nearest 1.0 mm. Laboratory analysis was conducted in the same manner as described for samples collected during the FJS.

Key contractors: TI, NAI, LMS, EA

Representative Publications: ASA 2015, Wilson and Weisberg 1993

2.3.4 Atlantic Tomcod Stock Assessment (ATSA)

The Atlantic Tomcod Stock Assessment (ATSA) in the lower Hudson River was performed during December through February (winter) beginning during the winter spawning run of 1973-1974 and continued through 2016-2017 with two winters not sampled (1984-1985 and 1986-1987). Data obtained by each winter ATSA were used to:

- estimate the size of the Atlantic Tomcod spawning population in the Hudson River by mark-recapture methods;
- analyze population age and sex composition;
- analyze sexual maturity and the timing of peak spawning activity;
- analyze length, weight, and condition of male and female fish;
- estimate age-specific, and population fecundity;
- determine pre-spawning and postspawning population movements;
- estimate an annual index of Atlantic Tomcod abundance based on trawl catch per unit of effort
- assess incidences of liver abnormalities and parasite infestation.

ATSAs conducted during 1974-1975 through 1981-1982 used Carlin tags or combinations of tags and fin clips to mark Atlantic Tomcod caught in box traps throughout the survey area. Box traps, impingement collections at Indian Point, Bowline Point, and Lovett generating stations, sport and commercial fishing returns, and incidental trawl catches from the utilities' monitoring programs provided recapture sampling efforts for these surveys. In 1982-1983, the ATSA was modified to include marking of Atlantic Tomcod only in box traps set north of the Bear Mountain Bridge using fin clip codes specific for one-week periods, and trawl sampling, primarily south of the George Washington Bridge, to maximize the recapture of marked Atlantic Tomcod in downriver regions.

During the 1983-1984 and 1985-1986 programs additional modifications to the design of the mark-recapture program were made. The 1987-1988 ATSA was similar to 1985-1986 except that weekly and biweekly marking periods were used instead of monthly periods to provide a more precise description of the temporal pattern of Atlantic Tomcod movements during the spawning period. The trawl effort in the Battery and Upper Harbor regions was used primarily to recover fish that had been fin clipped and released from box traps fished north of Yonkers.

Visual implant (VI) tagging was initially implemented for the ATSA in 1997-1998, and was used in place of finclips from 1998-1999 through 2016-2017. The ATSA ended after the 2016-2017 survey.

2.3.4.1 Field Methods

Gear deployment and sample handling procedures summarized below were described in detail in standard operating procedures manuals (SOPs). Box Traps (Figure 2-10) were deployed from December through February of each winter on the river bottom in 1 to 12 m of water at fixed sites along the east and west banks of the Hudson River between the Yonkers and Poughkeepsie regions (Figure 2-9). The traps were lowered into the water by wire cable and firmly attached to a solid shore structure (e.g. dock, pier, bulkhead). Traps were generally checked and reset daily, Monday through Friday.

The Hudson River from RM 25 (two miles south of the Tappan Zee Bridge) north to RM 76 in the Poughkeepsie region was used as the box trap release zone in these most recent series of surveys (Figure 2-9). The box trap zone use in winter surveys prior to the 1988-1989 ATSA extended south to Yonkers. All Atlantic Tomcod that were marked and released in this zone were tagged with soft VI-alpha (VI) fish tags (Figure 2-11) This tag is a small (1 mm x 3 mm), brightly-colored (orange or yellow) tag preprinted with a “tag number,” a unique three-character identification code consisting of a letter followed by two digits or letters. The tag was inserted with a tag injector into the flesh of the right side of the operculum of the fish (Figure 2-11), which was previously determined to be the tag location with the best long-term retention with the lowest handling mortality. The length of each fish tagged was recorded and the degree of external parasite infestation was noted before the fish was released. Fish recaptured with tags were released again as quickly as possible, approximately 25 to 50 meters away from the capture site, after recording the length, condition of the tag insertion site (healed or infected), tag number, and condition of the fish e.g., blind, fungus, fin rot. Recaptured fish with illegible tags, with tag wounds but no tags, or with other unusual features of the tag or tag wound were taken back to the laboratory for mark verification.

The Hudson River south of the George Washington Bridge and a portion of upper New York Harbor between Battery Park and Liberty Island were used as the trawl recapture zone. A 9-m high-rise trawl (Figure 2-12) was deployed each weekday in the Battery during 24 consecutive weeks, from November through mid-April if river ice allowed trawling. The 9-m trawl has been used in all ATSAs since 1982-1983. Tows were 10 minutes once the net was set on the river bottom, and towed against the current at a boat speed (through water) of between 1.2 and 1.7 m per second. The towing wire was set with a length-to-depth ratio between 2:1 and 4:1.

All Atlantic Tomcod collected in trawls were examined for the presence of VI tags, and otherwise processed as the marked fish from the box trap survey. Suspected Atlantic Tomcod recaptures from the current box trap survey or from previous winter surveys were taken to the laboratory fresh or frozen for tag verification. Fish from selected tows were taken to the laboratory for biocharacteristics analysis, and the remaining fish were released without tagging.

Once each week an entire day’s Atlantic Tomcod catch from each of five standard box trap sites (Table 2-10) and three randomly selected trawl tows was taken in fresh condition to the laboratory and examined for biocharacteristics, which included determination of each fish’s age, length, weight, sex, and reproductive condition. Fish from trawl samples were taken to the laboratory from more than one day during weeks with low abundance of Atlantic Tomcod in the trawl catch in an attempt to obtain a weekly sample of about 100 fish.

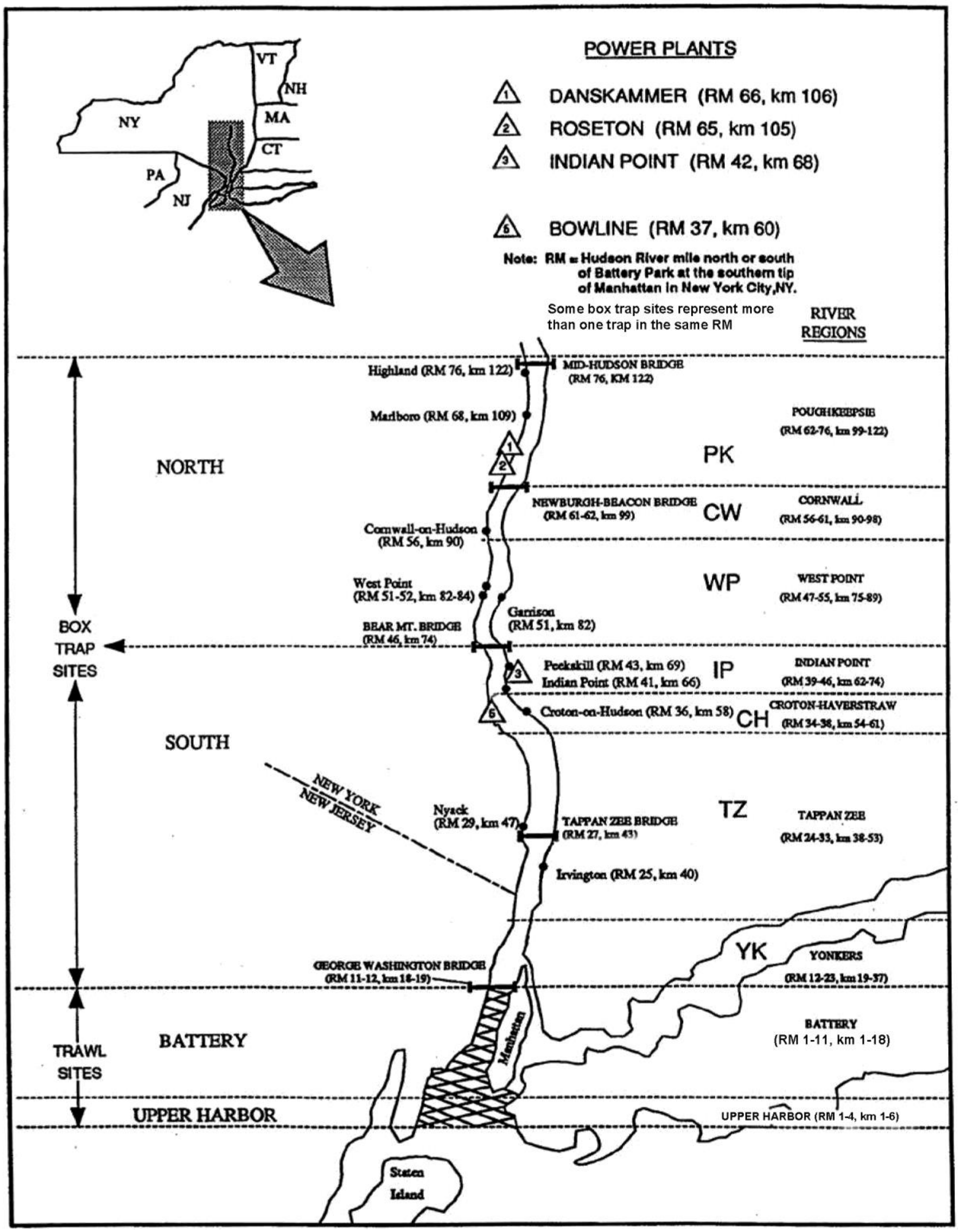


Figure 2-9 Box trap and trawl sampling sites and Hudson River regions used during the Atlantic Tomcod spawning survey.

Figure 2-10 1m x 1m x 2m box trap deployed to catch adult Atlantic Tomcod in the Hudson River.

Figure 2-11 Visual implant tag (circled) in an age 1 Atlantic Tomcod.

Figure 2-12 9-m high rise trawl used to sample Atlantic Tomcod and Striped Bass in the Hudson River.

Table 2-9 Specifications of the 9-m trawl.

Characteristic	Dimension
Head rope length	6.9 m
Foot rope length (sweep)	9.0 m
Legs (between doors and net)	6.0 m
Approximate vertical lift	3.6 m
Doors (steel V-doors)	1.0 m
Net body length	5.2 m
Cod end section	2.3 m
Mesh - body of net	7.6-cm (stretch) mesh polypropylene; polypropylene; 3-mm diameter twine
- cod end	3.8-cm (stretch) mesh, knotless poly-propylene; 3-mm diameter twine
Roller gear	25.4-cm rollers spaced with 5-cm cookie disks

Table 2-10 Standard Hudson River box trap sites for weekly collection of Atlantic Tomcod used in biocharacteristics analysis.

River Mile	Kilometer	Site	Location
25	40	East	Irvington
36	58	East	Croton Yacht Club
41	66	East	Indian Point
51	82	East	Garrison
51-52	82-84	West	West Point
56	90	West	Cornwall Yacht Club

Conductivity and water temperature were measured in situ, with measurements corresponding to each box trap or trawl sample collection. Readings were made at the water surface and at sampling depth at box trap sites, and at the surface and sampling depth immediately after the completion of each 9-m trawl tow. The GPS position at the start of each 9-m trawl tow (after 2000), the direction of tow, time of tow, date, and sample number were also recorded. A Yellow Springs Instruments (YSI) salinity-conductivity-temperature meter was used to measure surface (0.3 m) and bottom water temperature and conductivity at the end of each tow. All conductivity measurements were adjusted to 25ºC (specific conductance).

2.3.4.2 Laboratory Methods

The Atlantic Tomcod in each biocharacteristics sample (box trap or trawl) were received in fresh condition in the laboratory. Date and place of recapture were recorded for any tagged Atlantic Tomcod included with the laboratory samples. Tag number, age, length, and sex were also recorded for each verified recapture.

Total length (nearest mm), weight (nearest 0.1 g), sex, reproductive condition, age, and presence and relative abundance of external parasites were recorded for all Atlantic Tomcod in the weekly biocharacteristics samples. Reproductive condition categories included immature, developing, ripe, ripe and running, partially spent, spent, and resting (Table 2-11). Age was determined from one spawning season to the next. Atlantic Tomcod over 150 mm were aged by counting the annuli of the otoliths (number of dark annual growth rings) using reflected light, aided by a dissection microscope. Individuals 150 mm and under were considered to be Age 1 fish. The degree of external parasite infestation was categorized as none, light (1-5 parasites), moderate (6-20 parasites), or heavy (>20 parasites) (Figure 2-13). Ovaries were collected from up to 15 Atlantic Tomcod females per length group (8 groups of 25-mm with smallest group ≤125 mm, and largest group >275 mm) for fecundity analysis from box trap biocharacteristics samples. Ovaries were removed only from female Atlantic Tomcod determined to be in or approaching ripe condition. Excised ovaries were preserved in 10% formalin. After at least one month of preservation, the egg mass was separated from the rest of the ovarian tissue, and weighed to the nearest hundredth of a gram. A randomly selected subsample of approximately 2 g was weighed (nearest 0.01 g) and the eggs in it were counted.

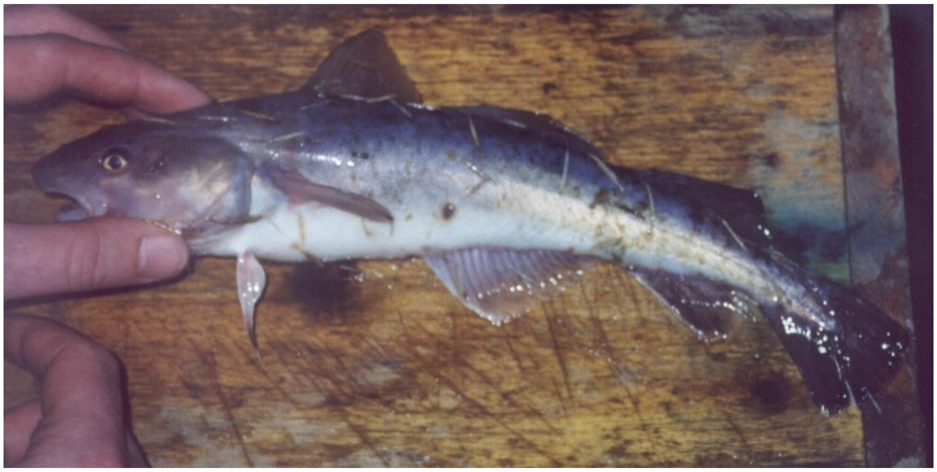


Figure 2-13 **Atlantic Tomcod with heavy infestation of external parasitic copepods.**

Table 2-11 Classification of Atlantic Tomcod gonads during ATSA laboratory examination.

Condition	Description
Immature	A specimen which is either male or female, but too young to spawn (sub-adult). Transparent or pinkish gonads, not developed.
Developing (Intermediate)	Applicable to sub-ripe fish heading into spawning season. Testes are opaque and reddish to reddish white. Ovaries may appear orange and eggs visible to the naked eye, granular, and whitish to orange-reddish. May or may not spawn.
Ripe	Adult in spawning condition; gonads well developed but no milt or eggs extruded upon application of pressure to gonadal area. Will spawn in current season.
Ripe and Running	Adult prepared to spawn immediately; expulsion of eggs or milt from body with little provocation.
Partially Spent	Sexual products partially discharged; gonads somewhat flaccid as opposed to the firmness of a developing gonad. Genital aperture usually inflamed, some hemorrhaging present.
Spent	Applied to adult specimens at completion of spawning activity. The sexual products have been discharged; genital aperture usually inflamed and hemorrhaging present. The gonads have the appearance of deflated sacs, the ovaries usually containing a few leftover eggs in a state of reabsorption and the testes have some residual sperm. Ovarian walls will become leathery.
Resting	Applies to adult fish with underdeveloped gonads.

Key Contractors: TI, NAI, EA, LMS

Representative Publications: McLaren et al 1988, Klauda et al. 1988, NAI 2016a

2.3.5 Striped Bass Stocking & Evaluation (SBSE)

As part of the HRSA, the Utilities were required to construct, lease or contract for operating a hatchery on the Hudson River with the intention of stocking 600,000 3-in fingerling Striped Bass annually from 1983 to 1991. The fingerling fish were marked with finclips and coded magnetic wire tags. Annual reports of hatchery production and stocking were produced. Studies were initiated to evaluate the efficacy of the stocking effort with respect to movement of the hatchery-raised fish, and their ultimate return and contribution to the wild population of juveniles and ultimately to the spawning stock.

The SBSE began in the spring of 1984 as an evaluation of fishing gear and techniques that were most efficient and effective to catch and handle Striped Bass for the purpose of recapturing stocked fish from the Verplank hatchery that were marked with coded wire tags and determining their proportion among the Age 1+ and Age 2+ wild cohorts. The best locations, times, and fishing gear were evaluated in the 1984 through 1987-1988 SBSEs to maximize total catch and catch per unit of effort of Age 1+ and Age 2+ Striped Bass while minimizing handling mortality. The SBSE was not performed during 1984-1985.

The Battery region of the Hudson River adjacent to Manhattan, and the upper New York Harbor region ("Upper Harbor") in the vicinity of Liberty Island provided the most consistent catches of overwintering Age 1+ and Age 2+ Striped Bass between early November and mid-April, and the 9-m trawl was the most effective gear for capturing Age 1+ and Age 2+ Striped Bass. This sample period and gear have been used consistently from the 1988-1989 through the present SBSEs. Concurrent with these gear evaluations, handling techniques were improved to increase the survival of Striped Bass that were caught, tagged, scanned for hatchery-administered magnetic tags, and released (Dunning et al. 1987, 1989). As the Verplank hatchery increased the annual production of fish, and more Striped Bass were recaptured with hatchery-administered tags, we also quantified magnetic tag detection efficiency (Mattson et al. 1990a) and improved the internal anchor-external streamer tag design (Mattson et al. 1990b, Waldman et al. 1990).

The SBSE from 1988-1989 through 2016-2017 was primarily a stock assessment program because hatchery production and stocking of marked Striped Bass fingerlings ended in October 1995, and because the program targeted overwintering juvenile Striped Bass of ages 1+ and 2+. Examination of fish for hatchery-administered magnetic coded wire tags ceased in the 2000-2001 SBSE. The SBSE ended after the 2016-2017 program. The SBSE has emphasized consistency of sampling gear and procedures, and the refinement of laboratory techniques for scale examination to accurately determine age (e.g. Humphreys et al. 1990). Annual mark-recapture estimates have been calculated for the total population and for the Age 1+ and Age 2+ sub-populations of Striped Bass found in the combined Battery and Upper Harbor regions from the 1985-1986 through 2001-2002 SBSEs. Subsequent to the 2001-2002 SBSE the mark recapture estimates were not calculated because the recapture data obtained failed to satisfy the assumptions of the closed-population estimator (Schumacher-Eschmeyer) previously used.

The objectives of SBSE from 1988-1989 through 2016-2017 were:

- describe the catch characteristics of the 9-m trawl used to capture Striped Bass in the lower Hudson River during the winter,
- describe the length, age-distribution and biocharacteristics of Striped Bass in the lower Hudson River during the winter,
- estimate the abundance of age 1+ and age 2+ Striped Bass overwintering in the lower Hudson River,
- maintain a collection of Striped Bass scales, and
- compare the results obtained in 1-3 with those reported from previous SBSEs.

The food habits analysis was performed with the objective of determining the extent of Striped Bass predation on Atlantic Tomcod, because both co-occur in the overwintering areas of the

Battery region of the Hudson River and upper New York Harbor (Dunning et al. 1997). The contents of each stomach were processed and classified according to one of four categories: empty, only vertebrates present, only invertebrates present, or both vertebrates and invertebrates present. If vertebrate remains were found, the vertebrates were classified as either Atlantic Tomcod or other vertebrates. Accordingly, with the exception of the 1991-1992 HRSBMP in which food items were identified to the lowest practical taxon, Atlantic Tomcod was the only prey item identified to species in the database.

2.3.5.1 Field Methods

A complete description of field and laboratory procedures is found in the SBSE Standard Operating Procedures, which were updated annually prior to the start of each field season and subjected to review and acceptance by NYSDEC. These procedures have remained essentially unchanged since the start of the 1988-1989 SBSE. The SBSE consisted of sampling in the Battery and Upper Harbor regions of the lower Hudson River with a 9-m trawl (Figure 2-12).

Sampling locations for each annual program were selected to maximize the catch per unit of effort of Age 1+ and Age 2+ Striped Bass in the lower Hudson River, based on the results of previous programs. A 9-m trawl was used from the 1988-1989 SBSE through the 2016-2017 SBSE to catch Striped Bass because the results of the 1987-1988 SBSE showed that the 9-m trawl was more efficient than other gear in catching Striped Bass of the target ages of Age 1+ and Age 2+. Striped Bass captured in each trawl sample were enumerated and fish >150 mm TL were marked with internal anchor tags (Figure 2-14) and released.

For 24 to 27 weeks, starting in early November and ending in mid-to-late April, with few exceptions in some weeks due to river ice conditions that prevented trawling, the 9-m trawl was deployed for sampling in the lower Hudson River. The 9-m trawl was fished in each week in the Battery region and on selected days in the Upper Harbor region. Tow duration was 10 minutes unless sampling difficulties such as bottom obstructions required shortening the tow. All Striped Bass captured by the trawl were handled in a manner that minimized stress before tagging (Dunning et al. 1989). The cod end of the net was opened and the contents transferred to holding containers or in the case of large catches, a holding pen/live car alongside the boat. Striped Bass were removed from the containers or pen for processing using the following procedures:

Fish were removed using a dip net,

All surfaces that came in contact with the live fish were wet,

Striped Bass were handled gently by the body and not handled by the eye sockets, gill arches, isthmus, or opercular flaps, and

Struggling fish were quieted by covering the head and eyes with a wet hand, cloth or glove.

All Striped Bass were measured (mm TL) and visually examined for external tags and tag wounds. All Striped Bass >150 mm TL in good condition, and not already tagged, were tagged with an internal anchor tag. Good condition was defined as:

No bleeding from gills or body wounds,

No significant loss of scales,

Strong opercular movement, and

No obvious external abnormalities such as blindness, fin rot, or skeletal abnormalities.

In the 1991-1992 and subsequent SBSEs, Striped Bass that were alive but not in good condition were also tagged to determine if the presence of certain gross anatomical abnormalities (such as blindness or bacterial infection) affected their survival. The nature of the particular abnormality of each Striped Bass was recorded prior to release. In SBSEs before 1991-1992, only Striped Bass in good condition were tagged and released.

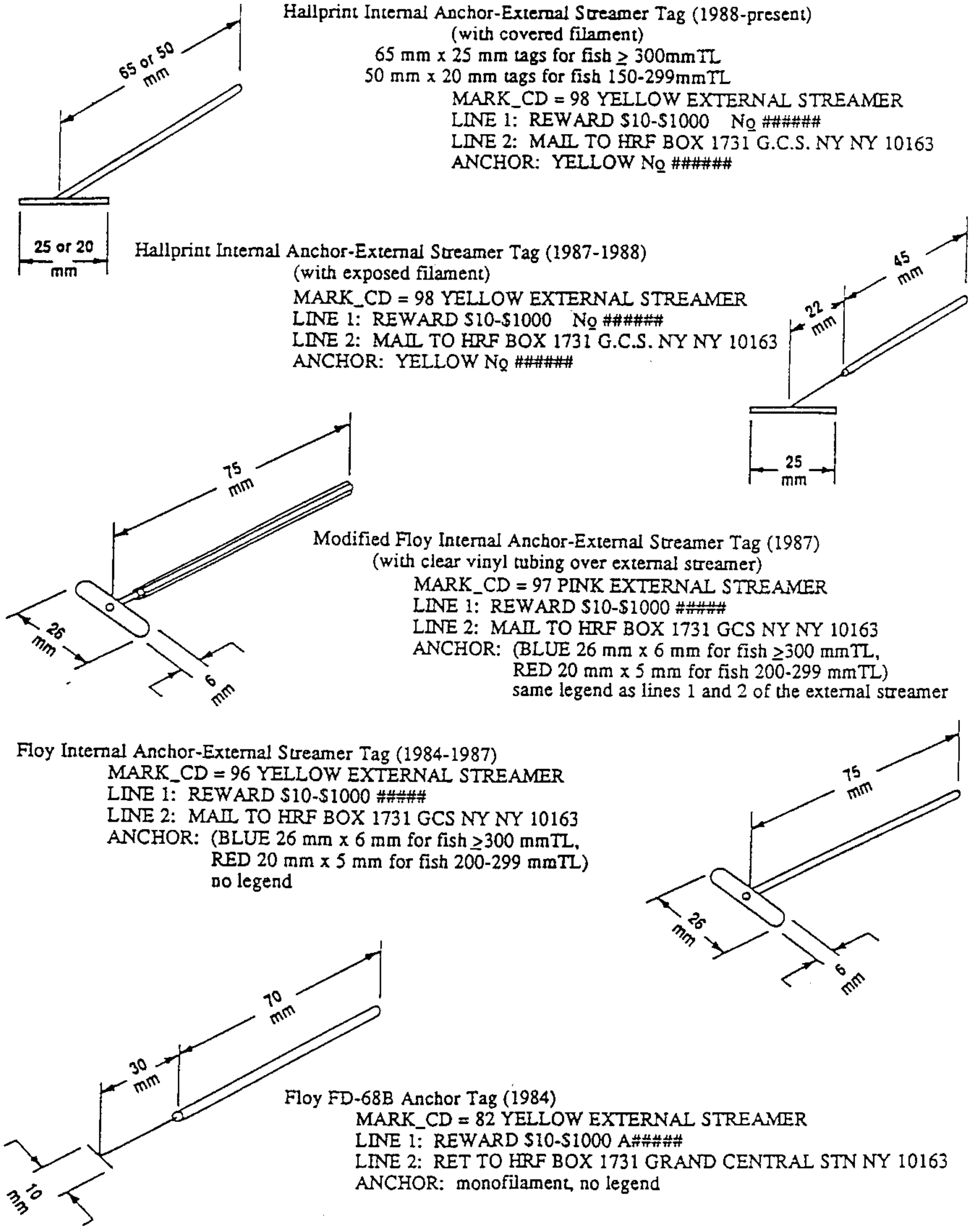


Figure 2-14 Tags used to mark Striped Bass during the 1984-2016 Hudson River Striped Bass Monitoring Programs.

The internal anchor tag was inserted by removing a scale midway between the vent and distal tip of the depressed pelvic fins, and five to six scale rows dorso-laterally from the ventral mid-line. This tag insertion site was selected to minimize the damage to internal organs during tag placement, based on gross anatomical examination of Striped Bass. A horizontal incision about 5 mm long was made with a hooking movement of a curved scalpel blade. The incision was made through the musculature but not deep enough to damage the intestines. The anchor of the tag was inserted through the incision and set with a gentle pull on the streamer. Scalpel blades were changed frequently to avoid tearing of the tissue and all incisions were treated with a merbromin-based topical antiseptic.

Scale samples were taken from the left side of each Striped Bass approximately 3-4 scale rows below the notch between the spinous and soft dorsal fins, except for fish <100 mm TL. Fish <100 mm TL were considered Age 0+. Scale samples from recaptured, tagged fish were taken from the right side of the fish to avoid regenerated scales from the recaptured fish. Scale samples were taken from recaptured fish only if the tag number indicated the fish had been released in previous programs. Condition of the tag and tag insertion site of recaptured Striped Bass were also evaluated.

After processing, Striped Bass were released into a recovery pen (1 m wide x 2 m long x 1 m deep) deployed alongside the tagging vessel. The pen was enclosed with netting on four sides, open on the top and bottom, and provided a refuge where Striped Bass could recover from processing without being preyed on by gulls. Bird predation was estimated to remove about 2.4% of the tagged fish released during the 1990-1991 SBSE, so a recovery pen is used to reduce this source of mortality at release. Any fish remaining in the recovery pen at the end of sample processing were considered dead, and these dead fish were taken to the lab for autopsy to determine biocharacteristics and food habits along with any other fish that died during sampling and fish suspected of having a tag wound

During each trawl sample, the GPS position at the start of the tow (after 2000), direction of tow, time of tow, date, and sample number were recorded. A Yellow Springs Instruments (YSI) salinity-conductivity-temperature meter was used to measure surface (0.3 m) and bottom water temperature and conductivity at the end of each tow. All conductivity measurements were adjusted to 25ºC (specific conductance).

2.3.5.2 Laboratory Methods

Biocharacteristics and Food Habits

Striped Bass biocharacteristics were examined from fish that died during sample collection and processing. This non-random, opportunistic sampling approach may bias the results if fish that died during capture were less fit or otherwise had an unequal chance of death from capture than those that survived. The biocharacteristics presented in this report include length, sex, and sexual condition (maturity). The SBSEs take place during early-November to mid-April, and sampled many sub-adult fish that use the Battery and upper New York Harbor areas of the lower Hudson River as overwintering grounds (Waldman 2006). Therefore, most of the Striped Bass captured in the SBSEs and examined were sub-adults (ages 0+ to 2+; <500 mm TL), and biocharacteristics results reflected this composition

Striped Bass were processed in fresh condition on the day of collection whenever possible. If they could not be processed while fresh they were refrigerated and worked up within 24 hours of collection. If laboratory schedules indicated the fish would be held more than 24 hours, fish were placed in a freezer the day they arrived.

Striped Bass were uniquely identified with a sample number and fish identification number, and individually processed sequentially so that (1) each length measurement was associated with the weight and sex of the same specimen, and (2) quality control determination could be made on an individual specimen basis. Each uniquely identified Striped Bass was processed in the following manner:

Maximum TL was measured to the nearest millimeter. The length of the fish in fresh condition as recorded on the field data sheet was considered the correct length unless large discrepancies were noted. These field (and laboratory) length measurements were subjected to a 10% average outgoing quality limit (AOQL) inspection plan with a ±3% tolerance.

Wet weight of fish <500 g was determined to the nearest 0.1 g, and fish ≥500 g to the nearest 1 g. (Weight was taken at the time of processing but before dissection began.)

A longitudinal abdominal incision was made from vent to isthmus passing through the axillary process of the pelvic girdle.

Sex and sexual condition were determined by examination of the gonads (Figure 2-15) using the criteria in Table 2-12.

The stomach contents of dead or badly injured Striped Bass (if available) were examined to determine the absence or presence of vertebrates and invertebrates. When vertebrates were present, the laboratory determined if they were fish, and, if so, whether they were Atlantic Tomcod. Also available were Striped Bass brought back to the laboratory suspected of having a tag wound. If more than ten Striped Bass were brought to the laboratory from a single day's catch, a random subsample of ten was selected for stomach contents analysis. Additionally, stomach contents were analyzed on all dead Striped Bass ≤ 750 mm TL. The number of Striped Bass examined for food habits in the laboratory decreased over time as sampling methods and handling techniques improved and fewer fish were injured or killed. Accordingly, subsampling of Striped Bass for stomach contents analysis has not been necessary in recent years due to smaller catches and improved handling techniques.

Table 2-12 Criteria used to determine sex and state of maturity of Striped Bass.*

State of Maturity	Code	Females	Males
Gravid or milting (ripe)	1	Ovaries full of yellowish granular eggs that are partially translucent. Eggs can be released when ovary is compressed.	Testes white, less firm in texture, and if compressed will readily milt.
Ripe and running	2	Adult prepared to spawn immediately; expulsion of eggs with little provocation.	Adult prepared to spawn immediately; expulsion of milt with little provocation.
Partially spent	3	Ovaries somewhat flaccid and convoluted, with a variable number of eggs left. Ovarian membrane somewhat vascular.	Testes whitish, somewhat flaccid and convoluted, with free flow of milt.

State of Maturity	Code	Females	Males
Spent	4	Ovaries flaccid, few translucent eggs left. Ovarian membrane very vascular or sac-like.	Testes brownish white, flaccid, convoluted, with no flow of milt upon compression.
Immature	5	Ovaries very small and string-like, thicker than testes, somewhat opaque and gelatinous in appearance.	Testes very small and string-like, thinner than ovaries, somewhat translucent, and extremely tender.
Not gravid or not milting (Resting)	6	Underdeveloped ovaries in an adult female. Ovaries larger, more firm, opaque, and relatively thick. No eggs discernible to naked eye.	Underdeveloped testes in an adult male. Testes larger, more firm, opaque, but still tender.
Semi-gravid semi-milting (developing)	7	Sub-ripe females heading into spawning season. Ovaries considerably larger, yellow, granular in consistency. Eggs discernible to naked eye, but not readily released when ovary is compressed.	Sub-ripe males heading or into spawning season. Testes considerably larger, white, firm in texture, but milt not running.

*From Con Edison Data Dictionary

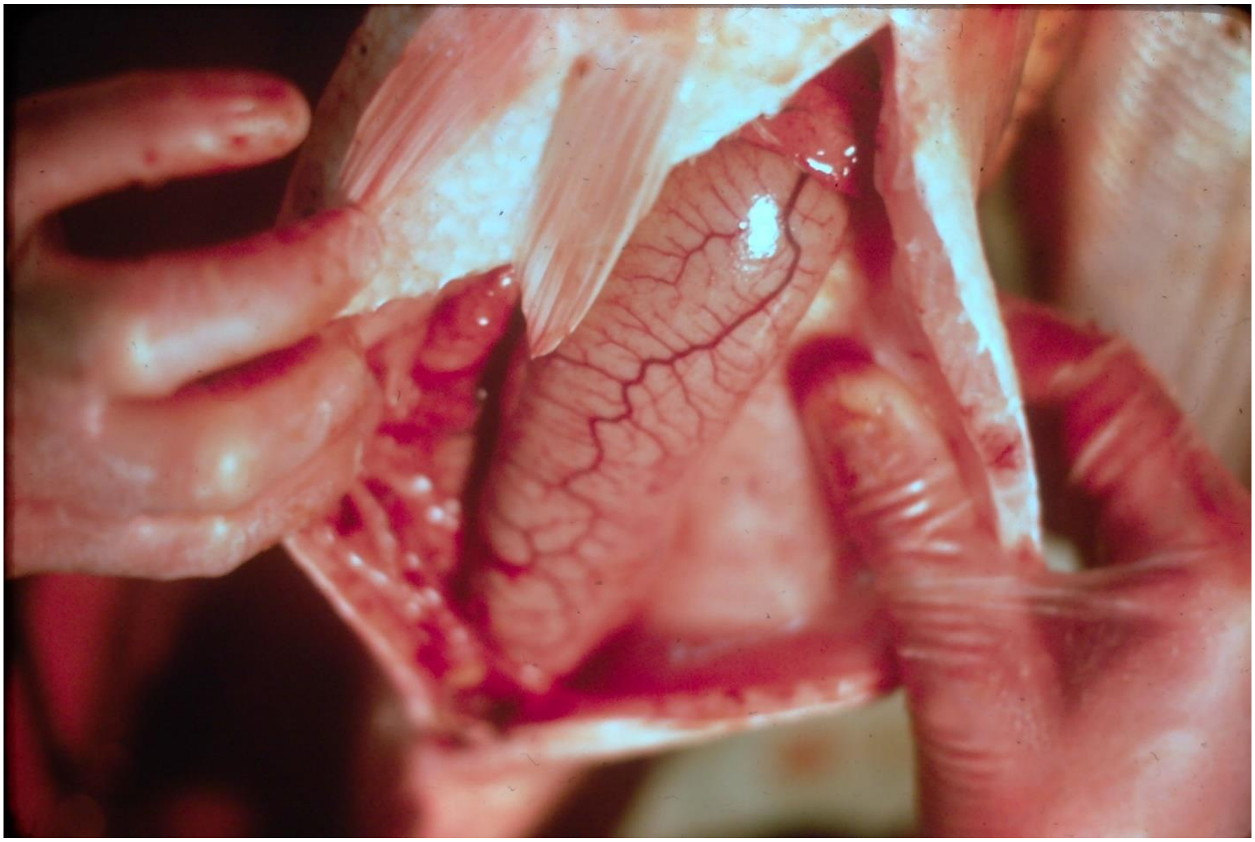


Figure 2-15 Striped Bass ovary

The following steps were followed to prepare each Striped Bass for stomach contents analysis.

- An abdominal incision was made in the fish from the vent to the isthmus.
- A transverse cut was made on the left side of the fish through the isthmus and behind the pharyngeal arch to expose a side view of the viscera.
- The esophagus was cut anteriorly and the entire digestive tract was removed, separating and discarding unwanted visceral organs. The intestinal tract was cut away just posterior to the stomach.
- Stomach contents were exposed by making an incision from the esophagus through the stomach cavity, being careful to avoid cutting food material in the stomach.
- Food material was removed into a dissecting pan or petri dish by rinsing or with forceps.
- Stomach contents were examined and the presence or absence of vertebrates and invertebrates was recorded. If vertebrates were present, the laboratory determined whether or not the remains were fish and, if so, if they were Atlantic Tomcod. Vertebrae remains were compared against prepared Atlantic Tomcod skeletal specimens noting vertebral counts, characteristics of the neural and haemal spines of the vertebrae, undamaged fin rays, jaw structures, gill arch counts, or other vestigial remains.

Identification of invertebrate and fish remains other than Atlantic Tomcod was made when possible.

Age and Growth

Age was determined for a stratified random sample of Striped Bass using scales collected from the fish in the field. All Striped Bass less than 100 mm TL were considered Age 0+ and scale samples were not taken. The stratified random subsample is based on the expected number of Age 1+ Striped Bass in each 10 mm length group. Expected numbers of Age 1+ Striped Bass in each 10 mm length group were calculated from age at length data obtained during the current and previous SBSEs.

The SBSE is conducted annually during the winter, overlapping two calendar years. To eliminate confusion that may be caused by a fish entering a new age class on 1 January part way through the November-April sampling season, the hatching date of Striped Bass is assumed to be 15 May. To note this, the convention of adding a "+" after the age of a fish is used. Therefore, for example, a Striped Bass hatched 15 May 1998 and collected in the SBSE from November 1999 through April 2000 would be designated "Age 1+." This same fish, captured from November 2000 through April 2001, would be designated "Age 2+." Therefore, the “+” associated with each age class represents approximately 0.5 years of age between the hatching date and the first capture date.

Striped Bass scales were pressed on 0.050-inch thick, grade GC acetate sheets with a Carver Press Model-C 12-ton hydraulic press equipped with a pressure gauge, electric hot plates, temperature controls, and thermometers. Scale impressions were then examined with a microfiche reader at approximately 46x magnification and the location of each annulus was determined. Criteria used to determine the presence of annuli on Striped Bass scales were (1) changes in the relative spacing of circuli in the anterior field of the scale, (2) crossing of circuli across previously deposited circuli in the lateral field of the scale, and (3) variations in the thickness and shape of the circuli. Generally an annulus exhibited all three of the above characteristics. The distance from the scale focus to each annulus was measured along a line drawn through the focus and perpendicular to the anterior edge of each scale.

Key Contractors: NAI, CES

Representative Publications: NAI 2016b, Dunning et al. 1990, Mattson et al. 1990a,b, Dunning et al. 1987, 1997

2.3.6 Water Quality Survey (WQS)

From the early years of the LRS, FJS, and BSS, water quality parameters (temperature, dissolved oxygen, conductivity, pH) were measured with each sample collected with a YSI water quality instruments. Turbidity was measured in water samples returned to the laboratory. After 1981, pH and turbidity were no longer measured. In 1983, the design of the water quality program was changed to a fixed station spaced approximately every 3 miles over the length of the river from RM 14 to RM 142. In 1996, the WQS was extended south to RM 1. Measurements of temperature, dissolved oxygen, and conductivity were taken once weekly in the channel at surface, mid-depth, and bottom at each station. When stations were adjacent to shoal areas, measurements were also taken in the shoal at surface and bottom.

Key Contractors: TI, NAI

Representative Publications: Cooper et al. 1988

2.3.7 White Perch Stock Assessment (WPSA)

The White Perch Stock Assessment study began in 1971 as part of initial near-field studies conducted for the Bowline Point facility. Standardized methods were used to sample White Perch in Haverstraw Bay region using a 9-m bottom trawl. Samples of White Perch were analyzed for biological characteristics (length, weight, age, sex). The program was expanded in 1978 to include sampling in the Tappan Zee region, and from 1983 through 1987 to sample between Piermont (RM 26) and Catskill (RM 107). The program was discontinued after 1987.

Key contractors: LMS, NAI

Representative Publications: LMS 1988, Wells et al. 1992.

2.4 PRE-HRSA COMPONENTS THAT WERE DISCONTINUED

2.4.1 Synoptic Subpopulation Study (SSS)

Phase I (1974) of the Synoptic Subpopulation Study involved sampling the Striped Bass spawning stock from the major Atlantic coast spawning grounds (Hudson, Chesapeake, Roanoke). Captured fish were examined for many morphometric and meristic characteristics, and blood samples were taken for electrophoretic analysis. Data for this study were used to develop a set of characteristics that could discriminate among the various spawning stocks.

Phase II of the study, in 1975, involved sampling fish captured in the Hudson and Chesapeake estuaries, and from the ocean, and applying the results of Phase I to estimate the relative contribution of the various stocks to the coastal fishery.

Key contractors: TI

Representative Publications: TI 1976, Grove et al 1976; Berggren & Lieberman1978

2.4.2 Interregional Trawl Survey (IRTS)

The Interregional Bottom Trawl Survey provided data on the relative abundances, distributions, and population characteristics of juvenile and older (primarily yearling) fishes inhabiting the bottom strata of the river. This survey also served as the deep-water, offshore recapture effort for marked fish. During alternate weeks from April through November, 38 fixed stations in the Tappan Zee through Poughkeepsie regions, RM 28 through Rm 75, were sampled with an otter-type bottom trawl (25 ft head rope) that had a fine mesh cod-end cover.

Catches were sorted by species and length class as for standard stations. Catches are typically analyzed at time of collection and fish are released. All species are identified, separated into the four standard length groups, and counted. Some samples were returned for laboratory analysis when required to fill quotas for more detailed analysis. A detailed description of the program and laboratory analysis is provided in Biocharacteristics section.

Key contractors: TI

Representative Publications: TI 1980b

2.4.3 Mark-recapture (M/R)

The objectives of the Mark-Recapture Program were 1) to estimate population sizes and 2) to determine movements of juvenile and yearling Striped Bass, juvenile, yearling and adult White Perch, as well as adult Atlantic Tomcod (as described in ATSA section). To accomplish these objectives, 100-ft, 200-ft, and 500-ft beach seines, box traps, and epibenthic sleds were used to collect the target fish for marking. Striped Bass and White Perch, usually juvenile and yearlings, were collected with beach seines and box traps and marked. The fish were marked and released throughout the study area. Marking of Striped Bass and White Perch was done during spring (April-June) and fall (September-November).

Two fins per fish (one medial fin and one paired fin) of juvenile Striped Bass and White Perch were clipped during the fall. Yearlings were finclipped during spring and tagged during the fall. Finclip combinations were specific to month, and marking region, which were combinations of the standard river regions. Tags, either a Floy fingerling tag or a nylon internal anchor tag (Figure 14) were applied to yearling and older fish according to the size of the fish. Striped Bass Age II and older, and Age II and older White Perch were tagged during both spring and fall. In 1979, Age II and older White Perch were tagged with vinyl stream tags (Figure 2-16).

Key contractors: TI

Representative Publications: TI 1979

Figure 2-16 Internal anchor tag being applied to a White Perch during the Mark-Recapture program in the 1970s.

2.4.4 Striped Bass Adult Stock Assessment (SBSA)

A comprehensive field and laboratory study of adult Striped Bass (≥ 200 mm TL) was conducted from mid-March through June (1976–1980) to determine the structure of the Hudson River spawning population, mortality rates, movements, and biological characteristics. Since the commercial fishery for Striped Bass in the Hudson River was closed in early 1976, age and size composition of the commercial catch were estimated by contracting commercial fishermen to fish in their usual manner and provide Striped Bass catches (Figure 2-17). Additional sampling was conducted with gill nets and a 900-ft haul seine. In addition, tag returns (rewards of $5 and $10 on approximately 10% of the tags) from sport and commercial fishermen provided information on movements and exploitation rates.

Figure 2-17 Commercial fisherman removing Atlantic Sturgeon from gill net during SBSA program in the 1970s.

Sampling effort was concentrated in the vicinity of the Tappan Zee Bridge and Croton-Haverstraw Bay early in the spawning season (March-April), upriver into and above Indian Point area as the season progressed (May), and downriver in June at the end of the spawning season. Two clusters of anchored gill nets were separated longitudinally in the river (designated north or south). Each cluster contained a minimum of four nets of different standard mesh sizes (4, 5, 6, and 7 in. stretch multifilament) and usually from one to four additional nets. A 900-ft haul seine, which is less size selective, was used to sample beaches primarily in Haverstraw Bay (RM 33-39).

All Striped Bass were measured and scale samples removed. Live fish that were in good condition and not needed for measurement of biological characteristics in the laboratory were tagged and released. Dead and dying fish were taken to the laboratory for processing. Striped Bass were examined in the laboratory to determine sex ratio, fecundity, age at maturity, diet, and age composition.

Key contractors: TI

Representative Publications: TI 1979, Hoff et al. 1988, Gardinier and Hoff 1982

2.4.5 Striped Bass Culture

As a condition of the FERC license for the Cornwall facility, Con Edison engaged in a program to assess the feasibility of culturing and stocking Striped Bass as a mitigative measure for potential entrainment losses. The program began in 1973 when 22 adult female Striped Bass were artificially spawned, 4.8 million larvae were shipped to Oklahoma for rearing in ponds, 10,700 fingerlings were shipped back to NY, and 427 fingerlings were stocked in the estuary. From 1974 through 1978 the program continued to refine spawning techniques, provide eggs and larvae for experimental studies related to entrainment, and evaluate culture techniques and post-stocking survival.

Figure 2-18 Tanks used for Striped Bass rearing during the culture studies in the 1970s

The success of the culture program in the 1970s (Figure 2-18) led to a 10-year hatchery rearing and stocking requirement in the 1981 HRSA. The Verplank laboratory used by TI as a base for the HRBMP was converted to an intensive culture facility, with a design capability of 600,000 3-in fingerlings per year. EA was contracted to design, construct, and operate the facility, and initial production occurred in 1983. Brood stock were collected from the Hudson River and manually stripped of eggs and milt (Figure 2-19). Hatching occurred in MacDonald jars, and larvae were stocked in circular culture tanks. Upon reaching approximately 3 inches in length, fish were marked and prepared for stocking. All of the fish stocked into the river were marked with a magnetic wire tag so that they could be identified if captured later so that survival, growth, and movements could be evaluated.

The facility was the largest intensive culture Striped Bass hatchery at the time. Although the flooded quarry on the hatchery site seemed an ideal water source, the initial years of the effort were plagued by die-off of larvae at about 30 days after hatch, which were attributed to low salinity of the water source, and deficiency of the food source. These issues were solved in the later years of the program as production of stocked fish approached the 600,000 fish goal (Table 2-13).

Table 2-13 Number of Striped Bass fingerlings stocked into the estuary during the post-HRSA hatchery effort.

Year	Number Stocked
1983	61,357
1984	147,153
1985	284,578
1986	529,563
1987	324,800
1988	48,611
1989	202,068
1990	234,387
1991	256,631
1992	210,746
1993	568,410
1994	306,529
1995	613,758
Total	3,788,591

Figure 2-19 Hatchery technicians stripping eggs from ripe female Striped Bass.

2.4.6 Indian Point Plant-Specific Studies

Studies conducted at the individual generating facilities were contracted by the company that owned/managed the facility. Studies conducted at Indian Point (Table 2-14) were contracted through Con Ed or NYPA, and thereby ownership of data and documents was transferred to Entergy upon purchase of the Indian Point units. The methods (and findings) of these studies were published in annual reports for each component, and are not provided in this document. There were also thermal discharge studies, including physical models, thermal surveys of the plume, and hydrodynamic modeling, conducted for Indian Point that did not directly involve biological components. These thermal-related studies are not described further.

Table 2-14 Indian Point Components of Hudson River Biological Monitoring Program 1971-2018.

Component	Years	Description
Nearfield Phytoplankton / zooplankton / ichthyoplankton	1971-1979	Abundance and distribution of planktonic organisms in the vicinity of Indian Point
Nearfield Fish (IPSS)	1974-1980	Abundance, distribution, and life history characteristics of fishes
Impingement Abundance/Survival/Mitigation	1972-1990	Impingement of fishes, survival rates, and efficacy of various technology alternatives
Entrainment Abundance	1973-1987	Entrainment of selected zooplankton and of fishes
Entrainment Survival	1973-1980, 1985,1988	Survival rates of entrained zooplankton and fishes
Entrainment Mitigation	2010-2011	Effectiveness of wedgewire screens to reduce entrainment
Thermal Discharges	1970s	Description and prediction of thermal discharge plumes

Plant-specific studies were also conducted at the other Hudson River facilities, but Entergy does not have ownership of data and documents and therefore cannot provide either, even though these programs fit under the broad classification of HRBMP. None of the plant-specific studies were used in preparing the Selected Findings in Section III.

2.4.6.1 Near-field Plankton Studies

Information on the seasonal and spatial distribution of entrainable phytoplankton, microzooplankton, macrozoplankton (focus on *Neomysis americana*, *Monoculodes edwardsi*, *Gammarus* sp., and *Chaoborus punctipennis*) ichthyoplankton and zooplankton in the near-field vicinity of Indian Point was collected from 1971 through 1979. Sampling was conducted at fixed stations at regular biweekly intervals from spring through fall months. Zooplankton and ichthyoplankton samples were collected with 0.5 m plankton nets.

The studies were done concurrently with sampling to estimate entrainment abundance and survival, and included physiological components to aid understanding of entrainment stresses. NYU conducted the studies from 1971-1977, while EA conducted the 1978-1979 studies and produced the reports for the 1977-1979 programs.

Key Contractors: NYU, EA

Representative Publications: NYU 1976, EA 1981

2.4.6.2 Near-field Fish Studies – (Indian Point Standard Stations – IPSS)

Study of juvenile and older fish in the vicinity of Indian Point initially began in 1969, but a more intensive program was initiated in 1972 and became known as the Indian Point Standard Stations Program (IPSS). Sampling involved 14 fixed stations between RM 29 and 43. Beginning in April and continuing through December, seven shore zone stations were sampled weekly with a 100-ft beach seine, and seven trawl stations were sampled biweekly using a bottom trawl (26-ft headrope). From July through December, each trawl site was also sampled weekly with a surface trawl. The entire catch from each sample was returned to the laboratory for evaluation of biological characteristics (age, fecundity, sex, maturity, diet, length, and weight). The laboratory analysis of biological characteristics was expanded to include fish captured in other sampling efforts, e.g. Interregional Trawl Survey and Mark-Recapture.

Key Contractors: TI

Representative Publications: TI 1980a

2.4.6.3 Impingement

The impingement sampling program at Indian Point began in 1972 and continued through 1990. Fish and blue crabs washed off the intake screens were counted and identified on each day the circulating pumps were operated from 1973-1980 (Figure 2-20), and according to a stratified design on approximately 110 days per year from 1981 through 1990. Ancillary studies were conducted to assess collection efficiency, survival of impinged organisms, and effectiveness of various mitigation technologies, including pneumatic poppers, air bubble curtains, lights, and sonic systems. After the modified Ristroph screens and fish return systems were installed and operational, the sampling program was discontinued.

Key Contractors: TI, NAI

Representative Publications: TI 1977, Mattson et al. 1988

2.4.6.4 Entrainment Abundance

Entrainment abundance sampling to estimate the number of organisms entrained began at Indian Point in 1971 and continued annually through 1987 (except 1982). Sampling in the 1970s was done with plankton nets placed in the plant intakes. In the 1980s abundance sampling was done in the discharge canal where velocity and turbulence were high to promote random sampling of the water and minimize avoidance. Laboratory analysis of the samples included identification of fish species and, during the 1970s, selected groups of micro and macrozooplankton.

In 1980 and 1981, continuous, except for short sample washdown periods, sampling covering a 24-hr period was conducted once (1980) or twice (1981) per week with an automated pump sampling system. From 1983-1987, samples covering a 24-hr period were taken daily from early May through early August. Replicate samples were collected to evaluate sampling variability, and other special studies were conducted in some years. Samples were analyzed in the laboratory where all ichthyoplankton were identified to species (or lowest possible taxon) and counted.

Key Contractors: NYU, EA, NAI

Representative publications: NYU 1976, NAI 1989

Figure 2-20 Technicians sorting impinged fish from debris at Indian Point in the 1970s.

2.4.6.5 Entrainment Survival

Entrainment survival studies at Indian Point began in 1973 using conical plankton nets in the intake and discharge. Additional studies were conducted to test specific stress components using pressure chambers and cooling system simulators. Actual through-plant survival was examined through 1979 by NYU using conical plankton nets for sampling, and by EA from 1977 through 1980, and again in 1985 and 1988. The earlier EA studies employed a pump-fed flume system to equalize sampling stress in the intake (control) and discharge samples, and studies in 1979 and later employed systems that did not pass organisms through sampling pumps.

Key Contractors: NYU, EA

Representative publications: NYU 1976, Poje et al. 1978, EA 1989, Young et al. 2009

2.4.6.6 Entrainment Mitigation

During 2010 and 2011, intensive laboratory and field studies were conducted to evaluate the potential for cylindrical wedgewire screens to reduce entrainment at the Indian Point Energy Center. During 2010, laboratory flume studies were conducted to evaluate effect of screen slot width, through-screen velocity, sweeping velocity, species, and size on the ability of fish larvae and eggs to escape entrainment, through avoidance capabilities, exclusion at the screen surface, or hydraulic bypass. Additional laboratory studies were conducted in 2011, as well as an in-situ comparison of entrainment through an open intake and through a 2-mm slot width screen, with a control measure of ambient ichthyoplankton density provided by a 1-m2 Tucker trawl.

Key Contractors: NAI, ASA

Representative publications: NAI & ASA 2011a, NAI & ASA 2011b, ASA & NAI 2012.

2.4.6.7 Other Studies

In addition to the plant-related and in-river studies, there were additional studies that were conducted to provide information important to all the facilities. One such program was an experimental study to describe thermal tolerances of larval fishes that are subject to entrainment at the Hudson River facilities. Other studies addressed specific issues associated with understanding of power plant impacts.

Key Contractors: Ichthyological Associates (IA), Ecological Analysts (EA), University of Rhode Island (URI), Applied Biomathematics (AB), Alden Research Laboratory (ARL)

Representative publications:

Tatham, T. R. 1970. Swimming speed of White Perch, *Morone americana*, Striped Bass, *Morone saxatilis*, and other estuarine fishes. Final Report on Summer Studies Using the MacLeod Apparatus. For Consolidated Edison Company of New York, Inc.

Meldrim, J. W. and J. J. Gift. 1970. An experimental study of temperature preference and avoidance of White Perch. For Consolidated Edison Company of New York, Inc.

Meldrim, J. W., J. J. Gift, L. R. King, and T. R. Tatham. 1970. Progress reports on temperature preference and avoidance, and of swimming speed of the White Perch and other fishes. For Consolidated Edison Company of New York, Inc.

Applied Research Group of URI. 1976. Life stage duration studies on Hudson River Striped Bass, *Morone saxatilis* (Walbaum). For Consolidated Edison Company of New York, Inc.

Ecological Analysts. 1978. Hudson River Thermal Effects Studies for Representative Species Final Report. Prepared for Central Hudson Gas & Electric Corporation, Consolidated Edison Company of New York, Inc., Orange & Rockland Utilities, Inc.

Ecological Analysts. 1979. Effects of heat shock on predation of Striped Bass larvae by yearling White Perch. Prepared for Central Hudson Gas & Electric Corporation, Consolidated Edison Company of New York, Inc., Orange & Rockland Utilities, Inc., and Power Authority of the State of New York.

Applied Biomathematics. 1983. Relative sensitivity of Hudson River Striped Bass to competing sources of mortality and the implications for monitoring.

Cassella, G., D. S. Robson, S. J. Schwager, and W. D. Youngs. 1986. Evaluation of Entrainment Abundance Sampling Designs. For Consolidated Edison Company of New York, Inc.

NAI. 1990. Responses of young-of-the-year White Perch and Striped Bass, and adult Atlantic Tomcod in an enclosure to underwater sounds generated by an electronic fish startle system. Prepared for New York Power Authority.

Applied Biomathematics. 1992. Ecological risk analysis of Hudson River fish populations. Phase I Final Report. Prepared for New York Power Authority.

Schreibman, M. P. and J. R. Young. 2002. Physiology investigations of the Atlantic Tomcod. Prepared for Central Hudson Gas & Electric Corporation, Consolidated Edison Company of New York, Inc., Orange & Rockland Utilities, Inc., and Power Authority of the State of New York, Dynegy Northeast Generation, Entergy Nuclear Indian Point 2, LLC., Entergy Nuclear Indian Point 3, LLC., Mirant Bowline, LLC.

2.5 CALCULATION OF DENSITIES, STANDING CROPS, AND ABUNDANCE INDICES

Standardized calculations for weekly regional densities for LRS, FJS, and BSS programs are provided in Appendix 2, section 2.5.

3. SUMMARY OF SELECTED FINDINGS OF THE HRBMP

The scope and duration of the Hudson River Biological Monitoring Program (HRBMP) provides many opportunities for addressing scientific questions concerning the status of fish populations and communities in the Hudson River, and the relationships of these populations and communities to key environmental and biotic factors. Many of the potential research topics fall well outside the range of issues addressed during the litigation-driven assessment studies discussed in Section I. Appendices 3 through 11 to this report provide detailed accounts of a small subset of the possible research studies that can be performed using HRBMP data. This section provides a brief summary of the findings documented in those appendices.

3.1 TRENDS IN WATER QUALITY METRICS

Data on three key water quality parameters, temperature, dissolved oxygen, and salinity, were collected throughout the duration of the HRBMP. However, there were several significant changes to the monitoring protocol over that time period. For example, from 1974 through1981 a sample was taken at the depth associated with each LRS and FJS tow sample. From 1982 through 2017, water quality sampling was disassociated from the stratified random sampling design of the LRS and FJS. Instead, measurements were taken from surface, mid-water, and bottom depths at 65 fixed stations located at approximately three-mile intervals from the George Washington Bridge (lower end of region 1) to the Federal Dam (upper end of region 12). This survey is termed the Water Quality Survey (WQS). Surface measurements were taken with each BSS haul throughout the duration of this survey, from 1974 through 2017. Water quality monitoring in region 0 did not begin until 1995.

This exploratory analysis of water quality data examined long-term riverwide trends in temperature, DO, and salinity, including regional and seasonal trends relevant to describing fish habitat characteristics during peak seasonal abundance. To reflect potential influences of program changes and to focus on specific regions and seasons, 12 different time series were extracted from the water quality dataset (Table 3-1).

In addition to quantifying long-term trends and spatial patterns in these water quality parameters, the analysis tested for correlations with the North Atlantic Oscillation index and annual freshwater discharge, and for evidence of cyclical patterns in water quality. To minimize the influence of program changes, these analyses utilized data derived from the WQS and BSS (time series 3-12).

3.1.1 Temperature

The year-to-year variability and magnitude of annual mean water temperature differed depending on the sampling design and time period selected. A statistically significant, but weak, linear increasing trend at a rate of 0.3° C per decade was observed in time series 3 (the standardized 1982-2017 riverwide WQS survey time series for weeks 19 through 27). Similar increases were observed in time series 7-9 (the region 1-12, 1988-2017 surface, bottom and depth-averaged time series for weeks 18 through 36), and in the corresponding region 1-7 time series for the same period (time series 10-12). No trend was present in the BSS shorezone data (time series 4 and 6). Time series 8, 9, 11, and 12 were negatively correlated with the NAO index, but not with river discharge. There was no significant signal of periodicity in any time series.

Table 3-1 Description of time series data of water quality measurements selected from the Hudson River Biological Monitoring Program.

Time Series	Years	Weeks (Months)	Regions	Survey(s)	Comments
1	1974–2017	8–50 (mid-Feb – Dec)	All (Battery – Albany)	LRS, FJS, WQS	• Not standardized in time and space
2	1974–2017	19–27 (mid-May – Jul)	Excludes Battery (Yonkers – Albany)	LRS, FJS, WQS	• Not standardized in space
3	1982–2017	19–27 (mid-May – Jul)	Excludes Battery (Yonkers – Albany)	WQS	• Standardized, fixed stations
4	1987–2017	24–42 (mid-Jun – mid-Oct)	Yonkers – Albany	BSS	• Shore zone • Period of weeks with similar effort • Same weeks not sampled every year
5	1988–2017	30–33 (late-Jul – mid-Aug)	Excludes Battery (Yonkers – Albany)	WQS	• Standardized, fixed stations; • Period with warmest average four weeks
6	1989–2017	30–33 (late-Jul – mid-Aug)	Yonkers – Albany	BSS	• Shore zone • Period with warmest average four weeks
7	1988–2017	18–36 (May – early-Sep)	All (Battery – Albany)	WQS	• Standardized, fixed stations; • Broadest season with similar effort • Battery excluded for temporal tends
8	1988–2017	18–36 (May – early-Sep)	All (Battery – Albany)	WQS	• Bottom measurements • Standardized, fixed stations; • Broadest season with similar effort • Battery excluded for temporal tends
9	1988–2017	18–36 (May – early-Sep)	All (Battery – Albany)	WQS	• Surface measurements • Standardized, fixed stations; • Broadest season with similar effort • Battery excluded for temporal tends
10	1988–2017	18–36 (May – early-Sep)	Yonkers to Poughkeepsie	WQS	• Standardized, fixed stations; • Broadest season with similar effort
11	1988–2017	18–36 (May – early-Sep)	Yonkers to Poughkeepsie	WQS	• Bottom measurements • Standardized, fixed stations; • Broadest season with similar effort
12	1988–2017	18–36 (May – early-Sep)	Yonkers to Poughkeepsie	WQS	• Surface measurements • Standardized, fixed stations; • Broadest season with similar effort

3.1.2 Dissolved Oxygen

Statistically significant long-term declines in DO were observed in all of the time series that were truncated to remove sampling inconsistencies (time series 3-12) (Figure 3-1). The trend was strongest in the shore zone data derived from BSS sampling (time series 4 and 6). The slope from linear regression of annual mean DO in the shore zone indicated an average decline of 0.67 mg/L per decade. The same trends were observed when the measured values were expressed as percent saturation to account for the effects of temperature on DO concentration.

DO was positively correlated with the NAO index in time series 3,4, and 8-12 but percent saturation was significantly correlated with the NAO index only in time series 9. Percent saturation was negatively correlated with river discharge in surveys 4, 9, and 12, but DO was not correlated with river discharge in any survey. Evidence for periodicity of DO was found in 6 of the 8 surveys examined, and evidence for periodicity of % saturation was found in 7 of 8 surveys.

3.1.3 Salinity

When measurements taken in region 0 (sampled only beginning in 1995) were excluded, there were no long-term trends in riverwide salinity observed in any time series. The position of the transition from estuarine salinities to freshwater varied from year to year between regions 3 and 7, but there was no long-term trend in the location of this boundary. Annual mean salinity was correlated with the NAO index in time series 3, but not in any other time series. Annual mean salinity was negatively correlated with river discharge in time series 4 and 8-12. Spectral analysis of time series 7-12 found a statistically significant periodicity with a cycle of approximately 2 years.

3.1.4 Conclusions

Sampling design clearly has a substantial influence on any analysis of trends in water quality. The surveys, years, and weeks included in any study that utilizes the HRBMP water quality data must be selected in a way that minimizes the influence of program changes on the outcome of the analysis. For the purpose of detecting long-term riverwide trends in water quality, the standard station WQS data collected beginning in 1982 provide the most consistent data set, but only over regions 1-12, however, it would be possible to extract generally comparable data from the LRS and FJS data from 1974-1981. The BSS data also provide consistent coverage over regions 1-12, but only for the shore zone. Studies of the abundance and spatial distribution of specific species require subsetting the data to focus on the weeks in which those species are present in the river. Appendix 3 provides program summary tables that can be used to identify the most appropriate surveys, regions, years, and weeks for use in any study.

One of the most obvious uses of the HRBMP water quality data is a search for evidence of long-term effects of climate change. The exploratory analyses documented in Appendix 3 identified long-term changes in temperature and DO that are worthy of further investigation. When pre-1982 data and data from region 0 are excluded, the WQS data show that the riverwide mean temperature of the river increased at a rate of approximately 0.3 °C per decade between 1982 and 2017, For purposes of comparison, monthly maximum temperatures measured at the Poughkeepsie Water Works increased by 0.15 °C over the period 1950-2016 (see Appendix 4, Figure 3). The long-term decline in DO observed over this period, especially in the shore zone, is a more surprising result and one for which we have no obvious explanation.

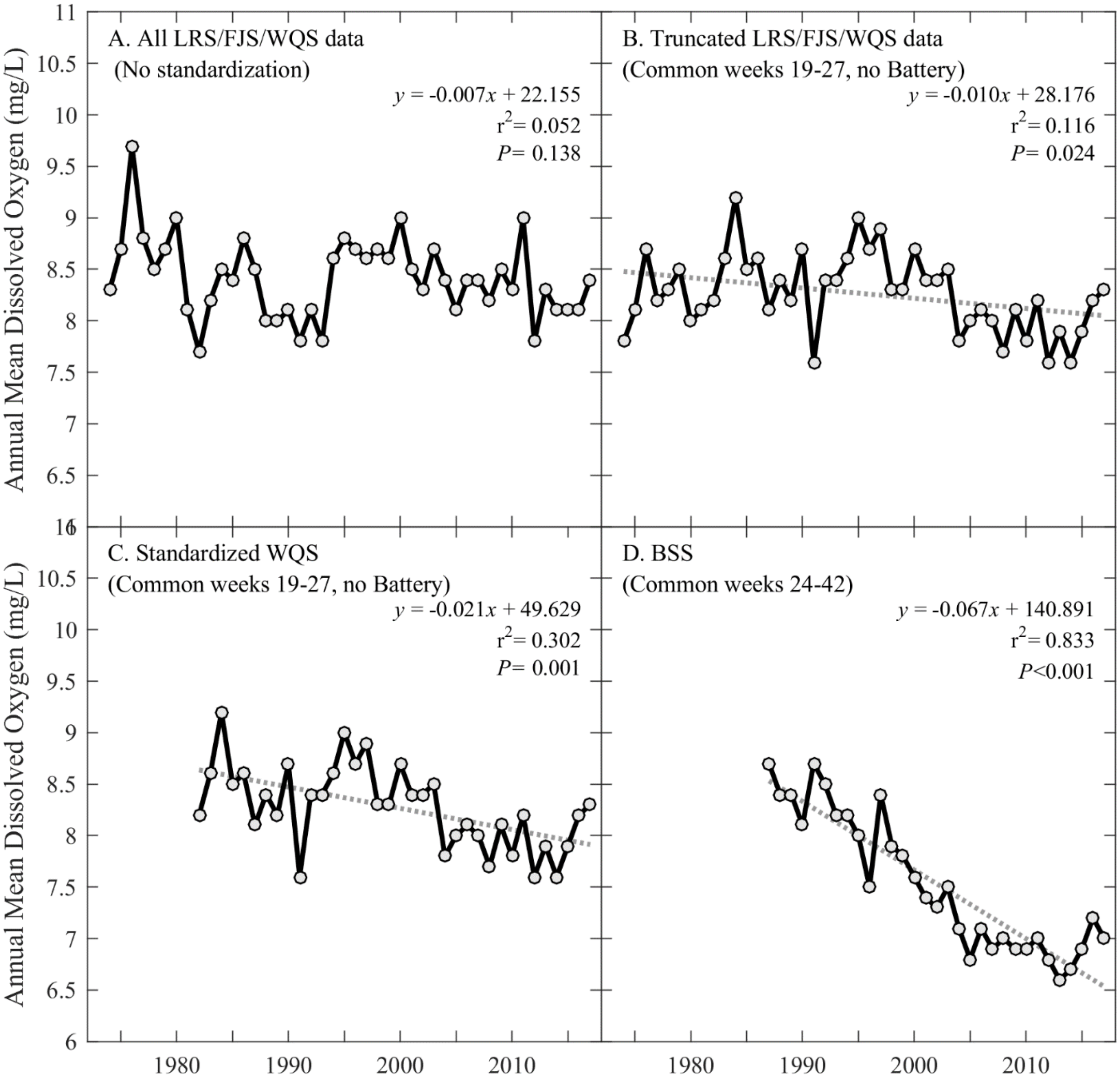


Figure 3-1 Annual mean dissolved oxygen (mg/L) in the Hudson River Estuary from 1974 through 2017. A) all measurements from LRS and FJS without regard to spatial or temporal differences in sample design; B) same as (A) except truncated for consistency in sampled weeks and regions over time; C) LRS/FJS data collected at the fixed sampling water quality stations standardized for common weeks and regions among years; D) all Beach Seine Survey data during weeks 23-42 representing a common period among the majority of years.

3.2 EFFECT OF EXTREME EVENTS ON HUDSON RIVER ECOLOGY

Appendix 3 of this report addresses long-term trends in key environmental variables that affect, the Hudson River ecosystem. Appendix 4 addresses the influence of extreme but infrequent events that force environmental conditions far outside their normal ranges. Many such events are related to major coastal storms such as nor'easters and hurricanes. The time series of sea level measurements at the Battery in New York City documents several such events between 1927 and 2017. The highest sea level on record occurred during Hurricane Sandy in 2012. Sudden increases in freshwater flows related to inland weather events as well as coastal storms are documented in discharge measurements at the Federal Dam at Green Island. High winter rainfall events or rapid warming can cause damaging releases of ice, which can carry large amounts of material from the riparian zone into the river, and also can scour the shoreline and river bottom.

Depending on when these extreme events occur, they can cause major disruptions in the life cycles of Hudson River fishes. Appendix 4 documents effects of four types of extreme events on Hudson River biota: high flow events that displace early life stages of fish from their normal habitats; rapid temperature drops during the spawning season, unusually high temperatures that cause increased mortality and reduced growth of a thermally sensitive species; and storm-related sedimentation that destroys submerged vegetation beds.

3.2.1 High Flow Events

The HRBMP data were used to demonstrate 3 examples of high flow events on the distribution and abundance of river herring, American shad, and Striped Bass larvae. One such event occurred in late May of 1984. River herring and shad spawn in the three uppermost regions of the estuary; larvae gradually disperse down river,but are not commonly found below region 7. After transformation, the YOY begin to spread to the lower estuary prior to emigration from the river during fall. Figure 3-1 of Appendix 4 depicts the spatiotemporal distribution of river herring eggs, larvae, and juveniles in 1995, which was a year with stable and low flow during the spawning season. By contrast, Figure 3-2 (reproduced here as Figure 3-2 of this summary) depicts the spatiotemporal distribution of river herring early life stages in 1984. In that year, an extreme high-flow event, measured at nearly 100,000 cfs at Green Island Dam occurred in late May, after spawning had begun. Spawning occurred normally in regions 10-12, but high flows transported the larvae rapidly down to the middle and lower estuary. By June 4, the peak of the larval river herring distribution was located in the Tappan Zee (region 2). By the end of June, all of these larvae had disappeared without any evidence they had survived to the juvenile stage. Following the end of the high flow event, a second round of spawning occurred in early June, again in regions 10-12. Larvae from this spawning event remained in the upper estuary and survived to produce a moderately successful year class. decline in DO observed over this period, especially in the shore zone, is a more surprising result and one for which we have no obvious explanation.

The same pattern was observed for American shad (Figure 3-3 of Appendix 4). Spawning occurred normally in early May in regions 9-12, but the larvae were transported downriver to the middle estuary by the end of the month. These larvae then disappeared and did not contribute to the year class. A second, smaller spawn occurred in early June in regions 10-12; larvae and juveniles from this spawn remained in the upper estuary and survived to produce a year class. A similar high flow event, illustrated by advection of Striped Bass larvae, occurred in 1990, and is depicted in Figure 3-4 of Appendix 4.

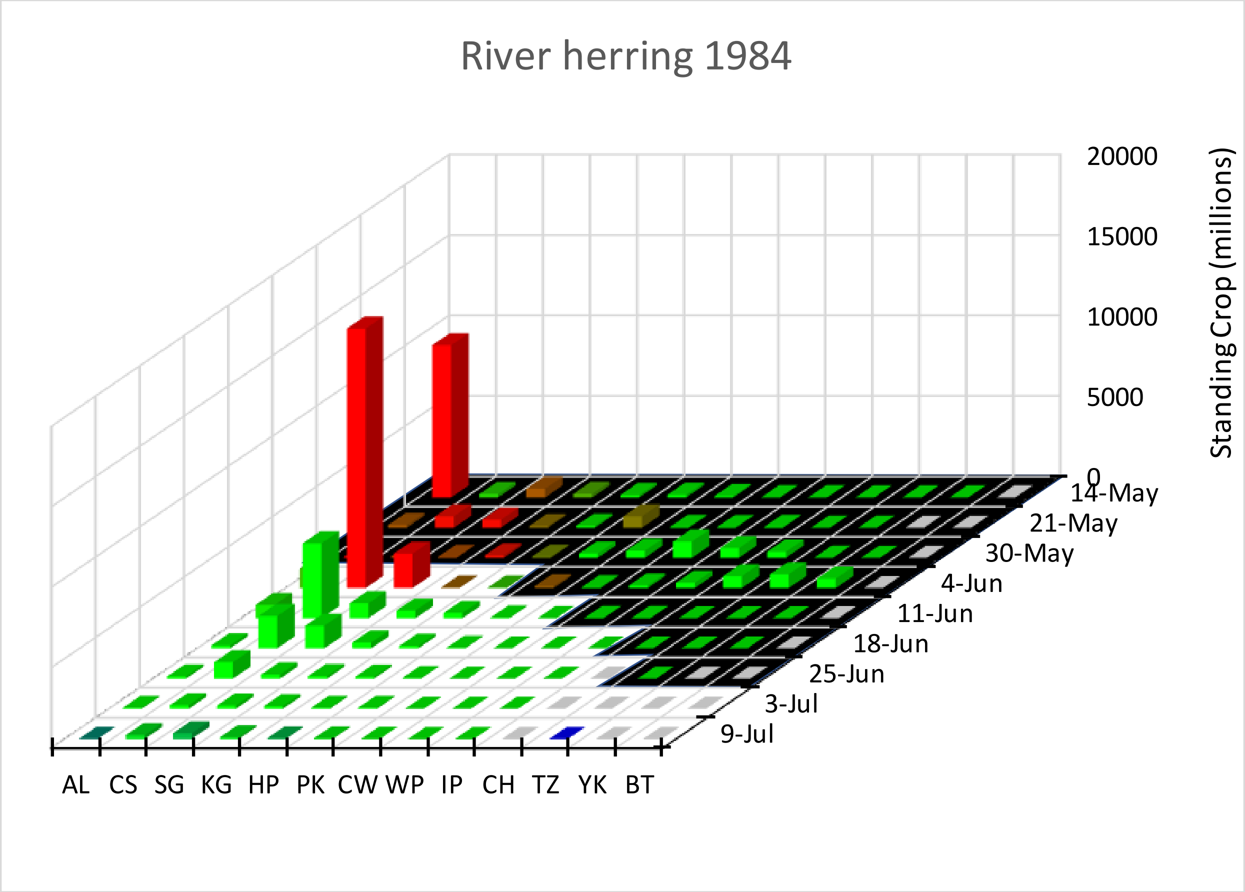


Figure 3-2 Standing crops of River Herring (*Alosa* sp.) eggs (pure red), larvae (pure green), and juveniles (pure blue) in each region and LRS survey week in 1984. Intermediate colors reflect the proportional mix of life stages. Standing crops in area with black base did not survive or contribute to the year class.

3.2.2 Rapid Drops in Temperature

Rapid drops in temperature can also affect spawning success. During May and June, typical patterns of temperature measured at Poughkeepsie exhibit a relatively smooth increase from 10-12 °C entering May, to 20-25 °C at the end of June. However, occasionally a cold weather snap will drive temperatures down by several degrees once spawning has started. Such events occurred in 1976, 1984, and 1990 (all associated with the high flows discussed above), as well as in 2000, 2002, 2004, and 2013. Dey (1981) documented the effects of the 1976 event on Striped Bass larval mortality rates. During this event, a sudden drop on temperature from 15 ° C to 12 °C caused larvae transitioning from the YSL to the PYSL stage to stop feeding and die before growing beyond 6 mm. Figure 3-6 of Appendix 4 shows the effect of a similar temperature drop in 2000. Unusually cool weather in June retarded the growth of Striped Bass larvae as compared to the warmer June, 1999. The smaller larvae would have been vulnerable to predation for a longer period, resulting in reduced survival.

3.2.3 Effects of High Flow and Rapid Temperature Decline on Resultant Year Class Strength

Although high flow and rapid temperature declines during the spawning season can have clear effects on survival of eggs and larvae present when these events occur, the effects on the resultant year class strength are not so clear. Annual YOY abundance indices derived for Striped Bass, American Shad, Alewife, and Blueback Herring from BSS sampling (See Appendix Section 2.5 for description of indices) are not uniformly low in years when these extreme events have occurred (Figure 3-7 of Appendix 4; reproduced here as Figure 3-3). The spawning phenology of all four of these species is to extend egg deposition and larval development over a prolonged period which increases the probability that some of them will encounter favorable conditions. This appears particularly effective for high flow events in that these years (1984, 1990, and 1996 indicated by open circles) produced year class strengths near or above the median in 8 of the 12 (4 species times 3 annual events examined) occurrences. The effects of rapid temperature drops appear more predictable in that 14 of the 20 (4 species times 5 annual events examined indicated by open squares) occurrences produced year class strengths well below the median level. It should also be noted that the very low flow year (1995) did not produce a particularly good year class for any of these species.

3.2.4 Extreme High River Temperatures

Extreme high temperatures can also adversely affect Hudson River fish species, especially species like Atlantic Tomcod, whose southernmost population is found in the Hudson. Thermal tolerance studies done as part of the HRBMP reported an upper lethal temperature for tomcod of 26.5 ºC (EA 1978). The years 1999 and 2000 provide a clear contrast of temperature extremes, with maximum summer Poughkeepsie temperature of 28 ºC in 1999 and only 24 ºC in 2000.

Observed bottom temperatures in 1999 reached or exceeded 27 ºC in the upper and lower regions of the estuary in early July, and by mid-July most of the estuary was above 27 ºC. FJS sampling showed that during this period the distribution of YOY Atlantic Tomcod became restricted to regions 5 (West Point) and 0 (Battery), which are typically somewhat cooler than other regions. By early August, tomcod were found only in regions 0 and 1, and in very low abundance.

The distribution of Atlantic Tomcod in the estuary were very different in 2000, when the maximum temperature at Poughkeepsie reached only 24 ° C. Bottom temperatures in 2000 never exceeded 25.3 ° C anywhere in the estuary. That year, the distribution of Tomcod remained centered in mid-estuary during July. Tomcod were found throughout the lower 11 regions of the estuary until October, when there was a movement upstream prior to spawning.

The resulting spawning populations following these two summers were 0.18 million from the 1999 summer and 2.5 million after the 2000 summer. These represent spawning populations near the lower and upper limits of observed spawning stock sizes since 1990. See Appendix 8 for detailed information on Atlantic Tomcod.

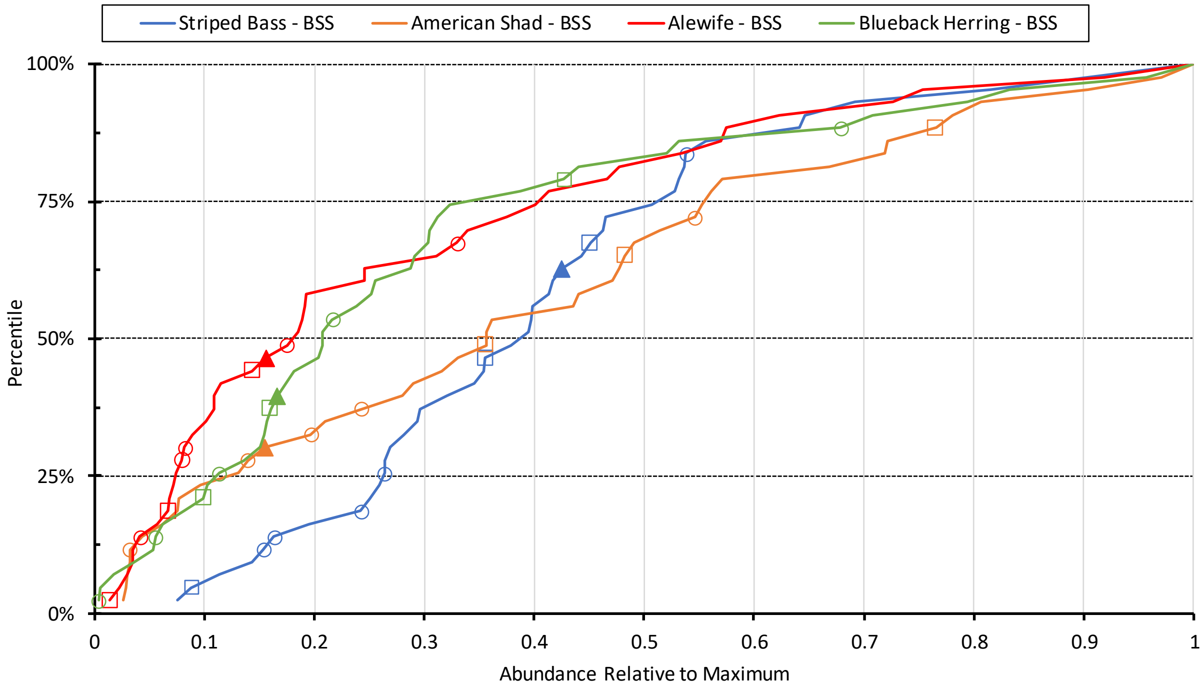


Figure 3-3 Cumulative distribution of relative year class strength for juvenile Striped Bass, American Shad, Alewife, and Blueback Herring derived from BSS sampling. Open circles indicate years with extreme high flows in May. Open squares indicate years with extreme temperature drop in May or early June. Triangle indicates 1995, a year of low and stable flow in May-June.

3.2.5 Storm-Related Habitat Destruction

Extreme events can also affect the physical habitat of the Estuary. As described above, ice flows and ice dams can scour the nearshore benthic habitat and riparian zones. While scouring of tributaries results in a great deal of organic matter being added to the Estuary, scouring in the Hudson River can displace and destroy shallow-water habitat. The sediment load carried into the Estuary during high flow events can also result in deposition in low velocity reaches.

Submerged aquatic vegetation (SAV) provides habitat where juvenile fish can hide from predators and feed on the macroinvertebrates that also reside in the vegetation. SAV beds also provide food for waterfowl and oxygenate the water during photosynthesis. Extreme flow events, such as tropical storms Irene and Lee in 2011, can cause major damage to this habitat. Ralston et al. (2013) estimated that Irene and Lee brought 2.7 megatons of sediment into the river, more than 5 times the annual average input, and that approximately 2/3 of this was deposited within the freshwater portion of the Estuary. The deposition is believed to be the cause of a 90% decline in SAV) observed in 2012 (NYSDEC 2013). By 2016, SAV had regrown to approximately 40% of the coverage documented in 2007, however an invasive spiny naiad (*Najas minor*) had displaced some of the native water celery (*Vallisneria americana*), compounding the effect of the invasive water chestnut (*Trapa natans*) which has long been established in the Estuary (NYSDEC 2017).

3.2.6 Conclusions

The Hudson River Estuary, like other estuaries around the world, is a highly variable environment even under ordinary circumstances. The extreme events documented in Appendix 4 illustrate the responses of Hudson River fish populations to conditions that may occur once in a decade or even once in a century. The Hudson River's native biota, including many of the fish species discussed in Appendix 5, have occupied the River since or shortly after the end of the last glaciation. They have persisted there in spite of occasional catastrophic events that kill or impair large fractions of the populations present or destroy large areas of essential habitat.

A branch of ecology known as "life history strategy" (Stearns 1992) holds that each population's combination of life history characteristics (e.g., growth rates, sex ratios, maturity and fecundity rates, natural mortality rates) reflects the selective pressures associated with its habitat, including those exerted by extreme events. Winemiller and Rose (1992) examined how environmental conditions have shaped the life history characteristics of 216 North American fish species from 57 families. They classified the combinations of life history characteristics into three basic strategies:

- Periodic strategists tend to "delay maturation in order to attain a size sufficient for production of a large clutch and adult survival during periods of suboptimal environmental conditions,"
- Opportunistic strategists "place a premium on early maturation, frequent reproduction over an extended spawning season, rapid larval growth, and rapid population turnover rates, all leading to a large intrinsic rate of population increase."
- Equilibrium strategists have "large eggs and parental care result in the production of relatively small clutches of larger or more advanced juveniles at the onset of independent life."

While some fishes can be classified distinctly into one of these three strategies, there are many species which adopt intermediate strategies. Striped Bass and American Shad are clearly periodic species which display the characteristics of migration, delayed maturation, large adult size, high fecundity, small offspring, low adult mortality, and repeat spawning. The opportunistic strategy is exemplified in the Estuary by Bay Anchovy and Atlantic Silversides. Atlantic Tomcod, Alewife, and Blueback Herring appear to be intermediate with characteristics of both the periodic and opportunistic strategies. The Sunfishes (e.g. Largemouth Bass, Smallmouth Bass) and Catfishes (e.g., White Catfish, Channel Catfish) are intermediate between the periodic and equilibrium strategies in that they exhibit relatively large adult body sizes, low fecundity, large offspring, low adult mortality, and repeat spawning, but provide parental care.

This variety of life history strategies demonstrates that there are many ways in which the fish species of the Estuary can successfully adapt to environmental variation and atypical conditions. Fish species sensitive to extreme events would not likely be found in estuarine habitats like those found in the Hudson River estuary.

Whether the dominant fish populations present in the Hudson River continue to persist and sustain themselves may be determined at least in part by the frequency of occurrence of extreme events. Temperature data discussed in Appendix 3 show that the mean temperature of the river has been increasing at a rate of approximately 0.3 ° C per decade. As the mean temperature increases, the frequency and duration of high-temperature conditions such as those that occurred in 1999 may likely to increase as well.

3.3 DIVERSITY OF THE JUVENILE FISH COMMUNITY OF THE HUDSON RIVER 1974-2017

Appendix 5 documents a quantitative analysis of the diversity of the juvenile fish community of the Hudson River based on the full 44 years data collected by the HRBMP. As noted in Appendix 5, many others have published studies of the Hudson River fish community, however, most of these studies have been purely descriptive. Hurst et al. (2004) performed a quantitative analysis of community diversity in the Hudson River, but their analysis was limited to the shore zone of a 15-mile segment of the estuary, and only over a 20-year period. Appendix 5 addresses the entire estuary, including all habitats sampled by the BSS and the FJS. In addition to common metrics such as species richness, total abundance, and frequency of occurrence, Appendix 5 applies a set of recently-developed diversity metrics based on "Hill numbers" (Chao and Jost 2015), which the ecological research community have accepted as the metrics of choice in diversity analysis.

The analysis addressed four questions related to fish community diversity in the Hudson River estuary:

1. Is the period of sampling common across all the years, weeks 32-40 (primary period) a relevant time to assess diversity?
2. Does diversity differ between the communities in the freshwater zone and in the brackish zone?
3. Which of the habitats of the estuary (shore, shoal, bottom, and channel) have more diverse communities?
4. What are the biological or environmental determinants of the observed patterns in diversity metrics?

3.3.1 Sampling and General Trends

The analysis focused on the brackish (defined as being north of RM 12 and with salinity > 0.5 ppt) and freshwater (salinity < 0.5 ppt) zones. The zone boundaries shifted with freshwater inflow to the Estuary. Within these salinity zones, four habitats were addressed: the shore zone, shoal, bottom, and channel. A total of 129 species of juvenile fish were collected in BSS and FSS sampling from 1974-2017, and 151 species when post-juvenile fish are considered. Although these are large numbers of species, many were only very rarely caught. A total of 28 species were collected less than once per decade on average. The 41 most frequently occurring species accounted for 99% of all occurrences (Figure 3-2 of Appendix 5, reproduced here as Figure 3-4), leaving the remaining 1% of occurrences divided among 88 other species. The top ten most frequent species provided 77% of all occurrences. The concentration of abundance in a few species was even more pronounced than for occurrence (Figure 3-4). The top 10 most abundant species accounted for 93% of the total catch, and 20 species accounted for 99%, with the remaining 109 species providing the last 1%.

3.3.2 Trends in Catch per Tow and Species per Tow

In the brackish portion of the estuary, all four habitats exhibited similar general patterns in catch per tow and species per tow. Catch per tow was typically high through the 1970s, except for channel habitat which was not sampled until 1979. In the two habitats sampled with epibenthic sleds, shoal and bottom, catch per tow dropped dramatically from a level fluctuating around 300 fish per tow, when the beam trawl replaced the epibenthic sled in 1985. The most likely explanation for this sudden drop is the relatively low efficiency of the beam trawl at capturing small fish, especially Bay Anchovy. Gear comparison studies summarized in Appendix 12 showed that the epibenthic sled is approximately 40 times as effective at capturing Bay Anchovies as the beam trawl.

Mean species per tow, calculated as total number of incidences divided by number of tows, declined over the 44 years of study in all four habitats sampled.

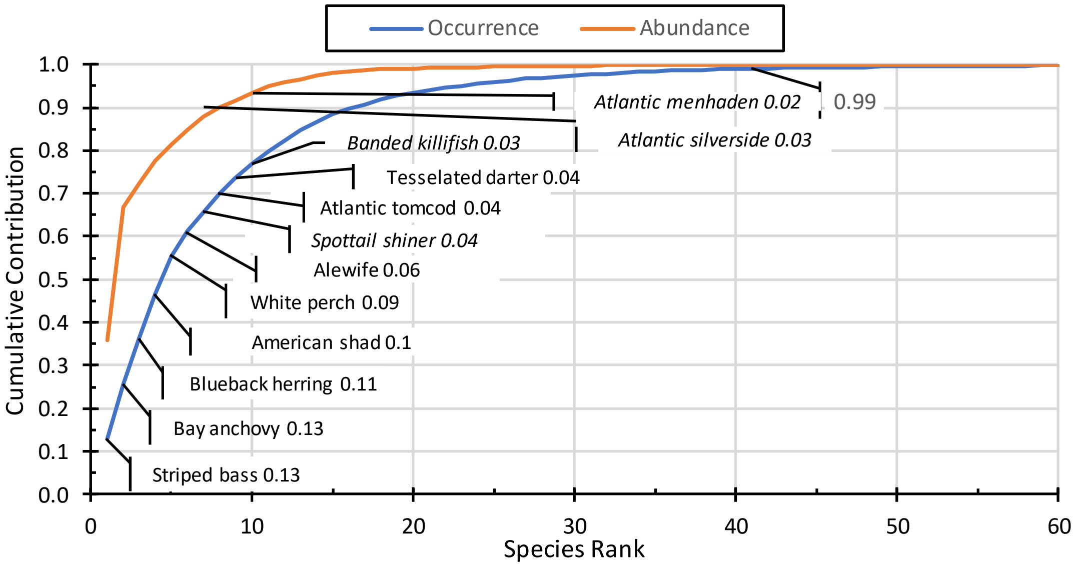


Figure 3-4 Cumulative occurrence and abundance curves for fish species collected as juveniles in BSS and FSS sampling, 1974-2017, with the 10 most frequent species. Eight of these species were also among the 10 most abundant. Species in italic font were only in the top 10 for curve indicated.

Patterns in the freshwater portion of the estuary were similar across the 4 sampled habitats In the shore zone catch per tow fluctuated around 250 fish per tow through the early 1980s, then declined. In most years after 2010 catch per tow was 100 fish. In shoal habitat, catch per tow declined abruptly when the switch to the beam trawl occurred in 1985. As appears to have been the case in the brackish zone, the decline may have been related to the bream trawl's lower efficiency at capturing very small fish. There was little obvious trend in catch per tow in the channel habitat. Species per tow in the freshwater shore, shoal, and bottom habitats all declined over the 44-years of study. There was no obvious trend in the channel habitat, but the number of species per tow in this habitat was much lower than in the other three, fluctuating around a mean value of approximately 1.4.

3.3.3 Diversity Profiles

Diversity, in an ecological context, is a function of three properties of the community: the number of different species, the evenness of the abundances or frequencies of the species, and the similarity or relatedness of the species to each other. Diversity increases as the number of species increases, the evenness increases, and as the similarity decreases. Ecologists have long searched for diversity metrics that incorporate these properties in the most appropriate way, although most of the commonly used metrics address only species number and evenness. The metrics chosen for this analysis are based on Hill numbers (Hill 1973, Chao et al. 2010). Hill numbers incorporate many of the historical metrics (e.g. species richness, Shannon-Wiener, Simpson) as special cases, and they can be modified to incorporate species similarity (Leinster and Cobbold 2012, Chao et al 2010). One key advantage of Hill numbers over many of the previously used metrics is that the diversity values are interpretable as number of species rather than as an abstract numerical index.

Diversity metrics can be based either on species abundances (number of individuals) or on species incidences (number of occurrences). In fisheries sampling, in which sample units are not individual organisms but instead are standardized net tows, incidence-based diversity is the more appropriate paradigm for calculation (Chao et al. 2015).

Appendix 5 documents the equations used to calculate Hill numbers of order q, where q is a measure of the sensitivity of diversity to species incidence frequency, denoted as ${}^{q}\Delta$. When q = 0, the metric (${}^{0}\Delta$) is completely insensitive to the relative frequencies of occurrence of different species and is simply the total number of species that have been observed. When q = 1, the diversity metric is equivalent to exp(H´) where H´ is the Shannon-Weiner diversity index. When q = 2, the diversity metric is equivalent to the inverse Simpson index. As q increases, the relative contributions of rare species to the diversity metric decreases.

The calculated ${}^{q}\Delta$ values are biased low in comparison to the true community values because some species that are present in the community may not be collected. This bias decreases with increasing sampling effort. Chao and Jost (2015) developed a method for estimating the “asymptotic” values of Hill numbers, i.e., the diversity metrics that would occur if every species present in the community were collected. Chao and Jost (2015) also developed formulas for calculating confidence intervals around estimated Hill numbers.

A typical diversity profile, in this case for juvenile fishes in the primary sampling period in the brackish zone, bottom habitat in 1992, is depicted in Figure 3-5 (Figure 5 in Appendix 5). The empirical profile (blue) indicates a species richness (effective species at q = 0) of 22 species, with confidence bounds of about ± 1.5 species. The profile declines to 10 effective species at q = 1, indicating the diversity is the same as that of a community with 10 equally frequent species. By q = 2, the profile indicates 7.4 effective common species, and by q = 3, 6.7 effective very common species. As q increases from 0 to 3, rare species have decreasing influence on the diversity.

The empirical and asymptotic diversity at q = 0 (species richness), and empirical diversity at q = 1 and q = 2 were examined to address the four questions posed in Appendix 5. Although species richness exhibits more variability from year to year than does effective species at q = 1 or 2, the latter measures are better indicators of ecologically significant changes in the community. Species richness is much more sensitive to sampling effort and sampling variation, than is diversity at higher values of q. Moreover, the ecological importance of very rare species, in this case often of vagrant marine species that are temporarily present in the estuary, is much less than of the more common species that dominate the Hill numbers at higher q values.

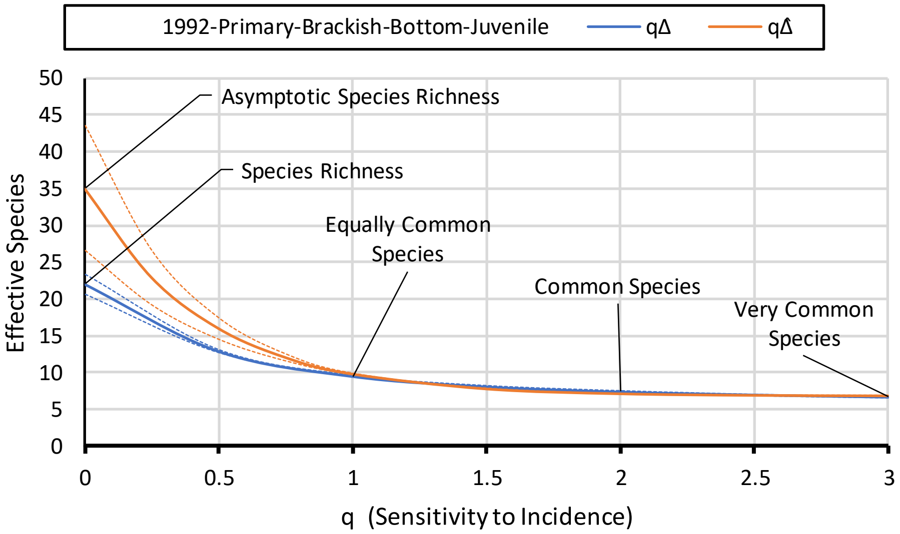


Figure 3-5 Diversity profile for juvenile fishes during primary period, in the brackish zone, bottom habitat in 1992. Blue lines represent the empirical profile with 95% confidence bounds. Orange lines represent the asymptotic profile with 95% confidence bounds.

Question 1: Is the period of sampling common across all the years (primary) a relevant time to assess diversity?

In terms of species richness ($^{0}\Delta$), the primary period generally had as many or more species than in the “Pre” period, and distinctly more species than in the “Post” period. Diversity at q = 1, was also as high or higher in the primary period than either before or after. Hence, the primary period for the diversity analysis, weeks 33-42, represent not only a period when sampling was relatively if not equally intense in all years, but also a period when the largest number of species of juvenile fish were present in the estuary. It is clearly the most relevant time period for assessing long-term trends in fish community diversity.

Question 2: Does diversity differ between the communities in the freshwater zone and in the brackish zone?

Diversity in the freshwater and brackish zones depends upon the species resident in each zone, and on species that pass through the zone as part of their normal life cycle, and vagrant species that by chance are there temporarily. In the Hudson estuary there is a relatively large number of vagrant species, that typically are low in abundance and incidence, and may also are not present in most years. For addressing the ecologically relevant aspects of diversity, the metrics that place more weight on species that are frequently collected, e.g., $^{1}\Delta$ and $^{2}\Delta$, are more meaningful.

Across all the habitats, and for most of the 44 years of these sampling programs, the freshwater zone was perhaps surprisingly more diverse, in terms of effective species, than the brackish zone. Early in the study, species richness ($^{0}\Delta$) was higher in the brackish zone, but from 1980 through 1995, richness declined in the brackish zone, while remaining stable in the freshwater zone. The more ecologically relevant metric ($^{1}\Delta$), shows a similar pattern for the shore zone, but over the last two decades the freshwater zone is more diverse. For the shoal, bottom, and channel habitats the diversity differences across zones is not large, but the freshwater zone has consistently been more diverse. The freshwater zone is less dominated by a few species that are highly abundant and frequent, than is the brackish zone where species such as bay anchovy, Atlantic silversides, Atlantic menhaden may be nearly ubiquitous at times. In the freshwater zone, the ecologically analogous species, alewife, blueback herring, and American shad, have declined in abundance since the 1970s, and become less dominant. This decline in dominance of a small number of species increases community diversity.

Question 3: Which of the habitats of the estuary (shore, shoal, bottom, and channel) have more diverse communities?

Relative diversity, as effective species, varies systematically among among the different habitats. Diversity is highest in the shore habitat and lowest in the channel habitat. However, year and salinity clearly influence the habitat differences. In particular, riverwide diversity (i.e., annual values averaged over the two salinity zones) differed between the time periods before and after the establishment of zebra mussels in the Hudson River. Diversity, ($^1\Delta$) values averaged 13.4 species in the shore zone from 1974-1990, and 12.1 species from 1991 to 2017, post zebra mussel invasion. Shoal habitats had fewer effective species than in the shore zone, 9.1 prior to zebra mussels and primarily with epibenthic sleds, and 7.8 after zebra mussels with beam trawl sampling. Bottom habitat, prior to zebra mussel invasion, had very similar diversity to shoal habitat (8.8 species), but after 1991 mean diversity was 9.6 species, which is consistent with a positive effect on benthos and benthic fish as a result of the zebra mussel invasion (Strayer et al. 2004?). Channel habitat is the least diverse, with an average of 4.5 effective species prior to zebra mussels and 3.7 afterwards.

Question 4: What are the biological or environmental determinants of the observed patterns in diversity metrics?

The dynamics of fish communities of the estuary cannot be understood solely through patterns in diversity measures. Examination of the biological species composing the communities allows congruent and contrasting patterns of occurrence to be identified. Appendix 5 documents long-term trends in the frequency of occurrence of major families and functional groups present in the river.

There have been many changes in the frequencies of occurrence of species within families and functional groups, but fewer trends in the long-term occurrences of the families and groups themselves. The freshwater spawning members of the Clupeidae family have declined approximately 2.5% per year on average over the entire 44-year time series. The three anadromous species have all declined since the early 1980s, but gizzard shad, although far less frequent than the others, has increased in frequency since the mid-1980s. The freshwater catfish family (Ictaluridae) has been increasing in abundance at a rate of 5.5% per year, and channel catfish, has replaced white catfish as dominant catfish species.

Changes in the frequencies of occurrence of other major families, the Moronidae, Sciaeanidae, and Centrarchidae, have been much smaller, on the order of 1% or less per year.

Functional groups addressed in Appendix 5 include forage fish, bottom-oriented fish, and freshwater predators. Although the relative abundances of different species within these groups has changed, frequencies of occurrence of all of these groups have been relatively stable, with long-term increase or declines of less than 1% per year.

3.3.4 The Hudson River in Context

The diversity of the Hudson River fish fauna has not previously quantified so that it could be rigorously compared to other estuaries. To facilitate these comparisons, Hill numbers for the Hudson River fish community and for fish communities present in other estuaries were calculated based on abundance rather than occurrence, because abundance data were available from the other estuaries. The equations and interpretations are similar, but the diversity metrics are denoted as ^{0}D and ^{1}D rather than $^{0}\Delta$ and $^{1}\Delta$.

Based these comparisons, the Hudson indeed is highly diverse. In comparison to other mid-Atlantic estuaries (Niantic River, CT; Great Bay and Mullica River, NJ, Delaware River estuary and bay, DE) and to Suisin Bay in the Sacramento-San Juaquin estuary in CA, and Bristol Channel in the UK, the Hudson has the highest reported species richness (^{0}D), and is exceeded in effective equally common species (^{1}D) only by Suisin Bay (Figure 3-6; Figure 3-24 of Appendix 5). While the higher richness in the Hudson is at least partially to be expected due to the length of the record, intensity of sampling, and multiple habitats sampled, the high ^{1}D value is more indicative of a different structure of the community In all the other estuaries except Suisin Bay, the communities are more concentrated in fewer species, whereas in the Hudson the abundance is more dispersed among a greater number of species. It should be noted that the Suisin Bay fish community is highly modified by introduced species, which comprise approximately ½ of the 54 species present.

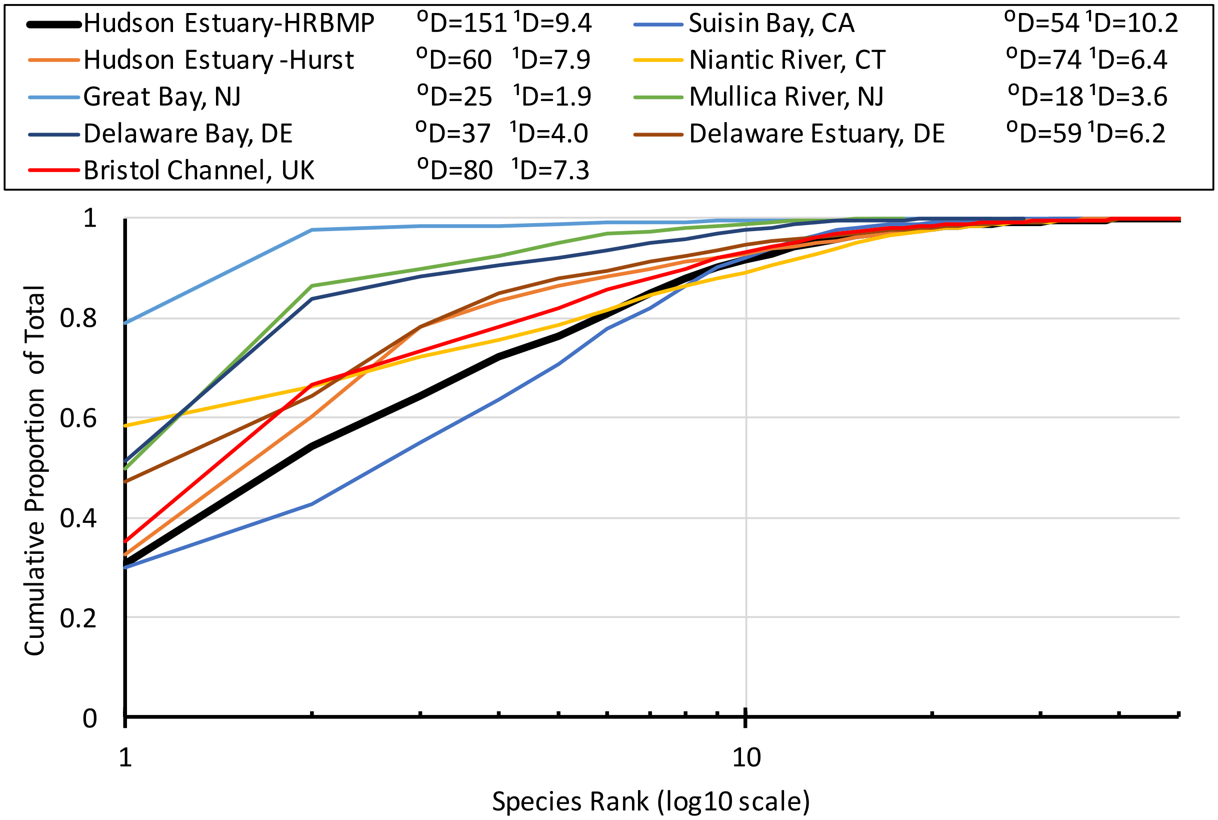


Figure 3-6 Concentration of catch in dominant taxa, and ^{0}D and ^{1}D values for HRBMP and for studies of other estuaries. Calculations based on species abundance reported for each study.

This initial quantification of estuary-wide fish community diversity demonstrates that the Hudson Estuary is diverse throughout its entire length and in all habitat types. Over the 44 years of the HRBMP, changes in fish abundance have occurred through time, but the community structure has been resilient and remains diverse, in the sense that it continues to contain a large number of species (151 in the subset of data examined here), and the number of relatively abundant species is also large, in comparison to other temperate estuaries.

Nevertheless, this analysis is just a next step in understanding of the history of the Hudson Estuary fish community over the last 5 decades from the HRBMP data set. It builds upon the prior analyses of Beebe and Savidge (1988), Gladden et al. (1988), Geoghegan et al. (1992), Strayer et al. (2004, 2014), Singkran and Bain (2008), and O'Connor et al (2012), but leaves a great deal of information about the community still to be extracted from the data. A similar analysis could be conducted for post-juvenile fishes from BSS and FJS sampling, or for eggs and larvae from the ichthyoplankton collected in the LRS program. This analysis examined only two of the three factors determining diversity, species richness and evenness. Information on similarity of the species within each spatial-temporal stratum could be incorporated by using the recently developed Hill number metrics (Leinster and Cobbold 2012, Chao et al. 2010). The similarity of communities across the years of study could also be examined through other diversity metrics or through multivariate techniques (Kwak and Peterson 2007). Much work remains to be done.

3.4 ANALYSIS OF EARLY LIFE STAGE ABUNDANCE AND MORTALITY ESTIMATES

The LRS, FJS, and BSS programs have provided more than 40 years of comprehensive data on the abundances of early life stages of important Hudson River fish species. Relationships among abundance and survival indices calculated from these data provide valuable insights into the population dynamics of these species. How is recruitment related to spawning stock abundance? How do changes in early life stage survival affect year-class strength? Is early life stage mortality or egg deposition the primary determinant of year-class strength? Appendix 6 of this report evaluated these questions for three major taxa for which the available data are especially comprehensive: Striped Bass, American shad, and white perch. Two species, Striped Bass and American shad, have been subject to intensive harvesting and to major changes in harvest policy over the 40-year duration of the HRBMP. How have alterations in policy affected the dynamics of early life stages of these species?

3.4.1 Selection of Metrics

Appendix 6 first identified and justified the abundance and survival metrics to be used in the analyses. Indices of early life stage abundance and YOY abundance for each species were derived using quantitative methods documented in Appendix 2.5. PYSL abundance, as determined from LRS data, was selected as a measure of annual reproductive output for each species. This choice was justified by previously published literature (Barnthouse et al. 2003) demonstrating that, over the years 1980-1997, spawning stock estimates from NYSDEC's commercial gillnet monitoring program were strongly correlated with estimates of PYSL abundance for the same years. Similarly, Wells et al. (1992) found that an index of adult White Perch in the Hudson River was positively correlated with egg, YSL, and PYSL indices calculated from LRS data.

Abundance estimates derived from the BSS program were selected as indices of YOY abundance. This choice was justified by previously published literature indicating that BSS data for both Striped Bass and White Perch are correlated with independently-derived estimates of the abundance of age 1 fish a year later (Barnthouse et al. 2003; Gallagher and Secor 2018).

Ratios of YOY abundance indices to PYSL abundance indices provide estimates of the relative survival of early life stages between spawning and the YOY stage.

3.4.2 Long-term Trends in Reproduction and Year-Class Strength

Indices of PYSL abundance (representing reproduction) were computed using data from the LRS Striped Bass, White Perch, and American Shad. Survey weeks for each species were selected based on the periods in which this life stage was present in the river. Methods for calculating PYSL abundance are documented in Appendix 2. As indicated in Heimbuch et al. (1992), for indices based on LRS sampling, the volume of water between the beach and 10 ft deep was divided into two substrata: beach and shore. The beach stratum, defined from the beach to water five ft deep, corresponds with the shallow waters sampled in the BSS. The shore stratum, defined as water greater than five ft deep and less than 10 ft deep, is an unsampleable region. Densities in these substrata were estimated based on fixed ratios to the densities in adjacent strata.

Indices of abundance (representing year class strength) using data from the BSS were calculated for juvenile Striped Bass, White Perch, and American Shad. Weeks 33 to 40 were selected as the only period consistently sampled in the BSS over the full 44-year survey period. Methods used to perform the computations are documented in Appendix 2.

Figure 1 of Appendix 6 shows long-term trends in reproductive output for Striped Bass, American Shad, and White Perch. For Striped Bass, the lowest levels of reproduction, measured in terms of PYSL abundance, occurred early in the time series, from 1974-1988. PYSL abundance then increased rapidly by approximately a factor of 30 from 1989 through 2000. Annual PYSL abundance has fallen substantially since 2000 but is still far higher than it was during the 1970s and early 1980s. This pattern is consistent with coastwide trends in Striped Bass spawning stock abundance (ASMFS 2016). The rapid increase in spawning stock biomass that began in the mid-1980s, has long been credited to a coastwide moratorium on Striped Bass harvesting that was enacted in 1986. The later decline in spawning stock biomass has been attributed to a weak Chesapeake Bay year class in 2012, combined with high fishing mortality. In response to this decline, the ASMFC took action in 2014 to again reduce Striped Bass harvesting (ASMFC 2014).

Trends in reproductive output of American Shad (Figure 1b of Appendix 6) also are consistent with coastwide trends documented by the ASMFC (2007), and with a detailed assessment of the Hudson River spawning population performed by NYSDEC staff (Hattala and Kahnle 2007). Both commercial fishery landings and fishery-independent spawning stock surveys show that the mean size, mean age, and mean abundance of adult American Shad all declined to very low levels between the late 1980s and the early 2000s and have remained low since that time.

Long-term data on PYSL abundance depicted in Figure 1c of Appendix 6 indicate that the reproductive output of Hudson River White Perch has been highly variable, but has fluctuated without trend since the mid-1990s.

With two exceptions, trends in the abundance of YOY fish (Figure 2 of Appendix 6) are roughly consistent with trends in reproductive output. The major exception is Striped Bass (Figure 2a of Appendix 6). In spite of the large increase in Striped Bass reproductive output following the closure of the Striped Bass fishery in 1986, there has been no appreciable change in the abundance of YOY Striped Bass. This anomaly has been previously noted in published literature (Pace et al. 1993; Barnthouse et al. 2003). These two studies were, however, based on much shorter time series than is available today. The full 1974-2017 time series supports the conclusions of earlier authors. There still has been no appreciable change in the abundance of YOY Striped Bass in the Hudson, in spite of the much higher production of larvae in the post-1988 period.

For American Shad (Figure 2b of Appendix 6), a sharp decline in YOY abundance occurred during the same period in which reproductive output declined, and YOY abundance has remained at a low level since 2001. The trend in abundance of YOY White Perch (Figure 2c of Appendix 6) is somewhat more complex. YOY abundance declined throughout the early part of the time series, from 1974 through 1996. YOY abundance then increased and has fluctuated with no appreciable trend.

3.4.3 Evidence for Density-Dependent Mortality of PYSL

A finding that the survival rate of PYSL to the YOY for a species was negatively correlated with PYSL abundance would be an indicator the survival of PYSL is density-dependent. Appendix 6 documents correlations between the PYSL abundance index and the PYSL survival index for Striped Bass, American Shad, and White Perch.

Data plotted in Figure 3-7a (Figure3a of Appendix 6) are consistent with strong density-dependence of early life stage mortality in Striped Bass. The Spearman rank correlation coefficient between PYSL abundance and PYSL survival is highly significant, with a value of -0.8941. The relationships between PYSL abundance and PYSL survival for American Shad (Figure 3-7b) is nearly as strong as for Striped Bass. Although this correlation is less strong for White Perch (Figure 3-7c), it is still negative and statistically highly significant. These results are consistent with the presence of density dependence in early life stages of all three species.

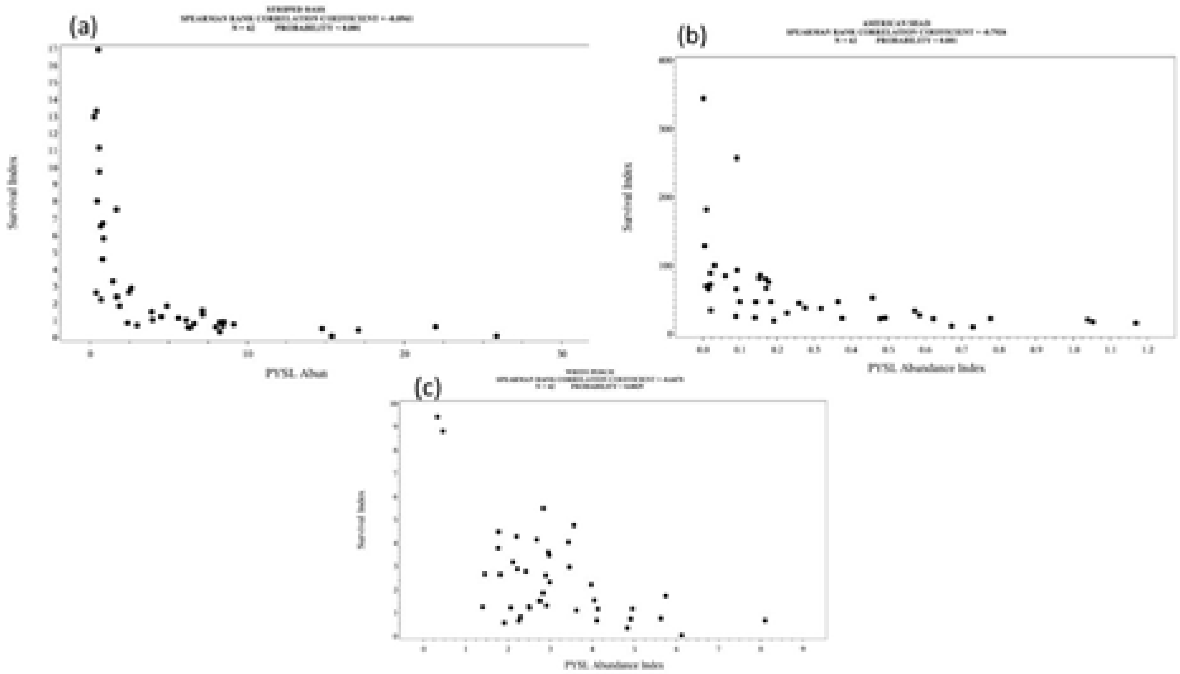


Figure 3-7 Correlations between PYSL abundance indices and PYSL survival indices.

3.4.4 Comparative influence of Reproduction and Larval Survival on Year-Class Strength

The HRBMP data also provide insights on the relative importance of reproductive output and early life stage survival in determining year class strength. If reproductive output is the more important factor, then YOY abundance should be more highly correlated with reproduction (measured as PYSL abundance) than with larval survival (measured as the ratio of YOY abundance to PYSL abundance). If early life stage survival is the more important factor, then YOY abundance should be more highly correlated with larval survival than with reproduction. If factors other than reproduction are the primary determinants of year-class strength, then YOY abundance might not be correlated with either reproduction or survival.

Spearman's Rank Correlation test statistic T was used to test for significant correlations (a) between year class strength and reproductive output, and (b) between year-class strength and PYSL survival.

Results are shown in Figures 4 through 6 of Appendix 6. YOY abundance of Striped Bass is correlated neither with PYSL abundance nor with PYSL survival (Figure 4 of Appendix 6). This is not surprising, because of the very strong negative correlation between reproduction and survival in this species. Inter-annual variability in YOY abundance is clearly determined by other factors.

The pattern is quite different for American Shad (Figure 5 of Appendix 6). For this species, there is a weak negative correlation between PYSL survival and YOY abundance, but a very strong and highly significant positive correlation between PYSL abundance and YOY abundance. This means that for American Shad, the recent low levels of YOY abundance reflect reduced reproduction, not reduced PYSL survival.

For White Perch (Figure 6 of Appendix 6), there is no correlation between PYSL abundance and YOY abundance, but a strong positive correlation between PYSL survival and YOY abundance. Hence, for this species, PYSL survival has a strong influence on year-class strength, but reproductive output has no discernable influence.

3.4.5 Influence of Management Actions on Striped Bass and American Shad Populations

During the period covered by the HRBMP, both Striped Bass and American Shad were targeted for fishery closures intended to promote recovery of depleted populations. The coastwide fishery for Striped Bass was closed in 1986 to promote recovery of the depleted Chesapeake Bay spawning population. Other spawning populations, in particular the Delaware River and Hudson River populations, also benefitted from the closure. In response to an extended decline in coastwide abundance of American Shad, the coastal intercept fishery for this species was closed in 2005. NYSDEC instituted a ban on all American Shad harvesting in New York waters in 2009. Effects of harvest reductions on reproductive success in these two populations were evaluated by comparing reproductive output and year-class strength before and after the actions.

The responses were characterized in terms of the difference in the average index of abundance between the years immediately before the closure versus immediately after the closure. For American Shad, only eight years of HRBMP data were available following the closure (2009 through 2016). For consistency, all comparisons were made with data from eight years prior to the closure and eight years following the closure. Accordingly, for Striped Bass the "before" years were 1978-1985 and the "after" years were 1986-1993. For American Shad the "before" years were 2001-2008 and the “after” years were 2009-2016. Details concerning the statistical tests employed are provided in Appendix 6.

Figures 8 and 9 of Appendix 6 show that these two species responded very differently to fishery closures. For Striped Bass (Figure 8), average annual PYSL abundance during the 8 years following the closure was more than 5 times as high as during the eight years preceding the closure. This increase reflects the increase in abundance of spawning Striped Bass, which were allowed to mature and reproduce rather than being harvested as immature fish during the coastal phase of their life cycle. However, due to the strong density-dependent mortality discussed above, there was no significant increase in abundance of YOY Striped Bass.

For American Shad (Figure 9), there was no increase in abundance of either PYSL or YOY following the fishery closure. Post-closure average abundance estimates for both life stages were significantly lower than for the 8 years prior to the closure.

3.4.6 Discussion

The availability of independent measures of reproductive output and resulting year-class strength over a time series of more than 40 years permits inferences concerning population dynamics that would not be possible if only a single abundance index were available.

The extended time series of data on multiple life stages provided by the HRBMP is sufficient to test for relationships between the abundance and survival that may indicate the operation of density-dependent regulatory processes in Striped Bass, American Shad, and White Perch.

These same data sets show that the three species differ qualitatively with respect to the relative importance of reproductive output and early life stage survival in determining year-class strength. In Striped Bass, the inverse relationship between reproductive output and PYSL survival is so strong that there is no observable influence of either reproduction or survival on year-class strength. Year-class strength in this species appears to vary around a relatively constant mean, independent of spawning stock size. In contrast, the strong correlation between reproductive output and YOY abundance in American Shad indicates that the low YOY abundance estimates in recent years reflect low spawning stock abundance, indicative of a depleted population. For White Perch, PYSL survival strongly influences year-class strength, with reproductive output having no detectable influence. In this species, year-class strength appears to be determined by environmental or biotic factors acting during early life stages.

Finally, the contrast in responses of Striped Bass and American Shad to fishery closures has substantial management implications. The immediate response of the Hudson River Striped Bass population to fishery closure, together with parallel increases of abundance of Striped Bass in Chesapeake Bay and the Delaware River, indicate that Striped Bass is a highly resilient species that, if properly managed, can support sustainable fisheries well into the future. The failure of the American Shad population to respond in a similar way should be of concern to fishery managers. The ASMFC (2007) concluded that the decline in abundance of American Shad was a result of increased mortality of shad during the oceanic phase of the life cycle, with the cause of the increase being unknown. Results provided in this report are consistent with this conclusion, but suggest that the cause is likely environmental factors unrelated to fishing.

A great deal of additional information exists in the HRBMP data set and specimens that could further elucidate the differences in these species responses to exploitation rate manipulations, and the mechanisms for these responses. For instance, lengths have been recorded for the larvae of all three species that would aid in examination of growth and mortality rates. In addition, since 1991, the actual specimens are still available for analysis so that additional information, such as feeding rates, could be obtained. Since 1996, additional samples have been preserved in ethanol so that daily otolith aging techniques could be employed to examine within and among year differences in survival.

3.5 HUDSON RIVER RAINBOW SMELT: CATASTROPHIC POPULATION DECLINE

As documented by the Hudson River Biological Monitoring Program (“HRBMP”) (ASAAC 2016) and noted in Daniels et.al. (2005), Rainbow Smelt *Osmerus mordax* were once abundant in the Hudson River, but have now nearly disappeared. The decline was catastrophic rather than gradual. More than 100 million PYSL and 1 million YOY per year were present from 1985 through 1995, but the abundances of both life stages fell to essentially 0 in 1996. Only a few Smelt PYSL, and no YOY, have been collected since 1995. Appendix 7 of this report documents the suddenness of the decline, shows how it could have resulted from 2 consecutive years of reproductive failure in the population, and identifies a potential cause of that failure.

3.5.1 Characterization of time series of abundances of Rainbow Smelt larvae, juveniles, and yearlings

Annual abundance estimates for PYSL over the years 1985-2016 were calculated using methods documented in Appendix 2. Survey weeks 18-26 were selected for analysis because those weeks were sampled in all years. Annual estimates of YOY and yearling and older (YRL) Rainbow Smelt were computed from FJS data, also using method documented in Appendix 2. As noted in section 2 of this report, the gear used to sample the shoal and bottom strata of the river changed in 1985, so that data collected before and after that date are not comparable for this purpose.

The abundance of Rainbow Smelt PYSL in the Hudson River varied by roughly 1.5 orders of magnitude from 1985 through 1995 (Figure 3-8a). In 1996, Hudson River PYSL Rainbow Smelt exhibited a catastrophic decline in annual abundance, from a high of over 300 million PYSL (a 9 week average) for the 1994 year class to fewer than one thousand per year on average for all year classes thereafter. No Rainbow Smelt were collected in most of these years.

The abundance of Rainbow Smelt YOY in the Hudson River varied by roughly 3 orders of magnitude over most year classes from 1985 through 1995 (Figure 3-8b). However, no YOY Rainbow Smelt were reported collected by the FSS during weeks 31-42 in 1989. In 1996, YOY Rainbow Smelt exhibited an extreme decline in annual abundance, from a high of almost 10 million YOY (a 12-week average) for the 1992 year class to zero for the 1996 year class and all year classes thereafter.

The abundance of Rainbow Smelt YRL in the Hudson River also varied by roughly 3 orders of magnitude for the 1985 through 1994 year classes (Figure 3-8c). In 1996, the 1995 year class of Hudson River YRL Rainbow Smelt exhibited an extreme decline in annual abundance, from a high of over 1 million YRL (a 12 week average) for the 1992 year class to zero for the 1995 year class and all year classes thereafter.

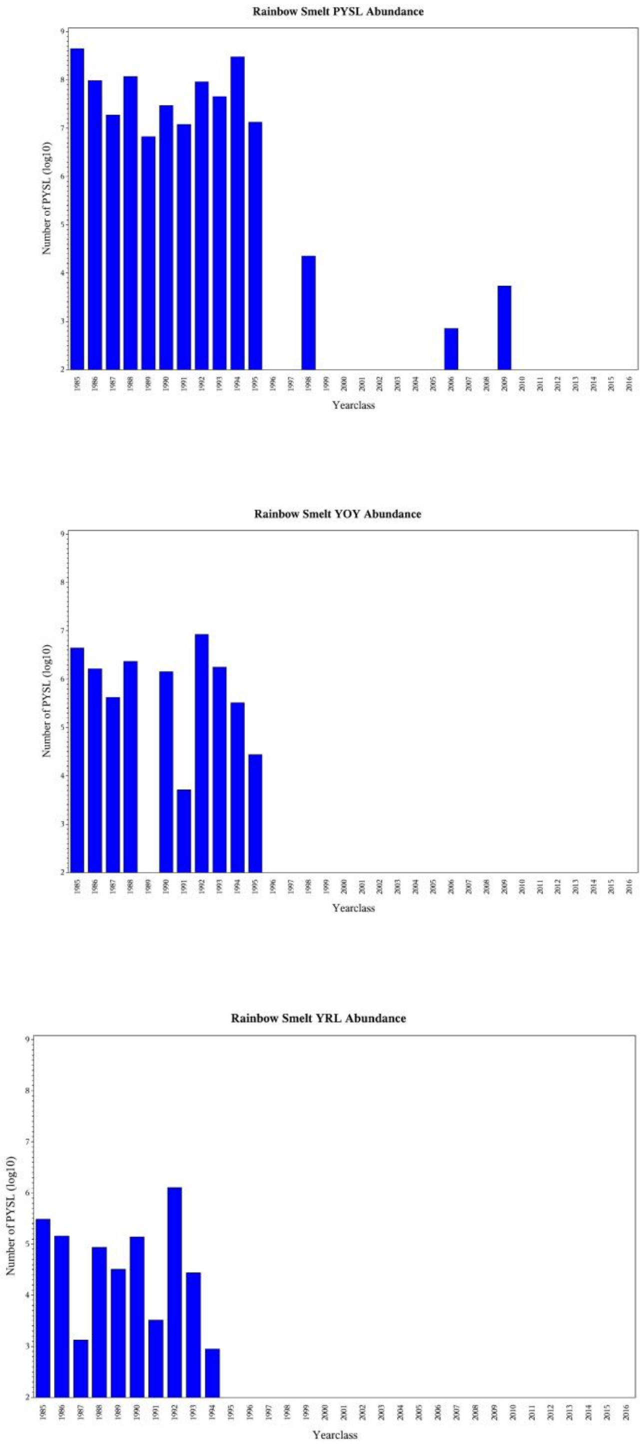


Figure 3-8 Abundance trends for Rainbow Smelt PYSL, YOY, and YRL, 1985-2016.

3.5.2 Changes in Abundance of Other Fish Species

If the catastrophic decline in Rainbow Smelt was due to degradation in the quality of the aquatic environment of the Hudson River Estuary, then other species might also have been affected. To address this possibility, changes in larval abundance of other fish species inhabiting the Estuary were characterized. This assessment focused on species that were numerically common prior to 1996. Because this assessment focused on larvae collected by the LRS (not life stages collected by the FSS), years prior to 1985 were included in the analysis. The average larval abundance for each common taxon was estimated separately for two 15-year stanzas of years – 1981-1995 (Period 1), and 1996-2010 (Period 2) bracketing 1996.

For this assessment, yolk-sac as well as post yolk-sac larvae were included in the estimates of annual larval abundance. This broader definition of larval abundance was intended to address, at least partially, differences in life histories (e.g., timing of early life stages in relation to weeks of sampling) of the many species collected by the LRS.

No other species suffered a decline in abundance comparable to the decline in Rainbow Smelt. Thirteen of the 30 common taxa had statistically significant changes in average abundance between the two periods of years. Of the 13 taxa with statistically significant changes in average larval abundance, 9 exhibited increases and 4 exhibited decreases. For the taxa with significant decreases (excluding Rainbow Smelt), the average larval abundances in Period 2 ranged from 61% to 13% of the Period 1 average abundance. For Rainbow Smelt, the average larval abundance in Period 2 was less than 0.01% of the Period 1 average abundance.

3.5.3 Assessment of Ages of Rainbow Smelt Spawning in the Hudson River

Literature accounts indicate that Rainbow Smelt aged 1 through 5 may contribute to annual egg production, with the age distribution of the spawning stock differing among populations. The proportionate contribution by each age class to the annual egg production of Rainbow Smelt in the Hudson River has not been documented. An analysis of the interannual variability in Rainbow Smelt PYSL abundance in the Hudson River was conducted to ascertain the relative contribution to annual egg production by each age class.

A multiple-regression analysis was used to estimate the relative contribution of each age class of Rainbow Smelt to annual egg production. The regression analysis identified 2-year-old fish as being the dominant contributors to egg production. The proportionate contribution to egg production was estimated to be 88% from age 2 fish and 12% from age-1 fish.

3.5.4 Year class-Specific Mortality Rates from PYSL through YR

To assess whether reproductive failure of key year classes (i.e., year classes just prior to 1996) could have been due to unusually high levels of mortality during age-0 and the beginning of age-1, the mortality rate for each year class (1985-1995) was characterized. As in the analysis of early life stage mortality rates in Striped Bass, American Shad, and White Perch (Section 3.4), a survival index for each year class was computed as the ratio of YOY abundance to PYSL abundance. Similarly, an index of survival from YOY to YRL was computed as the ratio of YRL abundance in one year to YOY abundance in the previous year.

Two stanzas of years were compared: 1985-1993 and 1994-1995. From PYSL to YOY, the average of measures of survival for the 1985 through 1993 year classes was 0.0404, and average for the 1994 and 1995 year classes was 0.0016. The average survival for 1985-1993 was approximately 25 times that for 1994-1995.

From YOY to YRL, the average of measures of survival for the 1985 through 1993 year classes was 0.1275, and average for the 1994 and 1995 year classes was 0.0016. Survival from YOY to YRL in the earlier stanza was approximately 80 times that in the later stanza. From PYSL to YRL, the average of measures of survival for the 1985 through 1993 year classes was 0.0032, and average for the 1994 and 1995 year classes was 0.000018. The ratio of average measures of survival for 1994-1995 over the average for 1985-1993 was 0.06%. Hence, the average survival rate for the 1985-1993 year classes was 1750 times higher than for the 1994-1995 year classes.

3.5.5 Parasitic Infestation of Rainbow Smelt by Glugea hertwigi

One possible cause of the sudden, catastrophic decline in Rainbow Smelt abundance, during a period in which no other fish species in the Hudson River suffered a similar decline, would be a disease that affects Rainbow Smelt but not other species. The microsporidian parasite *Glugea hertwigi* is one such disease agent. *G. hertwigi* is known to infest Rainbow Smelt and some infestation levels may be lethal. Normandeau Associates retrieved archived Hudson River ichthyoplankton samples from the five years immediately preceding this 1996 decline and examined a selection of the Rainbow Smelt in those samples to determine if *Glugea hertwigi* infestations were present (Appendix 7b).

A total of 1187 specimens collected by the LRS from 1991-1995 were examined for the presence of *Glugea hertwigi* xenomas. All specimens were age-0 Rainbow Smelt and ranged from roughly 5mm to roughly 105mm in length (Appendix 7b, Figure 6). Six levels of severity of infestation by (including no infestation present) were identified (Appendix 7b, Figure 7). Each examined specimen was assigned a level of severity (0-5) based on the results of the examination.

Infestation of age-0 Rainbow Smelt by *Glugea hertwigi* was present in every year. Collectively, the examinations of Rainbow Smelt collected by the LRS over the five year period documented the progression of infestation from low levels of infestation (or no infestation) in smaller Rainbow Smelt to more severe infestations in larger age-0 Rainbow Smelt (Figure 3-9). Of the largest YOY examined (>60 mm length), 100% were infested.

3.5.6 Discussion

The LRS and FSS data are consistent in showing a catastrophic decline in abundance in 1996 that affected the 1996 year class of PYSL and YOY and the 1995 yearclass of YRL Rainbow Smelt. In subsequent years through 2016 no YOY or YRL Rainbow Smelt were collected by the FSS (Figure 3-8b and c) during the late summer and early fall (weeks 31-42). During spring sampling (weeks 18-26) by the LRS (Figure 3-8a), PYSL were collected in only 3 of the 20 years after 1996, and the numbers collected were very low.

No other fish species common in the Hudson River Estuary prior to 1996 exhibited a catastrophic decline in abundance. The historical patterns of abundance for Rainbow Smelt, as compared to other fish species inhabiting the Hudson River, strongly support the conclusion that a severe species-specific event, or series of events, caused the sudden catastrophic decline in Rainbow Smelt abundance. What caused the near extirpation of Rainbow Smelt from the Hudson River was sudden and did not affect the other species.

Results from the regression analysis of age classes contributing to annual egg production and information on spawning ages in other Rainbow Smelt populations in the northeast region, support the conclusion that age-2 and, to a lesser extent, age-1 Rainbow Smelt were the major contributors to egg production in the Hudson River Estuary. In this case, the reproductive failure of two year classes – 1994 and 1995 – would have caused the catastrophic collapse of the stock in 1996.

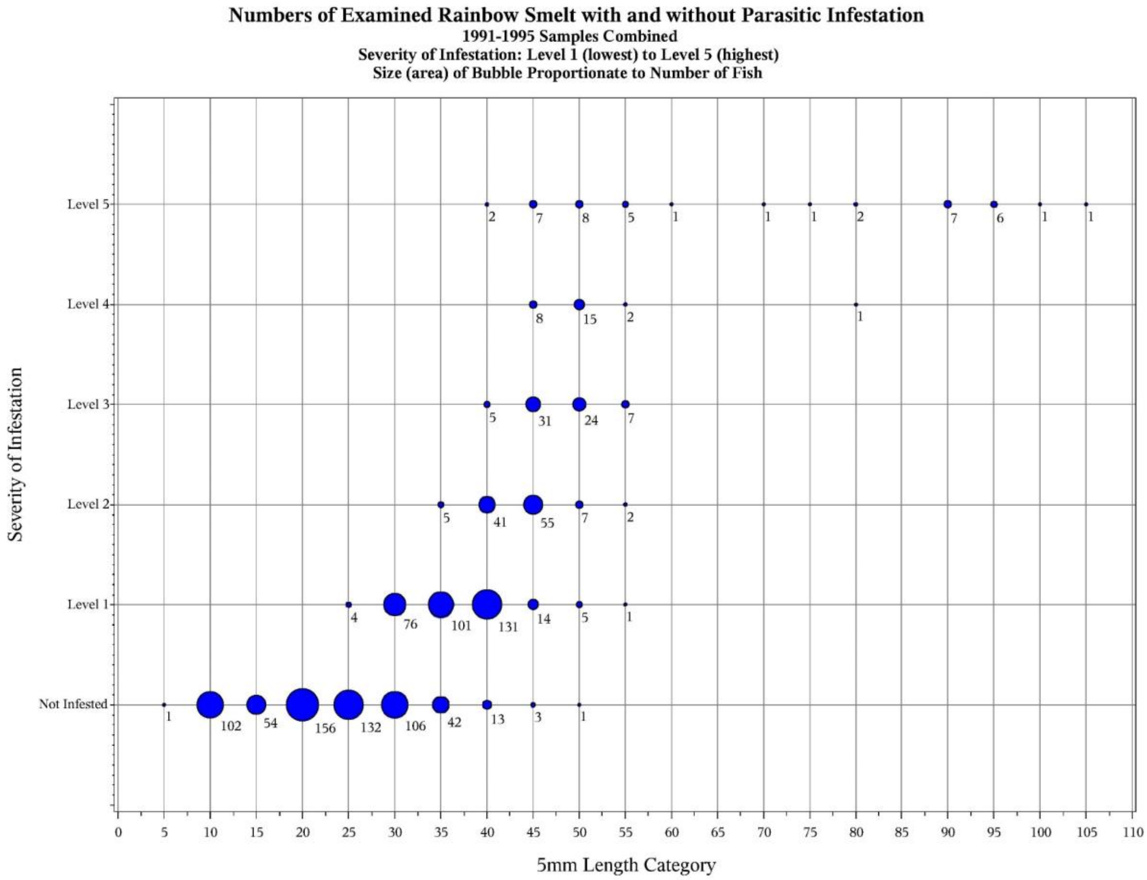


Figure 3-9 Summary of results from all Phase 1 and Phase 2 examinations of archived Rainbow Smelt collected from the Hudson River in 1991-1995.

The assessment of year class-specific mortality rates showed that the survival fraction from PYSL to YRL for the 1994 and 1995 year classes was only 0.06% of the corresponding survival fraction for the 1985-1993 year classes. In fish stock assessment, this value would be equivalent to a 99.94% reduction in spawning potential and would be expected to lead to a rapid decline toward extinction.

Published literature clearly demonstrates that the parasite *G. hertwigi* can cause mortality and reduced fecundity in Rainbow Smelt. Analysis of archived specimens from the HRBMP demonstrated that this parasite was present in Rainbow Smelt collected in all of the years 1991-1995, and that the degree and severity of parasitism increased with increasing length of larvae.

The presence of *Glugea hertwigi* in all five years suggest that parasitism by *Glugea hertwigi* may have been endemic in Hudson River Rainbow Smelt for many years. If *Glugea hertwigi* was the causal agent for the reproductive failure of the 1994 and 1995 year classes, then the severity of infestation must have increased in those year classes in comparison to previous years. However, the examinations were not conducted to support an assessment of whether rates of infestation differed among years.

The annual average abundance of PYSL Rainbow Smelt in the Hudson River increased substantially from fewer than 1 million in 1981 to over 300 million in 1994 (Appendix 7a, Figure 4). If the degree of infestation by *Glugea hertwigi* in the population was associated with population density, then the high abundance (the highest on record) in 1994 may have triggered epidemic-like conditions. Additional research on the epidemiology of microsporidian parasites in susceptible fish populations would be needed to confirm or disprove this hypothesis. Many preserved specimens from the 1991-1995 year class are still available in the archived samples.

3.6 ATLANTIC TOMCOD POPULATION DYNAMICS

Atlantic Tomcod *(Microgadus tomcod*) is a small (adults generally < 12 in) member of the cod family (Gadidae) distributed from the St. Lawrence River to the maritime provinces of Canada, and along the coast of the United States south to, formerly Virginia, but presently only to the Hudson River Estuary. Due to its small size, and perhaps its habit of spawning in mid-winter, it had historically been studied very little. As a result of work done in the HRBMP, the Hudson River Atlantic Tomcod is today, at least unofficially, the most-studied Tomcod population of all. Appendix 1 lists 43 scientific publications specifically on Tomcod arising from the HRBMP. Thirty-six (36) of these relate to contamination and/or cancer, all since the initial report of liver tumors in Tomcod from the HRBMP efforts (Smith et al. 1979). Other topics covered are food habits (2), spawning (1), and general life history (4).

Tomcod have been a designated Representative Important Species (RIS) since the early days of the HRBMP because they were very abundant in the lower Estuary, and subject to entrainment and impingement (McLaren et al. 1988). Because of the RIS designation, and its unique life history, dedicated sampling programs were set up to focus on Atlantic Tomcod.

3.6.1 Life History

Atlantic Tomcod in the Hudson Estuary spawn in early winter in the middle estuary in freshwater. This area is typically from the Tappan Zee (TZ) to Poughkeepsie (PK) regions (Klauda et al. 1988). The eggs are demersal and adhesive (Booth 1967). Hatching occurs in late February and early March (Dew and Hecht 1994). The larvae are initially pelagic, and disperse throughout the lower Estuary, and may be displaced downstream due to high spring freshwater inflow, but tend to concentrate around 1 ppt salinity (Dew and Hecht 1994a). Upon reaching the juvenile stage, young Tomcod grow rapidly in late spring and early summer, but typically grow slowly, if at all, during July and August (McLaren et al. 1988). Summertime bottom temperatures in the Estuary at times exceed its upper incipient lethal temperature (temperature at which higher acclimation temperatures cannot increase tolerance) of 26.6°C (EA 1978). (Estuary temperature patterns are presented in Appendix 3 and response of Tomcod to high bottom temperatures in Appendix 4). When water temperatures decline again in the fall, rapid growth resumes and young Tomcod reach 125 mm TL or larger by November. Both males and females reach sexual maturity at the end of their first year. The spawning population in the Hudson, over the entire span of the HRBMP, has been dominated by age 1 fish which generally comprise at least ¾ of the spawning population. The remainder is comprised of age 2 fish, but occasionally a few age 3 fish, all females, have been detected.

The fact that the Hudson Estuary population is currently the southernmost of the species, suggests that temperature may in some way be an important factor in it's population dynamics. The HRBMP has addressed this issue directly through thermal tolerance studies on Tomcod (EA 1978), which determined an upper incipient lethal temperature of 26.6 C, a temperature below those sometimes prevalent within the Estuary (See Appendices 3 and 4). Bonvegna et al (2001), using juvenile Tomcod raised from adult spawners captured in the ATSA, reported daily growth rates begin to slow when water temperatures exceed 20ºC and cease when water temperatures exceed 24ºC.

The Hudson Estuary population of Atlantic Tomcod has experienced large fluctuations over the course of the HRBMP, and like populations in CT, is much less abundant than it was a few decades ago (Fried and Schultz 2006). The knowledge gained through the ATSA and other components of the HRBMP Various aspects of their life history described by the HRBMP are useful in understanding the population dynamics and what factors may be influencing them.

3.6.2 Trends in population components

Five measures of cohort abundance were determined for 1975 through 2017 year classes: number of eggs deposited, number of age 0 (PYSL and juvenile stages) in May, number of age 0 in September, number of 1-year-old spawning adults (Age 1 January), and number of 2-year-old spawning adults. Some metrics could not be calculated for some years. All stages were determined to have declined from the abundances common during the early years of the HRBMP during the 1970s, as exemplified by the first three stages (Figure 3-10).

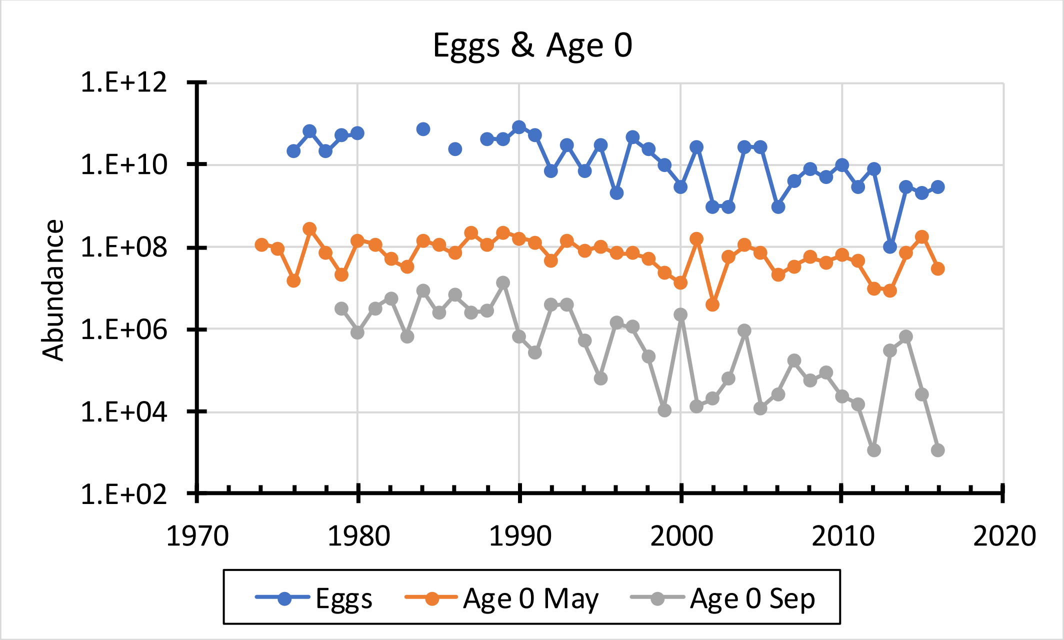


Figure 3-10 Abundance estimates for 1974-2016 year classes of Hudson River Atlantic Tomcod as eggs, Age 0 in May, and Age 0 in September.

3.6.3 Growth of larvae and juveniles

Past studies showed rapid in growth spring and fall, low or no summer growth (McLaren et al. 1988). Bonvegna et al. (2001) demonstrated the direct relationship of growth with temperature, in that grow slows above 20 °C and ceases above 24 °C. To quantify the relationship of growth rate with temperature, an instantaneous daily growth rate was calculated as $g = [\ln(\bar{X}_{i+1}) - \ln(\bar{X}_i)] \,/\, days$ where $\bar{X}_i$ is mean length in sampling run i and days is the number of days between the sampling runs. The mean riverwide bottom temperature was calculated from the WQS data.

Growth estimates from the LRS program, which are primarily for larvae and early juveniles at a time of generally increasing temperatures, exhibited a dome shape with maximal growth rates between 10 °C and 15 °C (Appendix 8, Figure 3-2). Growth rates declined rapidly at temperatures above 20 °C and the fitted curve predicted zero growth above approximately 25 °C. These empirical growth rates incorporate not only temperature, but also actual food availability in the wild, and the effects of any size-dependent mortality, such as predation.

The FJS program sampled Atlantic Tomcod during summer and fall months over a period of decreasing temperature. Summer grow rate estimates, at temperatures near 25 °C, are highly variable, but in general are low (near 0), while estimates from cooler fall temperatures are higher (Appendix 8, Figure 3-3), but still substantially below those of the larval and early juveniles. However, instantaneous growth rates are relative to the size of the organism and thus fall growth rates from the FJS program may still reflect higher growth in mm/day than the LRS rate estimates. Late fall is a period when Atlantic Tomcod are rapidly increasing in weight as the spawning season approaches, thus length data would not reflect these physiological changes.

3.6.4 Diet and Consumption

The Tomcod diet study conducted from 1996-2005 documented the seasonal shift in amounts and types of food eaten by Atlantic Tomcod. Consistent with minimal growth during the summer months, mean weight of food items per fish collected in July and August was 0.06 g. Consumption increased slightly in September to a mean of 0.10 g, and then more rapidly though the fall to 0.25 g in September, 0.41 g in October, and 0.70 g in December (Appendix 8, **Error! Reference source not found.**).

The diet of Atlantic Tomcod depends to a great extent on where they are in the Estuary (Appendix 8, Figure 3-5). In primarily brackish regions (YK through IP), Decapoda (crabs and shrimp) formed the major part of the died, with significant contributions from Mysidacea (mysid shrimp), Amphipoda (*Gammarus* sp.), and Isopoda. The increase in consumption in the fall was not due to a new prey item, but to greater feeding on the same prey taxa. In the freshwater region, Amphipoda were the dominant food source, with Isopoda and Insecta also significant. During the fall months, Decapoda were also significant.

Diet of Atlantic Tomcod in 1996-2005 was consistent with the findings of Grabe (1978, 1980) on Atlantic Tomcod captured in Haverstraw Bay in the 1970s, although Grabe's results are more applicable to the brackish regions than freshwater regions.

3.6.5 Population dynamics

By matching the abundance estimates from the ATSA, LRS, and FJS programs for each year class, the mortality rates from one stage to the next were estimated. The poor relationship between Age 0 abundance in May and September suggests that this may be the critical period determining the ultimate success of the year class. The HRBMP studies of this species provide evidence for at least four factors that may affect survival over this period: temperature, liver tumors, parasite infestation, and predation.

3.6.5.1 Temperature

Summer mortality for Age 0, and annual mortality for Age 1, both exhibited a significant positive relationship with an index of heat stress for Atlantic Tomcod. The heat stress index (HSI) was calculated from the average bottom temperature for each region in each week, $\bar{T}_{wr}$:

$$HSI = \sum_{weeks} \sum_{regions} \max(0, (\bar{T}_{wr} - 24))$$

Temperatures above 24 °C were used for the heat stress index because this is the temperature at which growth ceased (Bonvengna et al. 2001). Both summer mortality for Age 0 and annual mortality for Age 1 were positively related to the heat stress index (Figure 3-11), indicating that the spatial and temporal extent, and severity of high bottom temperatures in the Estuary may be adversely affecting the Atlantic Tomcod population. Schreibman and Young (2002) reported that thermal stress may differentially affect small and large Tomcod, with smaller fish being more sensitive.

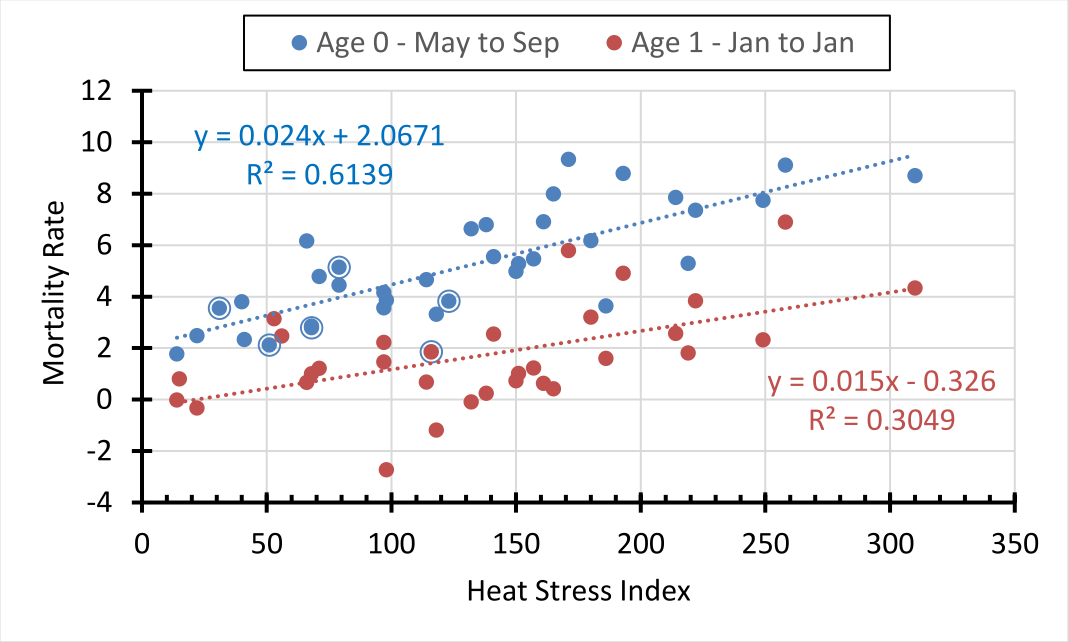


Figure 3-11 Relationship of Age 0 May-Sep mortality and Age 1 annual mortality with a Hudson River heat stress index. Circled points are based on epibenthic sled sampling in FJS. Uncircled points are based on beam trawl sampling in FJS.

As discussed above, Atlantic Tomcod have been reported to stop growing over the summer months (McLaren et al. 1988) when water temperature exceeds 20 °C (Bonvegna et al 2001), and food consumption is very low (See Section 3.6.4). Water temperatures in the estuary sometimes exceed lethal temperatures (See Appendices 3 and 4), indicating that summer is a stressful period for the Hudson population. Age 0 and Age 1 Atlantic Tomcod collected in the IPSS program from 1974-1980, which measured both length and weight, demonstrated not only a cessation of growth, but also a drop in condition factor ($K = \text{Weight}\cdot10^5 \div \text{Length}^3$) in July and August (approximately weeks 27-35), followed by a recovery of condition in the fall when temperatures dropped (Appendix 8, Figure 3-12).

3.6.5.2 Liver Tumors

Liver abnormalities in Hudson River Atlantic Tomcod were first observed in the early 1970s (Dey et al. 1993), and confirmed as cancerous in 1979 (Smith et al. 1979). Rates have appeared to decline since they were originally reported. Dey et al. (1993) observed an incidence rate of 44% of Age 1 spawners in the winter of 1983-1984, and 93% of Age 2 spawners. Schreibman and Young (2002) reported abnormal (Category 2 and 3 using Dey et al. classification) livers in 23% of fish under 200 mm, and 35% in fish over 200 mm from the 1997-1998 spawning season. Tumor prevalence had declined to less than 25% of all spawners examined in 2002-2003 and to 1% in 2015-2016 (Appendix 8, Figure 3-13). Wirgin et al. (2011) suggested that PCB susceptibility had exerted an evolutionary selection pressure on the population for genotypes that were resistant to PCB's effect, but this change in genotypes may also have a cost of lowered fitness with respect to other unknown factors.

3.6.5.3 Parasites

Atlantic Tomcod in the Hudson are infested by at least two different parasites, an internal Acanthocephalan in the reproductive tract, and an external *Lerneae* copepod (Schreibman and Young 2002). No information on frequency or severity of infestation is available prior to the 2002-2003P ATSA. External parasitic infestation has also varied since 2003 when the ATSA began recording infestation rates, but no information is available on rates of Acanthocephalan incidence.

Even with both liver tumors and parasites, affected Age 0 fish are not obviously in poorer condition than unaffected, so the degree of impairment may be poorly reflected in weight and length or condition factor. Although both types of impairment appear greater for Age 2 fish, the increase in Age 0 mortality over the summer since 1990, and high proportion of eggs that come from Age 1 spawners suggests that Age 0 is the critical period that has changed the population dynamics.

3.6.5.4 Predation

Predation is another factor potentially capable of altering Atlantic Tomcod population dynamics. Although Dunning et al. (1997) found no evidence that immature overwintering Striped Bass fed on Atlantic Tomcod, Juanes et al. (1993) reported that Bluefish, particularly larger Age 0 Bluefish, seemed to prefer Atlantic Tomcod. Zima et al. (2002) reported that American Eel, Striped Searobin, Striped Bass, Age 1 Atlantic Tomcod, White Catfish, Weakfish, and White Perch all preyed upon Age 0 Tomcod in the Hudson River in the summer of 2001, and that predator community changed with location. The location of Age 0 Atlantic Tomcod with respect to the density of potential predators may be aggravated by high summer temperatures, which may force the cohort out of the warmer upper regions of the Estuary so that they are concentrated in the lower more-saline cooler regions, which have a different mix of predators (See Appendix 4). One other aspect of predation is that spawning adults have be found to consume Tomcod eggs (McLaren et al. 1988).

3.6.5.5 Density Dependence

Density dependence, a relationship, usually inverse, of life history characteristics such as survival rates, growth, or fecundity, with population density or size, may also play a role in the stock dynamics. A negative relationship of age-specific fecundity with the number of spawners was recognized early in the HRBMP (McLaren et al. 1988, EA 1983), and has continued throughout the study (Figure 3-12). This relationship may be one mechanism by which the Tomcod population has been able to produce relatively large year classes after a winter with low spawning stock abundance.

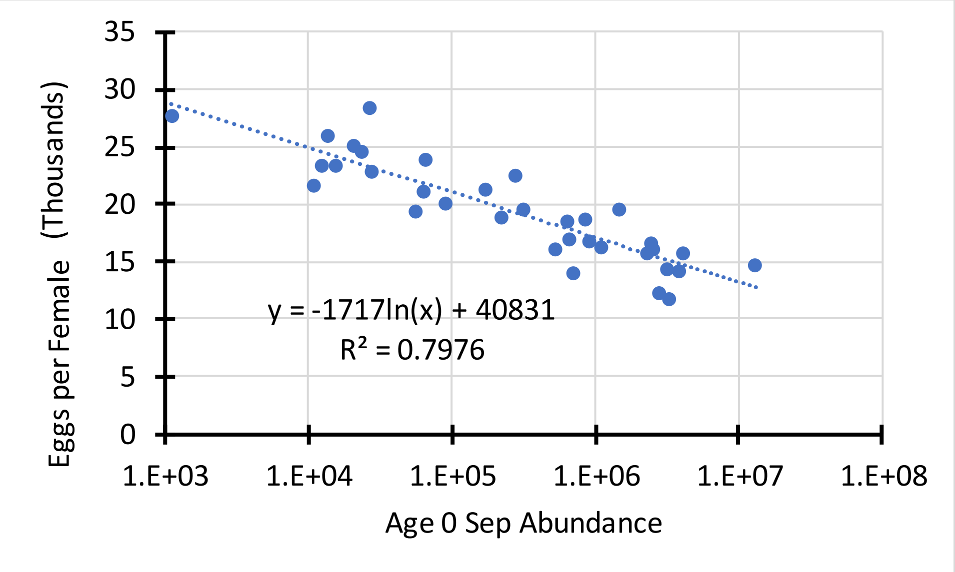


Figure 3-12 Relationship of mean Age 1 fecundity of Atlantic Tomcod with Age 0 September abundance.

3.6.6 Conclusion

All Atlantic Tomcod populations are short-lived, but the Hudson River population appears to be the most truncated (Klauda et al. 1988). Schreibman and Young (2002) held post-spawning Age 1 Tomcod to determine whether the short life span was pre-determined, i.e. physiologically semelparous, and concluded that it was not. The Hudson population may have evolved in an environment where heavy predation on all ages exerts selective pressure toward early maturity and high reproductive effort (including migration to suitable spawning habitat and large energetic investment in gametes by both sexes), to the extent that Age 2 and older fish are typically demographically irrelevant, with the caveat that their relatively high fecundity in comparison to Age 1, can provide a sufficient level of spawning to sustain the population through an extremely poor year class of Age 1. In the earlier years of the HRBMP, an alternating pattern of high and low spawning populations suggested that mortality may be density-dependent, and there is some evidence of density-dependence in growth (NAI 2019) and fecundity during the first year of life (NAI 2019). A more complete analysis of the Atlantic Tomcod information available in the LRS, FJS (including food habit studies from 1996-2005), WQS, ATSA, IPSS, and Mark-Recapture programs, and integration with the work at NYU (Wirgin work group), NMFS Sandy Hook Laboratory, and HRF-funded studies on Atlantic Tomcod may solve some of the remaining questions about this population.

3.7 STATUS OF ENDANGERED STURGEON POPULATIONS

Only two of the 171 species collected in HRBMP sampling are listed as threatened or endangered, Atlantic Sturgeon (*Acipenser oxyrhynchus*) and Shortnose Sturgeon (*Acipenser brevirostrum)*. This Appendix 9 describes observations in the data available from encounters with these two endangered sturgeon species during the Hudson River Biological Monitoring Program (HRBMP) surveys from 1974 through 2017. Shortnose Sturgeon (range-wide) was listed during the original implementation of the Endangered Species Act in 1967, and the New York Bight distinct population segment (DPS) of Atlantic Sturgeon, which uses the Hudson River Estuary most often (along with most other DPSs), was listed in 2012 in response to low abundance levels.

The HRBMP has never specifically attempted to collect either species, thus all sturgeon captures have been incidental. However, the HRBMP data still are useful in describing the spatial and temporal distribution of various sturgeon life stages within the Hudson River Estuary, temporal trends in abundance over the last four decades, and information on length-weight relationships of both species.

3.7.1 Shortnose Sturgeon

The Shortnose Sturgeon is a benthic fish that spends most or all of its life in fresh or brackish waters, making infrequent forays into saltwater and when doing so, remaining relatively close to shore. They prey largely on benthic invertebrates including mollusks, crustaceans, polychaetes and insects (Dadswell et al. 1984).

Seasonal migrations, habitat usage, and reproductive activity of shortnose sturgeon are well-described in published literature (Dovel et al. 1992, Geoghegan et al. 1992, Baine 1997). Collections of shortnose sturgeon eggs, larvae, juveniles, and adults by the HRBMP age generally consistent with this published literature.

Data summarized in Appendix 9 confirm that the distribution of Shortnose Sturgeon eggs and larvae occur primarily upriver from the Highlands (RM 46–52). Subadult and adult Shortnose Sturgeon are distributed throughout the Hudson River Estuary in the summer and fall, where they have been encountered by the gears used in both the LRS and FJS. The large majority of Shortnose Sturgeon encountered in the FJS were in the beam trawl, with few in the smaller epibenthic sled, and only one in the midwater Tucker trawl. In the LRS, 142 Shortnose Sturgeon were captured in the epibenthic sled and 3 were captured in the Tucker trawl. The number of Shortnose captured in these surveys annually ranged from 0 (1975) to 87 (1993) and averaged 26. The BSS, which collected 59,529 samples between 1974 and 2017, did not encounter any sturgeon.

In addition to the distribution of Shortnose observed in the summer and fall months via the LRS and FJS, the Striped Bass survey encountered Shortnose Sturgeon in the winter and spring months (Nov–Apr) in the Battery and Upper Harbor. A total of 227 adults and zero juvenile Shortnose Sturgeon were encountered in the Striped Bass Survey from 1989-2017. This survey was conducted in the lowest portion of the Hudson River Estuary in Upper NY Harbor and adjacent to Manhattan, suggesting that this lower section of typically higher salinity is relatively poor habitat for the juvenile life stage of this species. The presence of Shortnose in all surveys during all seasons is a good indicator of the wide use of habitat both spatially and temporally for this species in this estuary, although habitat usage varies among life stages.

Appendix 9 includes an analysis of the depth distribution of shortnose sturgeon encountered by HRBMP sampling gear, based on the sample depth distribution observed from the tow locations in the HRBMP and bathymetry of the available potential habitat in the Hudson River Estuary.

Figure 9-4 of Appendix 9 (reproduced here as Figure 3-13), reports the frequency of occurrence of Shortnose Sturgeon relative to depth of all samples collected by HRBMP bottom gear (beam trawl and epibenthic sled) over the period 2000-2017. This figure shows a distinct preference of shortnose sturgeon for water deeper than 40 ft. In contrast, shoreline habitat less than 10 ft deep, water column of the channel, and bottom areas of erosion and scour were low-valued habitat for Shortnose Sturgeon. These results are consistent with the conclusions of (Dadswell et al. 1984) concerning habitat preferences of this species.

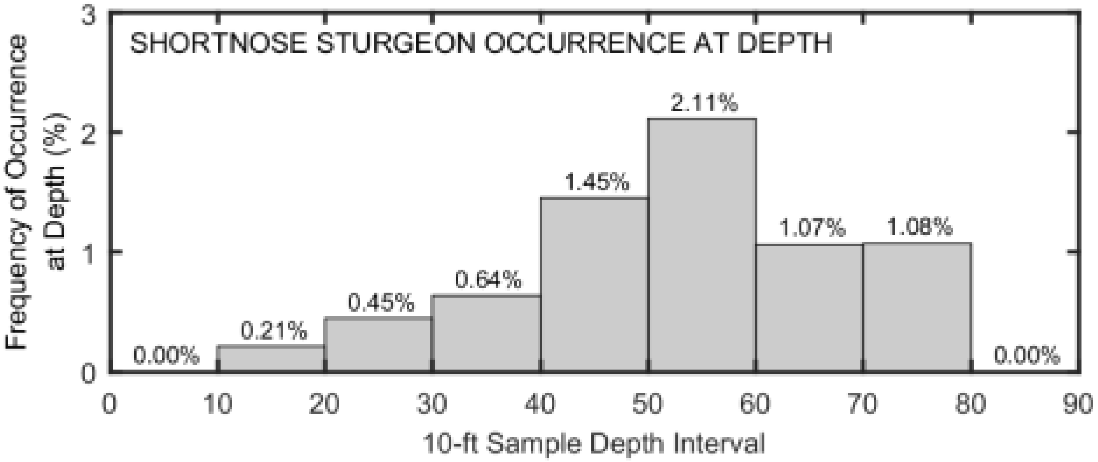


Figure 3-13 Frequency of Shortnose Sturgeon occurrence in samples collected by bottom gear in each 10-ft depth interval.

Appendix 9 also summarizes data on the length distributions, length-weight relationships, and abundance trends for shortnose sturgeon collected during the HRBMP. Trends indices calculated from HRBMP data are consistent with other estimates of Shortnose Sturgeon population trends in showing a peak in the early 1990s, followed by a gradual decline (Figure 9-7 of Appendix 9, reproduced here as Figure 3-14).

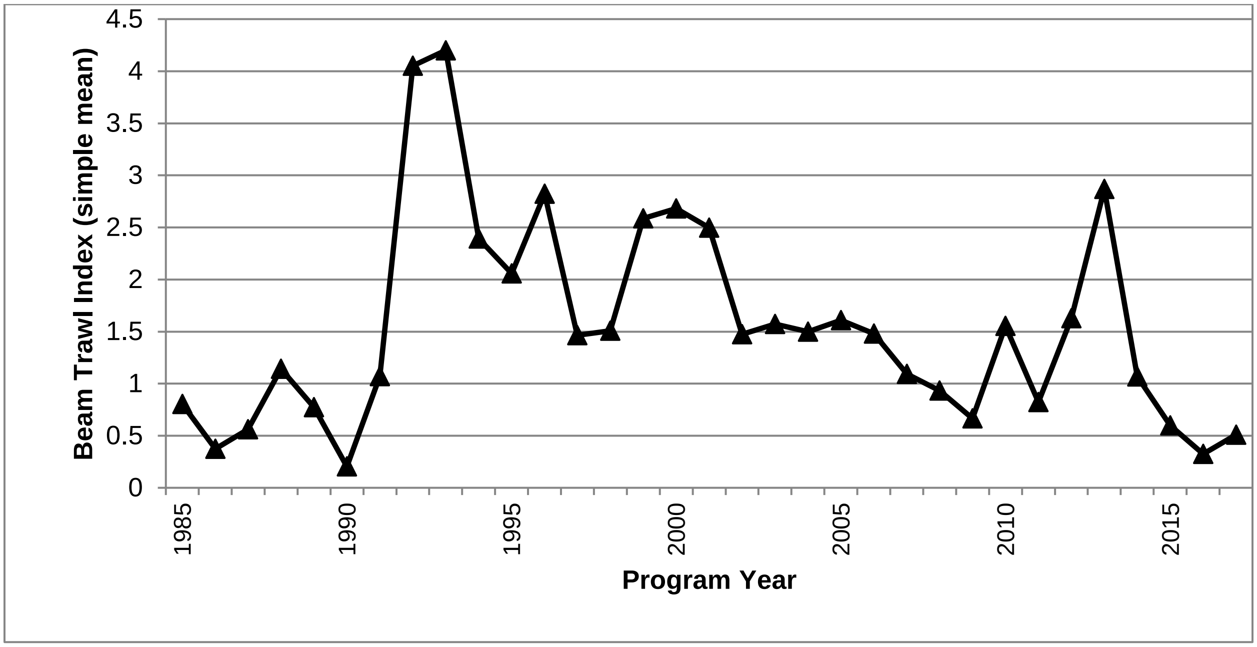


Figure 3-14 Simple mean density (#/1000 m^3) as an index of abundance for Shortnose Sturgeon in the HRBMP Fall Shoals Survey, beam trawl, 1985 through 2017.

3.7.2 Atlantic Sturgeon

Atlantic Sturgeon range from Nova Scotia to Florida and are anadromous; spawning occurs in freshwater, but adults reside for many years in marine waters. Bain (1997) concluded that spawning females enter the Hudson River in mid-May and migrate along deep channel areas directly to freshwater spawning grounds upriver near Hyde Park (RM 81) and Catskill. Spawning males enter the Hudson River starting in April and some may remain in the estuary as late as November. During their upstream migration, male sturgeon reside in channel areas in water greater than 25 ft (Dovel and Berggren 1983, Bain 1997). Females return to marine waters quickly after spawning; embryos and larvae are intolerant of saline conditions and some significant length of river habitat is needed downstream of a spawning site to accommodate dispersal of these life stages (Bain 1997). These observations are supported by empirical data obtained from the LRS ichthyoplankton surveys from 1979 through 2017These data demonstrate that Atlantic Sturgeon eggs, larvae and young of the year rarely occur below the West Point region (RM 47). In fact, only one young of the year Atlantic Sturgeon and one unidentified larval sturgeon (probably an Atlantic Sturgeon) were observed downstream from the Highlands (RM 46-52) between 1974 and 2017. The presence of both was likely related to storm events and high freshwater flows that displaced eggs or larvae downstream from the upstream spawning grounds.

Juvenile Atlantic Sturgeon are distributed over much of the Hudson River from July through September and use deep channel habitats as in other life stages (Bain 1997). The HRBMP FSS and LRS encountered Atlantic Sturgeon young-of-the-year, early juveniles, and late juveniles in all years from 1974 through 2017. The majority of Atlantic Sturgeon encountered in summer and fall months were captured in the FJS beam trawl. No Atlantic Sturgeon were encountered in the BSS. In all cases during the years where length data were collected, late juveniles were the most abundant Atlantic sturgeon life stage. In the fall, juveniles overwinter in brackish water between RM 1-46, however they remain in deep channel areas. Data from the Striped Bass Survey (November through April) shows the presence of Atlantic Sturgeon in the lower part of the river during the winter months.

As in the case of Shortnose Sturgeon, analyses of the frequencies of occurrence of Atlantic Sturgeon in samples collected at different depths showed that the highest frequency of occurrence of this species is in water deeper than 40 ft. These data are consistent with other published literature, including a habitat study performed by NYSDEC (2009), that demonstrate that Atlantic sturgeon prefer deep areas with soft sediment and avoid near-shore areas and areas with hard substrates.

An index of juvenile Atlantic Sturgeon abundance over the years 1985-2017 derived from the FJS beam trawl data shows that Atlantic Sturgeon abundance was comparatively high from 1985 through 1989, then was relatively low and stable from 1990 through 2011, and finally increased increase in abundance during the most recent years (Figure 9-15 of Appendix 9, reproduced here as Figure 3-15).

Appendix 9 summarizes data on weight-length relationships in Atlantic sturgeon captured by the HRBMP. Atlantic Sturgeon in the HRBMP averaged 477 mm total length, with individuals ranging in total length from 51 to 1320 mm and representing the young-of-the-year, early juvenile and late juvenile life stages.

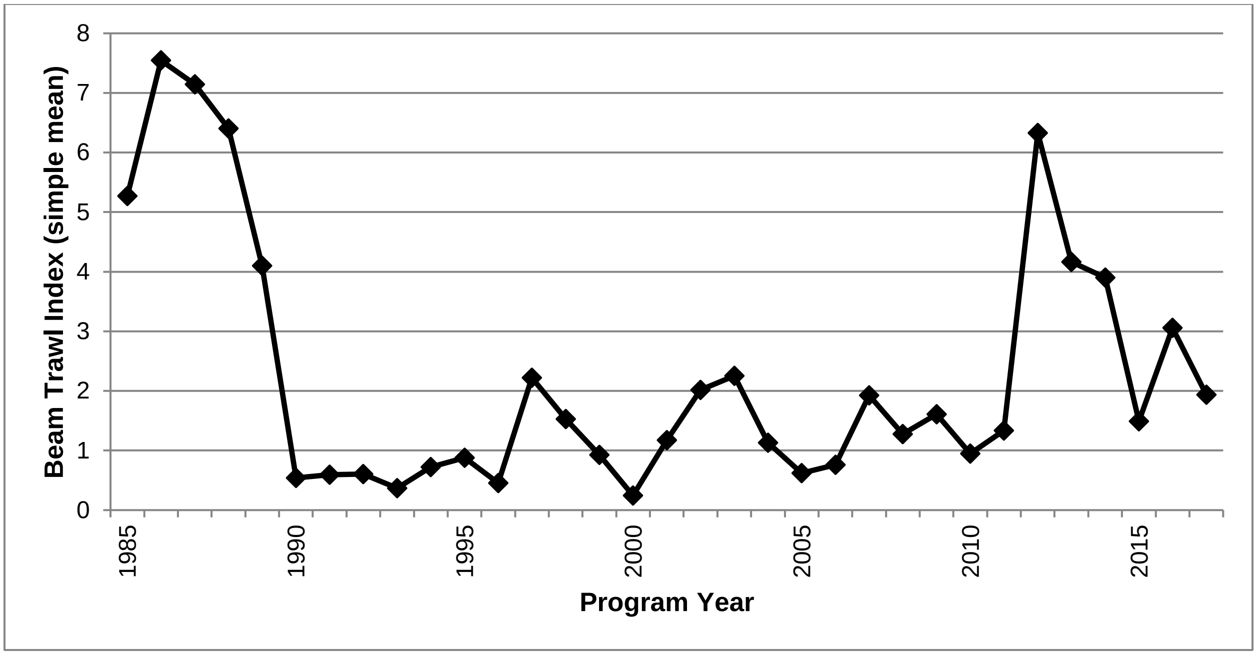


Figure 3-15 Simple mean density (#/1000 m^3) as an index of abundance for Atlantic Sturgeon in the HRBMP Fall Shoals Survey beam trawl (36,224 use code = 1 tows), 1989 through 2017.

3.8 AMERICAN EEL IN THE HUDSON RIVER ESTUARY

The American eel (*Anguilla rostrata*) is a wide-spread and previously common species in the eastern United States in general, and in the Hudson River Estuary in particular. American eel undergo several morphological changes from larvae (or leptocephali), to glass eel, to juvenile yellow eel, and finally a mature silver eel). The larval and silver eel life stages migrate thousands of miles between marine waters of the Sargasso Sea and continental waters from Venezuela to Canada. Larval migration starts as passive entrainment in ocean currents but metamorphosed larvae (glass eels) are believed to actively swim across the continental shelf without direction toward specific estuaries or rivers. Shortly after entering reduced salinity waters, glass eels become pigmented elvers (i.e., small yellow eels). Yellow eels grow for 2 to 30+ years before maturing and returning to the Sargasso Sea to spawn and die.

There has been a recent surge in interest in American eel as a result of its decline in abundance over the last 2 decades throughout its entire range across the Atlantic coast of North and South America. A similar decline has affected the European eel (*Anguilla anguilla*), a species that has nearly identical life history. However, their size, shape, and unique life history make eels a relatively poor fit to typical fisheries sampling programs.

Potentially important information on American Eel is available in the HRBMP data, as evidenced by the use of 1987 captures in LRS and FJS sampling by Mattes (1989). This report will extract some of the information and attempt to place it in context with what is known about the species generally, and with other directed studies of Eel in the Hudson River Estuary, much of it sponsored by the Hudson River Foundation.

3.8.1 American Eel Collection

American eel may be collected in nearly any of the sampling gear employed in the HRBMP, however, their shape, small size as glass eels and elvers, and slipperiness makes most of the sampling relatively inefficient at retaining them. The LRS program, which uses 0.5 mm mesh nets is the only gear that can effectively sample glass eels and elvers. All eels ≤ 150 mm are be considered to be either glass eels or elvers recently arrived in the estuary. Nearly all eels > 150 mm are considered be immature yellow eels. The sampling program probably occasionally catches mature silver eels on their way out of the estuary, but occurrences of this life stage are relatively rare.

During the Indian Point Standard Stations (IPSS) program from 1974-1980 (See Section 2., American eel were collected in a bottom trawl with and without a small mesh liner in the cod end, and with the standard 100’ beach seines, and taken to the laboratory for length and weight measurements.

3.8.2 American Eels in the Hudson River

The IPSS program provides information on the length frequency and length-weight relationship of American eel in the Hudson River Estuary during the 1970s. The lengths of eels collected in bottom trawls, with and without a liner, and in beach seines demonstrates both habitat selection, and distinct size selectivity. The bottom trawl with a liner collected eels ranging from less than 100 mm to greater than 500 mm, with a distinct mode at 350 mm and a second mode around 150-200 mm. Without the liner, the bottom trawl collected only larger yellow eels, primarily between 250 mm and 450 mm. The collection of the smaller group of yellow eels in the trawl with the liner indicates that the offshore areas are inhabited by recently arrived elvers and yellow eels of a wide range of sizes. In the shore zone however, beach seine collections were dominated by eels 200 mm and less, with very few larger eels. The relative lack of larger yellow eels could be due to their scarcity in the shallower habitat, or to a very low capture efficiency for larger eels.

Abundance of eel was estimated through the mean LRS standing crop of glass eels and elvers combined during the spring and early summer (weeks 18-26), LRS standing crop of yellow eels during this same period, and mean FJS standing crop of yellow eels from weeks 32-40. Due to the different mesh sizes and selectivity, the standing crops are not directly comparable across the surveys, but each survey provides a consistent measure of abundance over the time span available. The FJS data are restricted to 1985-2017, the period when a beam trawl was used for sampling on the bottom.

Estimates of eel standing crops from LRS and FJS surveys demonstrate the decline in abundance of the last two decades. Glass eels and elvers exhibited large changes in abundance from the 1970s through the 1990s, with peaks occurring in 1979, 1993, and 1974. In peak years, standing crops ranged from 5.7 to 8.7 million, but in non-peak years abundance was generally less than 3 million. During this same period, yellow eel abundance ranged from 13 million in 1974 to less than 2 million, with a period of relatively high abundance from 1984-1987. From 1985 through the 1990s, yellow abundance in the FJS exhibited a consistent declining trend.

Since the 1990s, all three of the abundance measures have fluctuated at levels far below those observed early in the HRBMP, although both LRS measures show slight increases over the last decade. The recent trend of glass eels and elvers in HRBMP is roughly consistent with an increasing trend in glass eel and elver abundance in tributaries sampled by the Eel Project.

3.8.3 Other Research on American Eel in the Estuary

Substantial directed research on American Eel in the Estuary has been conducted over the last 30 years, much of it funded by the Hudson River Foundation. These studies have examined the general ecology of American Eel in the Estuary (Mattes 1989), parasitic infection rates (Barse and

Secor 1999, Machut 2006, Machut and Limburg 2008), aging techniques (Secor 2000), contamination (Baker et al. 2002, Secor and Arsian 2006, Limburg et al. 2008), use of tributaries (Petersson and Schmidt 2004, Anderson and Schmidt 2006, Machut 2006, Limburg and Schmidt 2008, Machut et al. 2008, Camhi and Grippo 2018), and silver eel use of tributaries (Limburg and Schmidt 2017)

3.9 HABITAT UTILIZATION BY MARINE FISH SPECIES

Although the primary focus of the HRBMP's study design was on anadromous and estuarine species, the HRBMP collected data on the seasonal abundances and spatial distributions of all species susceptible to the gears used in the three primary surveys. Many commercially important marine species inhabit estuaries, such as the Hudson River Estuary, during certain parts of their life cycles. Some of these are species for which the National Marine Fisheries Service is required to designate Essential Fish Habitat (EFH) under the Magnuson-Stevens Sustainable Fishery Act (Magnuson Stevens Act or Act). For example, the Hudson River Estuary is designated as EFH for Atlantic butterfish, Atlantic herring, black seabass, bluefish, red hake, summer flounder, windowpane, and winter flounder. Appendix 11 illustrates how HRBMP data could be used to more precisely identifying the regions of the Hudson River estuary that are utilized by EFH species.

3.9.1 Long-term Average Habitat Use, by Region

For all three programs, sampling and data analysis focused on the 152-mile tidal river from the Battery Point to the Federal Dam, subdivided into 13 sampling regions (cite to figure?). Because the lowermost and most marine sampling region (Region 0, beginning at Battery Point) is not included in the BSS, the LRS and the FJS are the primary data sets used here to evaluate riverwide habitat utilization. The LRS began sampling Region 0 in 1988; the FJS began sampling this region in 1996. Hence 30 years of data are available for characterizing the utilization of the estuary by eggs, larvae, and early YOY fish; and 22 years of data are available for older YOY.

Although all 8 of the EFH species have been collected by the HRBMP, most of these species have been collected very infrequently. For example, only 3 red hake larvae and 2 red hake YOY were collected, between 1988 and 2017. Only 34 black seabass larvae were collected, and 32 of these were collected in a single year (2012) in Region 0. Five or fewer Atlantic butterfish larvae were collected in most years of the HRBMP. Total numbers of four uncommonly collected species, by life stage, are documented in Appendix 11. All four species were collected primarily in regions 0-3, and only a few organisms were collected above region 6.

The EFH species and life stages that have been most commonly collected by the HRBMP are Atlantic herring larvae, Bluefish YOY, windowpane eggs and larvae, and winter flounder larvae. Appendix 11 documents estimates of the distributions of these species and life stages among the 13 river regions, based on the standing crop metric. The standing crop metric weighs the density of organisms measured in each sample stratum (habitat x gear combination) by the total volume of that stratum. The methods for performing these calculations are documented in Appendix 2 of this report.

To calculate long-term average habitat use, the standing crops of each species and life stage within each region were averaged over all sampling events in which that species and life stage was present in the river. The resulting values are estimates of the average annual abundance of each species and life stage in each region, during the period when that species and life stage is present in the river. These values were then used to estimate the percent of the total riverwide standing crop that was present in each region.

The cumulative distributions of standing crops, starting with Region 0 were used to define average habitat usage for each of these species. Tables 2 through 5 of Appendix 11 identify, for each species and life stage, the regions containing 50% and 95% of the average annual standing crop.

Atlantic herring larvae have been collected in every region except Region 7, although the great majority of larvae are found in the lower estuary. More than half of the larval population occurs in Region 0, and 98% are found between Regions 0 and 2. Less than 1% of the annual average standing crop occurs above Region 3.

Only 4 Bluefish larvae and no Bluefish eggs were collected by the LRS between 1988 and 2017. Bluefish YOY are abundant in near shore areas throughout the Middle Atlantic Bight, but also enter the Hudson River, where they have been collected as far upriver as Region 9 (Kingston). Bluefish YOY are collected both by the LRS and the FJS. Since these two surveys are conducted during different seasons, differences between the distributions estimated from these surveys reflect seasonal differences in the riverwide distribution of YOY Bluefish. As shown in Table 3 of Appendix 11, for both surveys the median of the cumulative distribution falls in Region 2. However, the 95th percentile is shifted upstream from Region 6 in the LRS to Region 7 in the FJS, with 1% of YOY Bluefish being collected as far upriver as Region 8.

Windowpane eggs have been collected in all 13 regions, and that larvae have been collected in all regions except Regions 10 and 11. However, standing crops of windowpane eggs and larvae are very low in all regions above Region 2. More than 99% of the average annual standing crop of windowpane eggs occurs in Regions 0 and 1, and 97% of the annual standing crop of windowpane larvae occurs in Regions 0-2.

Winter flounder larvae have been collected in all regions except Region 11. However, 67% of winter flounder larvae occur on average in Regions 0 and 99% occur in Regions 0-2.

3.9.2 Influence of Salinity on Habitat Use

As discussed in Section 3.2 and Appendix 3, the HRBMP data sets include comprehensive measurements of dissolved oxygen, temperature, and salinity throughout all river strata. All three parameters vary substantially both within and between years. It might be expected that these variations would influence the spatial distributions of the fish species present in the river. In particular, the distributions of marine species such as those discussed in this chapter might be expected to vary in responses to changes in salinity, moving upriver or downriver in response to shifts in the salinity distribution.

The mesohaline zone of the Hudson River is defined as the zone with salinities between 5 and 18 ppt (Cooper et al. 1988). Table 7-18 of Appendix 3 contains annual mean salinities from the HRBMP Water Quality Survey for regions 1-12 for the years 1988-2017 and for regions 0-12 for the years 1995-2017, over survey weeks 18-36 (May through early September). This is the time period in which the species addressed in this chapter are found in the river. Table 7-18 of Appendix 3 shows that the upper limit of the mesohaline zone (5 ppt) typically is found in region 2 during this period, but occasionally is as high as region 3 or as low as region 1.

Figure 3-16 (Figure 1 of Appendix 11) plots the regions in which the 95th percentile of the distribution for each species occurred during each year from 1988 through 2017, together with the position of the boundary between the mesohaline and oligohaline (5 ppt-0.3 ppt) zones during those years. The mesohaline/oligohaline boundary occurred in region 2 in 18 of the 30 years, in region 3 in 7 years, and region 1 in 5 years. The 95th percentiles of the distributions of 3 of the 4 species discussed here were located within the mesohaline zone during most, but not all, years. The spatial distributions of YOY Bluefish were more variable than the distributions of the other 3 species, with the limit of the distribution ranging from region 3 to region 7.

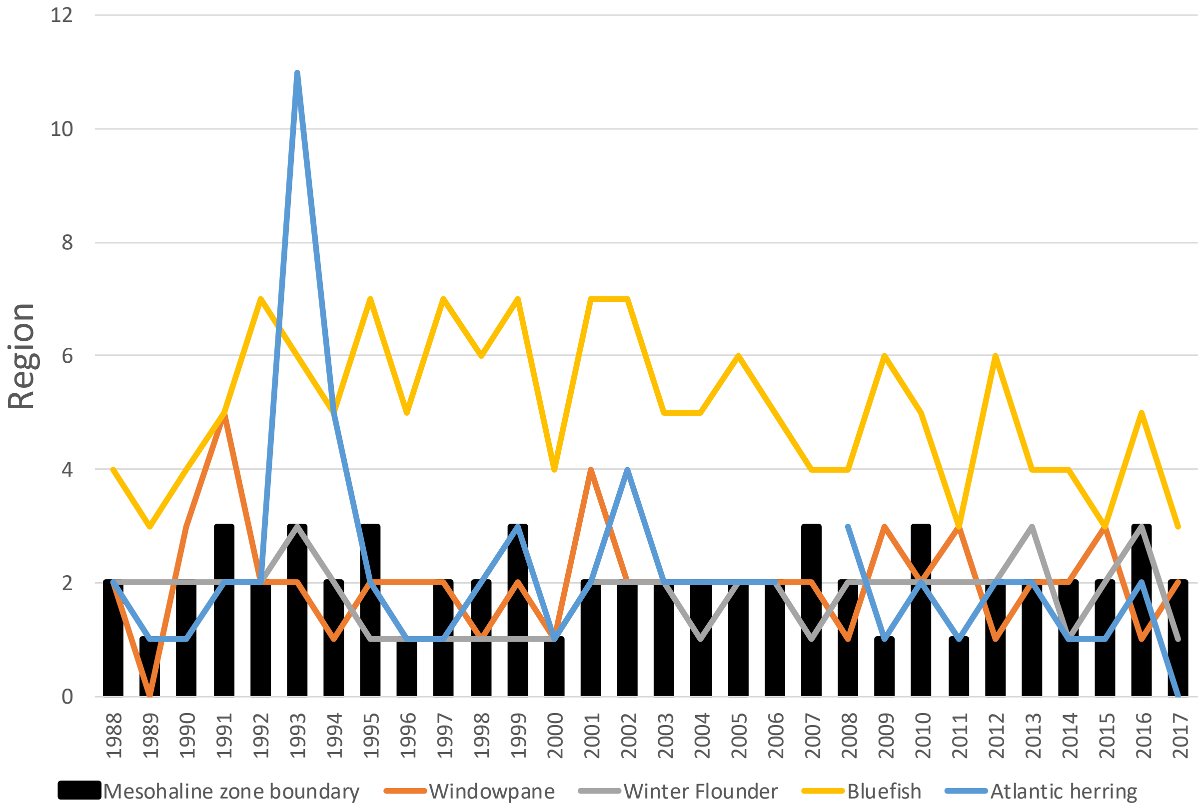


Figure 3-16 Region containing 95th percentile of larval distribution relative to region containing mesohaline/oligohaline boundary.

Figure 3-17a (Figure 2a of Appendix 11) plots the salinities in regions in which the median and 95th percentile of the YOY Bluefish distributions in the LRS data set occurred from 1988 through 2017. Figure 3-17b (Figure 2b of Appendix 11) plots the same values from 1996 through 2017 in the FJS data set. According to both data sets, in most years YOY Bluefish were most abundant in the mesohaline zone but were present throughout the oligohaline zone as well.

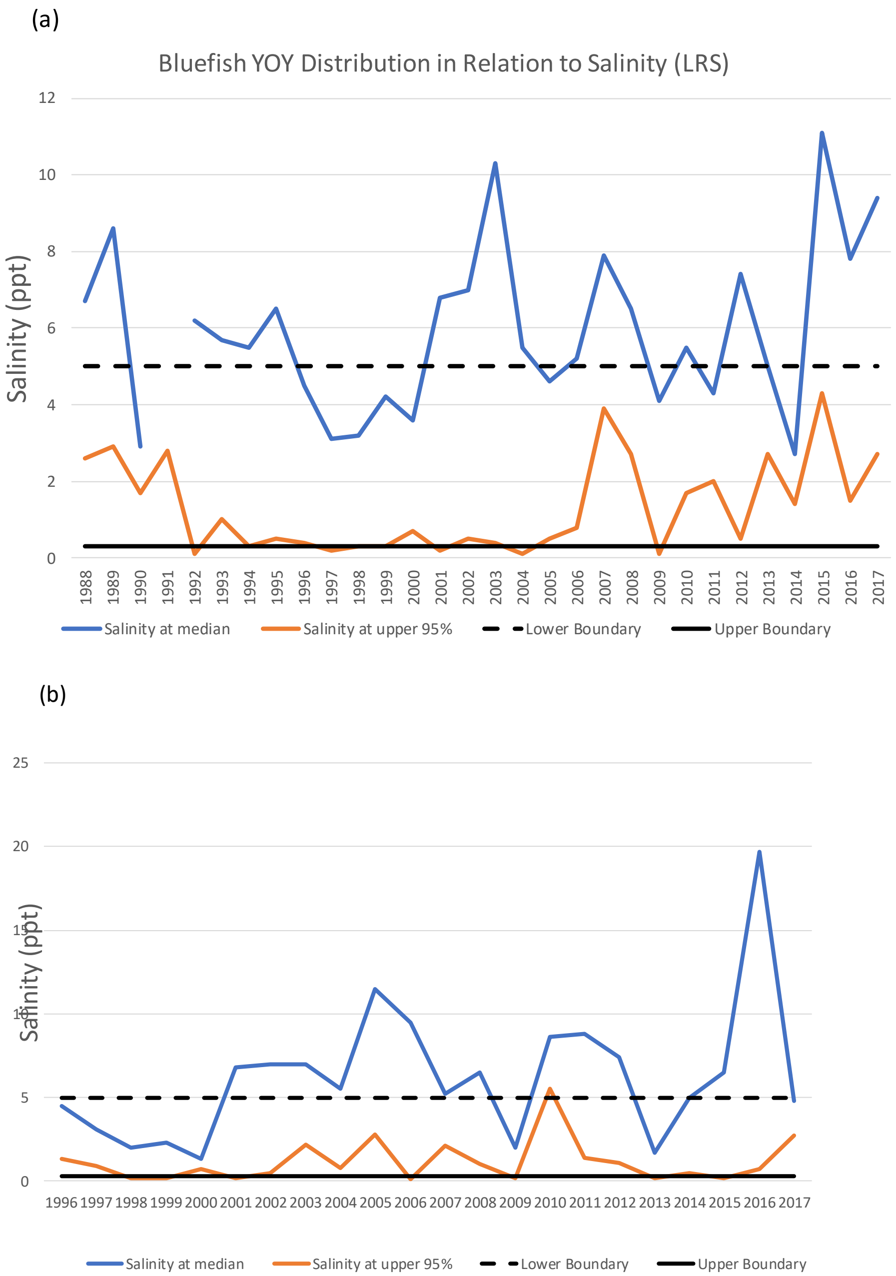


Figure 3-17 Salinity of regions containing median and 95th percentiles of the distributions of YOY Bluefish relative to salinities at the lower and upper boundaries of the oligohaline zone: (a) LRS data set; (b) FJS data set.

3.9.3 Discussion

Appendix 11 provides an example of the utility of the HRBMP data for studying the spatiotemporal distributions of fish species that, although not considered when the program was designed, are still effectively sampled because of (1) the variety of sampling gears employed and (2) the riverwide design of the program. The results presented here show that the distributions of 7 of the 8 EFH species are largely restricted to the mesohaline zone of the estuary which typically includes regions 0-2 (Battery to Tappan Zee) but sometimes extends upriver to region 3 (Croton-

Haverstraw) and occasionally is limited to regions 0 and 1 (Yonkers). The life history of Bluefish is quite different from the life histories of the other EFH species, in that (1) only YOY are found in the estuary, and (2) these fish are widely distributed throughout the mesohaline and oligohaline zones.

It should be noted although the 8 species discussed here utilize habitat in the lower estuary, they comprise a very small fraction of the total fish community. For even the most abundant EFH species, only a few hundred to a few thousand organisms were collected in any given year. By comparison, the HRBMP collected nearly 12 million Striped Bass larvae and more than 6 million bay anchovy larvae between 1988 and 2017. Only the intensive nature of this sampling program permitted the characterization of habitat usage by the EFH species.

4. END OF AN ERA

This Chapter summarizes the perspectives of the leading scientists and regulators who have materially participated in the design, development, execution and analysis of data and information obtained in the multi-decadal, Hudson River Estuary-wide collection program that has become known as the Hudson River Biological Monitoring Program (HRBMP). Thus, this Chapter is designed to reflect informed individual perspectives.

More conceptually, this Chapter's purpose is to create an accessible, human, narrative record of the HRBMP from those who worked on and with it for over the more than five decades of its creation and execution (i.e., from 1966 through 2018).

Why do this? This Chapter is designed to allow the next generation of scientists to better understand how this generation of scientists and regulators undertook and continued a monumental ecological survey with a degree of commitment, continuity and clear-eyed scientific purpose that is, by all accounts, unique. We hope it serves as both a guide and template for comparable ecological efforts in the future, as well as an accessible overview to the HRBMP for those who are and will be the working ecologically based biologists, statisticians, mathematicians, regulators and economists of the future.

4.1 THE INTERVIEWS

I interviewed ten (10) individuals, the majority of whom (eight of ten) are leading fisheries scientists or ecological statisticians. To capture diverse perspectives, I deliberately included regulators and scientists who had been critical of the Indian Point owners at different points in time. To capture informed historic and currents perspectives, I interviewed those from the early and modern HRBMP periods, provided that each interviewee had at least a decade of meaningful exposure to the HRBMP. Several had more than four decades of continuous work with or assessment of HRBMP data. All interviewees are identified, with CVs that were voluntarily provided in response to my request, in Table 4-1.

The interviews lasted from approximately thirty minutes to two hours. The general form of questions asked, as they naturally evolved during each discussion, are attached at Appendix B. I retained the Q&A format below to facilitate incorporation of responses and insights with the highest degree of fidelity to each interviewee's response. Each person interviewed reviewed and approved the final form of this summary of the interviews.

I want to, personally, thank each person for their willingness to speak, candor and commitment of time to this process.

Q: What was the initial purpose of the HRBMP?

A: All interviewed understood that the initial purpose of the HRBMP was to assess the potential impact of the construction and operation of multiple, then-planned power plants on the Hudson River fisheries, particularly the representative important species that employed the Estuary as nursery habitat, such as Striped Bass (e.g., Lawrence W. Barnthouse, Ph.D.; Fred Dacimo; Richard B. Deriso, Ph.D.; Dennis J. Dunning, Ph.D.; Peter Henderson, Ph.D.; Douglas G. Heimbuch, Ph.D.; William G. Little, Esq.; Mark T. Mattson, Ph.D.; John Waldman, Ph.D.; John R. Young, Ph.D.).

All involved at the HRBMP's outset stated that, at the time or shortly after the onset of the HRBMP, the work was understood to be a fundamental ecological assessment and an important scientific endeavor performed on a monumental scale, e.g., over the 150-odd mile Estuary over a substantial period of time (e.g., Barnthouse, Dunning, Heimbuch, Mattson, Waldman, Young). Those involved more recently stated that the HRBMP continues to be understood as such today (e.g., Barnthouse, Dunning, Heimbuch, Henderson, Little, Mattson, Waldman, Young). Dr. Waldman observed, with respect to the HRBMP, that “if you want to see the heartbeat of a river, this is a good way to do it.”

Some involved at the HRBMP’s outset voiced their belief, early on, that a discernible, if not a material, impact would be shown as result of power plant operations, but that a key – and surprising -- observation of the HRBMP has been that commercial fishing was a dominant force or signal on some Hudson River fish populations (e.g., Barnthouse, Dunning, Mattson, Waldman).

Q: What was the confluence of factors that contributed to the creation and continuation of the HRBMP?

A: Most interviewed identified a confluence of factors leading to the creation and continuation of the HRBMP. As Dr. Dunning observed: “I think it was truly a unique set of circumstances that led to the collection of such an extensive database of such high quality that it is unlikely to be matched elsewhere because it costs a lot of money.” These factors included the following:

- the uniqueness, size, cultural and commercial importance of the Hudson River, even as it existed in the 1960s in a compromised state (e.g., Little, Waldman, Dacimo);
- the size and scale of the then-proposed power plants and expectation of substantial public opposition (e.g., Dunning, Mattson);
- the contemporaneous advent of environmental law and policy, particularly the passage of the Clean Water Act and certain of its provisions applicable to the power sector (e.g., Heimbuch, Little, Waldman);
- the activism of regulators and environmental advocacy groups committed to improving the health of the River (e.g., Dacimo, Dunning, Heimbuch, Little, Waldman);
- corporate commitment and the stature of Charles Luce, chairmen and chief executive of ConEdison at the outset of the HRBMP initiative and a committed environmentalist, with Entergy’s retained commitment over its ownership period (e.g., Barnthouse, Dacimo, Dunning, Little)[8] ; and
- a will to answer a critical emergent scientific question with engineering rigor in a collaborative fashion (e.g., Dacimo, Heimbuch, Mattson, Young).

Specifically, most interviewed stated that the Hudson River’s iconic historical and ecological status, and the advent of rapid industrialization into a highly valued aesthetic resource, played a role in the mandate for and development of the HRBMP (e.g., Deriso, Little, Waldman). Several mentioned that the Hudson’s iconic status was, as one scientist stated, magnified by “an amazing cast of environmentalists who were fearless and really protective” (e.g., Waldman). Several also mentioned the fact that the Hudson Estuary is unique ecologically -- a highly productive temperate Estuary (e.g., Henderson, Mattson), with a fjord-like quality (e.g., Mattson, Waldman). Some interviewed emphasized that the Hudson River essentially retained its full complement of indigenous species, unlike other major United States estuaries, such as the Connecticut River, where Atlantic salmon and other species had been extirpated (e.g., Mattson, Waldman). One

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[8] Con Edison, the then-majority owner of several Hudson River power plants, engaged a committed collaboration across those plants. This Chapter would be remiss in not underscoring the contributions to the HRBMP and Hudson River ecological assessment of Bowline, Roseton, Danskammer and Lovett Stations.

scientist mentioned the fact that the Hudson River was undammed in the Estuary main stem and therefore available for use by anadromous species to a degree not typical in many Eastern seaboard estuaries (e.g., Mattson).

Several interviewed underscored the commitment to science, scientific transparency and environmental stewardship over a protracted period of time (e.g., Dacimo, Dunning, Little, Mattson). These observers credited the sustained regulatory scrutiny affected by regulators, particularly the New York State Department of Environmental Conservation (e.g., Dacimo, Dunning, Little), in addition to the scrutiny of environmental advocacy groups (e.g., Dacimo, Dunning, Little, Waldman), as creating the need for and continuation of a major scientific endeavor. The concurrent specter or presence of litigation was repeatedly mentioned as a factor that drove rigor and continuation of the program (e.g., Barnthouse, Little).

Some interviewed also observed that the HRBMP program attracted the "best and brightest" of a generation, including from leading, innovation-based corporations and institutions, such as Alden Laboratory, Raytheon, Texas Instruments, New York University and Martin Marietta (e.g., Deriso, Dunning, Heimbuch, Little)[9]. Dr. Heimbuch echoed this idea, describing the HRBMP development team as "a powerhouse of really good scientists." Mr. Little likened the HRBMP to a "space program" for ecologists, statisticians and applied mathematicians focused on large-scale biological and ecological modelling. Dr. Barnthouse emphasized how the newly formed or augmented regulatory agencies, including the Nuclear Regulatory Commission and the United States Environmental Protection Agency, themselves went out of their ways to retain leading scientists, including from the National Laboratory network, to undertake what was recognized at the time as a pioneering effort at ecological analysis and assessment under new regulatory regimes.

Others mentioned the importance of scientific culture and continuity among the organizations performing the HRBMP (e.g., Waldman, Young), and how the program minimized changes in consulting groups that could have produced transition-related anomalies or dissonance, despite the quality assurance/quality control program employed (e.g., Mattson, Waldman).

Q: Does the HRBMP capture an important period in the history of the Hudson River ecosystem?

A: Most of those interviewed answered this question on whether the HRBMP captured an important historical era both affirmatively and unequivocally: "Yes" (e.g., Barnthouse, Dacimo, Deriso, Dunning, Heimbuch, Little, Mattson, Waldman). Many interviewed discussed the wholesale changes in the Hudson River over the timespan that the HRBMP was performed, i.e., from the mid-1960s to date (e.g., Heimbuch, Mattson). Several acknowledged that, at the outset of the HRBMP, the Hudson River was, to some degree or another, impaired in at least some of its urban reaches (e.g., Heimbuch), with those who grew up in the New York City region having inculcated the notion that the 1960s Hudson River was treated "basically an open sewer" (e.g., Dacimo).

This group of interviewees acknowledged that today, water quality has improved materially, and the Hudson River supports certain healthy fish populations (e.g., Heimbuch, Henderson,

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[9] Among these, the HRBMP included world-renowned and highly respected academicians and committed regulators whose participation was sought and expertise utilized to enhance the HRBMP, including James Colquhoun, Charles Coutant, Ph.D., the late Ian Fletcher, Ph.D., Ray Hilborn, Ph.D., Edward Horn, Ph.D., Karin Limburg, Ph.D., Ed Radle, Doug Robson, Ph.D., the late William Sarbello, the late Webb Van Winkle, Ph.D., and Carl Walters, Ph.D.

Waldman). None countered the view of material improvements in River water quality or fish species general health, although most interviewed recognized or offered their informed perspectives on the current challenges that the Estuary, and its fish species, face and will continue to face (e.g., Barnthouse, Henderson, Heimbuch, Little, Mattson, Waldman, Young). These challenges are addressed in detail below.

Q: Is the HRBMP dataset, as it currently exists, unique or important? And is this importance separate and apart from its original purpose?

A: All answered these twin questions regarding the uniqueness and importance of the HRBMP affirmatively and emphatically: “Yes,” irrespective of their historic roles or positions in the often front-page disputes between and among the Hudson River power plant owners, the environmental and anti-nuclear NGOs, and the regulatory community (e.g., Barnthouse, Dacimo, Deriso, Dunning, Henderson, Heimbuch, Little, Mattson, Waldman, Young). Dr. Mattson noted the potential scope and breadth of scientific use of aspects of the HRBMP database well beyond the original stated goal of assessing potential power plant impact to representative fish species.

The scientists interviewed identified the HRBMP as unique in terms of geographic scope, consistent level of intensity over time, and breadth (e.g., Barnthouse, Dunning, Henderson, Heimbuch, Mattson, Waldman, Young). Several highlighted the fact that the HRBMP samples using multiple gear types, mostly on a random stratified basis, throughout an entire large-scale Estuary (of approximately 150 miles), inclusive of virtually all segments of the water column from bank to bank, over more than forty-three years (e.g., Barnthouse, Dunning, Heimbuch, Henderson, Mattson, Young, Waldman). To convey the scale of the HRBMP study area, Dr. Mattson, who has led the HRBMP field collection effort since 1979, stated: “I have said on more than one occasion to more than one person in the sciences and outside of the sciences in my personal life that you can see my study area from the moon.”

Several interviewed, including those most familiar with the HRBMP dataset, also identified the comprehensive nature of the information retained on all species of fish collected across the major life stages, with the result that the HRBMP provides digitized information and after 1991 often specimens of the more than 170 species that have frequented the Hudson River since HRBMP monitoring began systematically in 1974 (e.g., Barnthouse, Heimbuch, Mattson, Young, Waldman).

Several scientists interviewed acknowledged the importance of the HRBMP’s rigor, based on its pioneering quality assurance/quality control (“QA/QC”) program, and how that rigor led to a data set that is widely considered reliable (e.g., Dunning, Heimbuch, Mattson, Waldman). Dr. Mattson described both: (1) how, at the HRBMP’s outset and uniquely in his experience, the HRBMP team applied QA/QC measures from the manufacturing and defense sectors in a quantitative manner to ecological field, laboratory, data entry and analytical processes, and (2) that the HRBMP approach is now an industry standard. Observations about dataset reliability extended beyond the scientific team. Mr. Little observed that the quality of the dataset was a credit to all, and conferred on all of the various participants a credibility for decision-making, even where the points of view differed.

Virtually all interviewed remarked on the HRBMP’s unparalleled longevity, with the program continuously and consistently performed after an initial start-up phase from 1974 through the end of most of its components in 2017 (e.g., Barnthouse, Dunning, Henderson, Heimbuch, Little, Mattson, Waldman, Young). With a notable outlier or two (e.g., Barnthouse, Heimbuch), most expressed genuine surprise that the HRBMP had continued for so long, with several opining that they had expected the HRBMP to continue for no more than ten to fifteen years at its outset (e.g., Barnthouse, Mattson). Dr. Waldman observed: "[a]s time went on and the years added up, I guess I kind of thought it would go on forever . . . that with each additional year, the value rose so it would be harder and harder to see it disappear . . . ."

Importantly, several scientists remarked on how the HRBMP work was designed with a view to a rapidly evolving scientific age, and therefore was able to effectively meet new forms of analysis, with technologies and methodologies either unknown or largely untried when the program began. Some, for instance, emphasized the uniqueness of the random stratified sampling that is a defining attribute of the HRBMP (e.g., Heimbuch, Mattson), and how it seems to have anticipated large-scale, computer-assisted statistical analysis (e.g., Heimbuch, Henderson, Waldman). This has allowed the dataset to evolve as statistical methodologies and computing power have evolved, e.g., ensuring that is has been used more broadly than it might otherwise have been if pioneering efforts had not initially been employed. Others focused on how the HRBMP field-collection work evolved, over time, to account for developments in ecology (e.g., Deriso, Dunning, Mattson, Young). Still others focused on how historic specimens have been maintained and can be used for analysis, particularly genetic analysis, that was unheard of in the late 1960s and early 1970s when the HRBMP program was conceptualized and developed (e.g., Mattson, Young).

Q: Looking at the Hudson River ecosystem through the lens of the HRBMP, what are the scientific lessons learned that surprise you most?

A: Overwhelmingly, the scientists interviewed remarked on what they have learned, through the HRBMP, about the natural elasticity or accommodative capacity of large-scale fish populations to function within a highly changeable world, one subject to natural and manmade perturbations, even those rising to the level of catastrophes (e.g., Barnthouse, Dunning, Heimbuch, Mattson, Waldman, Young).

Several underscored that an unexpected lesson learned was the criticality of regulating fishing mortality, with the Hudson River Striped Bass population consistently identified as demonstrating how limiting fishing mortality can revive a compromised or at-risk population (e.g., Heimbuch, Henderson, Mattson, Waldman, Young). Several suggested a closer look at fishing regulation, e.g., for American shad, and population health in the future (e.g., Heimbuch, Little, Young).

Others underscored the myriad of evolving scientific and analytical uses of the HRBMP, typified by the ability to analyze the HRBMP dataset to address newfound and often large-scale concerns of importance well beyond the Hudson River, such as Climate Change, the influx of non-native, exotic or nuisance species, the biological ramifications of large-scale oceanic currents (fluid dynamic), correlations between species in the western and eastern Atlantic, and ecological pathogens and disease, in part because of the scope, breadth and continuity of the HRBMP dataset (e.g., Barnthouse, Heimbuch, Henderson, Mattson, Waldman, Young).

Q: What were the early and more recent challenges for the HRBMP?

A: Those involved in the early years underscored the absence of existing analytical criteria, including ecological models, for designing, performing and assessing the HRBMP (e.g., Barnthouse, Dunning), and the corresponding gravity and innovative spirit with which they approached their mission of performing the first large-scale ecological analyses. In response to my question about whether the framework for assessing HRBMP data was modeled or based on prior efforts, Dr. Barnthouse aptly captured the dynamic that they faced in the 1970s: “[w]e had to make them up. There were none existing.”

Others interviewed mentioned the magnitude and breadth of the dataset, particularly during a period when statistical analysis and computing power were emerging and growing in importance (e.g., Dacimo, Dunning, Heimbuch). As Dr. Barnthouse observed about the first years of the HRBMP: “It seemed like probably the largest dataset that any of us had ever seen. We had been doing analyses with printed tables and hand-held calculators. We were forced to adopt computer-based data storage and statistical software.” Years later, that dynamic persisted, as Dr. Heimbuch explained: “The dataset was set up when computer storage was at a premium. There wasn’t a lot of available storage space, and computers were quite slow.” The scientists closest to the HRBMP database remembered processing queues and multi-day processing lags on questions now answered in a matter of seconds (e.g., Dunning, Young). As the person closest and most responsible for the SAS database over the life of the HRBMP, Dr. Young also underscored the scale of the computing challenge, and the creative batching systems for HRBMP data that were employed as a necessity to address a form of challenge which, today, would barely resonate as a hiccup.

Several interviewed mentioned the difficulty in confirmed identification of early life stages of certain species, particularly at the larval stage, as an early challenge that was surmounted in a manner that involved, and has benefitted, the larger scientific community (e.g., Dunning, Mattson, Waldman, Young).

Several interviewed also communicated that the initial focus of the HRBMP on Morone spp., particularly Striped Bass, was perhaps less a function of rigorous science than to its role as a charismatic, compromised species with high potential economic value, initially to the commercial, and later to the recreational sport, fisheries (e.g., Barnthouse, Deriso, Mattson, Waldman). Most emphasized that the fact that the HRBMP, particularly the extensive laboratory analyses associated with the Long River Survey component of the HRBMP, offset this focus by performing a full assay or survey of all species collected and remains in part a contributing factor in the HRBMP’s current value (e.g., Dunning, Mattson, Young).

Several interviewed noted the litigation context surrounding the HRBMP work, including the irony that the years of protracted disputes that precipitated continuation of the HRBMP also may have stifled the distribution and use of the HRBMP information and therefore its purely scientific use (e.g., Barnthouse, Henderson, Young). As noted below, that period has ended.

Q: What is the future of the HRBMP?

A: Virtually all interviewed seemed to understand intimately – and voiced gratitude for -- the existence of the HRBMP program over the last five decades (e.g., Barnthouse, Dacimo, Dunning, Henderson, Heimbuch, Little, Mattson, Waldman, Young). Some, understandably, articulated a sense of loss for the HRBMP fieldwork, the majority of which ceased in 2017 (e.g., Henderson, Waldman).

Most recognized, supported, and welcomed the future, and with it both the known and unknown scientific work that will be undertaken with the HRBMP dataset and archived specimens. Such work will be possible, with the transfer of the HRBMP dataset and specimens to a robust, scientific, and educational institution. There, we expect the many diverse biological, ecological, and ecosystemic questions, some of which the scientific team has said cannot be anticipated at this time, will have the access to and time with the HRBMP (e.g., Barnthouse, Dacimo, Dunning, Heimbuch, Henderson, Little, Mattson, Waldman, Young).

Table 4-1 Interviewees with long-term involvement in the Hudson River Biological Monitoring Program.

Name	Title	Organization	Biographical Information
Lawrence W. Barnthouse, Ph.D.	President and Principal Scientist	LWB Environmental Services, Inc.	Available upon request
Fred Dacimo	Chief Executive Officer and President	Hallocks Bay Marina, Inc.	Available upon request
Richard B. Deriso, Ph.D.	Chief Scientist	Inter-American Tropical Tuna Commission	Available upon request
Dennis J. Dunning, Ph.D.	Partner	Embroidery Designs	Available upon request
Peter Henderson, Ph.D.	Director & Senior Research Associate	Pisces Conservation Ltd.	https://www.researchgate.net/profile/Peter_Henderson7
Douglas G. Heimbuch, Ph.D.	Associate Vice President	AKRF, Inc.	Available upon request
William G. Little, Esq.	Bureau Chief	Bureau of Energy, Climate Change and State Environmental quality Review, NYS Department of Environmental Conservation.	Available upon request
Mark T. Mattson, Ph.D.	Vice President	Normandeau Associates, Inc.	Available upon request
John R. Waldman, Ph.D.	Professor of Biology	Queens College, City University of New York	http://qcpages.qc.cuny.edu/biology/Waldman/index.html
John R. Young, Ph.D.	Sr. Scientist	ASA Analysis & Communication, Inc.	https://www.linkedin.com/in/john-young-5ba94b22/
Elise N. Zoli, Esq.	Partner	Jones Day	https://www.jonesday.com/ezoli/

4.2 THE QUESTIONS

1. When did you become first aware of the HRBMP? And how, e.g., in what capacity?
    a. How long have you been involved? In what capacity?
2. What were your initial thoughts about the HRBMP work?
3. Did you view the HRBMP as unique, in scope, magnitude and cost, initially?
    a. Could you summarize your sense of its purpose initially?
    b. Did its purpose change/evolve over time?
    c. What did you consider to be the hypotheses that were to be tested with the data generated by the HRBMP? Initially? Over time?
    d. Did you think it would go on for 40 years?
4. What was the focus of the HRBMP in the beginning in terms of species, e.g., on Striped Bass?
    a. What was your understanding as to why the focus was on Striped Bass?
    b. Did it make sense biologically and politically? Why?
5. What was the geographic scope of the HRBMP in the beginning?
    a. Why not north of the dam at Albany?
    b. Why not into the harbor or sound?
6. What was the temporal/seasonal scope of the HRBMP in the beginning?
    a. How did you select the timing?
    b. Was it for practical reasons or for scientific/biological reasons?
    c. When and why did it expand and contract?
7. What did you think about the Hudson River’s status at the start and today?
    a. Did you think the fish species were generally ok? In trouble?
    b. Did the PBC contamination seem serious? How about now?
    c. Did you view it as clean? How about now?
    d. Did you swim in it? How about now?
    e. Did you eat fish out of the Hudson then? How about now?
8. Was it hard pulling together the multiple funders of the HRBMP?
    a. Happened early?
    b. Was Con Ed’s overlapping ownership a material factor?
    c. Were the Hudson River facilities looking at different issues?
    d. Were the HRBMP funders subject to different pressures?
9. Do you recall when the HRBMP or dataset became a gee whiz dataset?

    a. Have you recommended its use to other scientists? Which ones? What were they studying?
    b. Have you used the dataset yourself? For what purpose? Did you publish?
    c. Why isn't there an HRBMP in every major River system in the United States?
        i. Was it an iconic Ecosystem?
        ii. Does the absence of dams and the fact that the River was unobstructed for 150 miles make a difference?

10. Do you remember what the early challenges were?
    a. In the field?
    b. QA/QC process?
    c. Computing power and analytics. Requisition forms and getting information out of the data. Card decks.
    d. Sampling design?
    e. Gear selection?
    f. Statistical Power? Was it hard to minimize sampling error and get to a robustness that was defensible? [Ron.]
    g. What about costs. What was it really costing? More than HRSA specification, in pre-1970's.
11. Did the litigation affect the HRBMP design over the years? If so, how?
    a. Didn't change in the 1980's, 1990's, 2000's, 2010's?
    b. Isn't there an integral recognition of the value of the work?
        i. How was the data used by fisheries managers? Is that part of the reason it survived unscathed?
        ii. Was it a sort of auto-pilot?
        iii. Was it possible that the absence of a scientific advisory committee made a difference?
        iv. Restoration and the hatchery? If the hatchery had been wildly successful, would money have been put there?
12. What are the best attributes of the HRBMP, the thing that makes it special?
    a. All life stages of all species over many years? Continuity in effort and ownership matters?
    b. Continuity of personnel and experts?
    c. Continuity of regulatory and NGO focus?
    d. Size of dataset?
13. What are the worst attributes/limitations of the HRBMP?
    a. Is the dataset sometimes difficult to work with?

   b. How do you feel about SAS?
   c. Do you have a view as to the feasibility/utility of converting the database into a more modern format?
   d. Was the litigation overlay a complicating factor or a distraction? The density dependence dynamic?
   e. Do you have thoughts/recommendations for addressing these limitations in the future?

14. Knowing what you know now, what would you do differently with HRBMP? Alternatively, if you were starting today, what would you expect to do differently?
    a. What hypotheses would you expect to do differently?
    b. Lower trophic levels and food density?
    c. What about older life stages of fish? Is the ASMFC and state databases enough?
    d. Do you wish we'd had a focus on genetics and genomics since the 1970's? What do we have, in terms of samples, that is ready to be used, but hasn't been?
    e. Different sampling design? Geographic scope? Temporal/seasonal scope?
15. Looking at the ecosystem or the HRBMP, what really floors you?
    a. Ecosystem resilience?
    b. Inter-annual variation in data?
    c. Fishery closure effects? Rapidity and magnitude of recovery of Striped Bass abundance, and how effective the sport and commercial fisheries were at depleting Striped Bass stocks? Contrary effect for shad?
    d. Storms?
    e. Invasive species? Compared to Great Lakes or San Francisco Bay, where there are mostly introduced or invasive species?
    f. Temperature?
    g. Do you consider the HRBMP and the public/private management of the studies a success? Why or why not?
16. The Future
    a. Are you concerned about the termination of the HRBMP, or at least major components of it? Reduction in scope?
    b. Should it be continued in some form so as to maintain continuity?
    c. What would you like to see happen in terms of future river-wide studies on the Hudson?
    d. If it does not continue in some form, will that undermine fisheries management objectives going forward?

5. WHAT NEXT?

The HRBMP began as a deliberately bold aspirational enterprise at the onset of a new scientific and environmental age. Its novelty, scope and breadth were clear, including to the lead governmental scientists reviewing the then-proposed ecological studies, who stated: "Between 1963 and 1980, the Hudson River estuary was the focus of one of the most ambitious environmental research and assessment programs ever performed." (Barnthouse 1988). These scientists were the first of many to laud the HRBMP. In the 1990's, the scientific lead for a new generation of government scientists christened it, publicly, as "probably the best dataset on the planet."[10] As the HRBMP continued in the new millennium, a new and broader cohort of scientists continued to champion the program, while employing the data and specimens for new uses, such as genetic analysis (Daniels 2005; Wirgin 2011).

Yet, over the years, what began as a great leap of science seemed somehow to become predictable. In good weather and bad, the field collection teams went out and obtained the thousands of tows, seines and trap efforts (known as samples) of fish and water quality data on a randomized stratified basis throughout the 152-odd mile Estuary's length, width and depth. (Only hurricanes, the U.S. Coast Guard closure of the River to boat traffic after September 11, 2001, and restrictions on sampling to protect endangered species have prevented or delayed consistent field sampling across the decades.) Year-round, the field and laboratory teams painstakingly performed their intricate work of processing those samples, identifying and differentiating by species the different life stages of fish (eggs, larvae, juvenile fish and adults), then tabulating the breadth of information about each specimen, e.g., where and when it was found, its stage of development, condition and correlating water quality information. Also, year-round, the statistical and technical teams digitized the field and laboratory data so it could be meaningfully analyzed. All of this work – from the fieldwork to development of the computer database -- was subject to quality assurance and quality control procedures that originated in defense contracting and paved the way for validated ecological data everywhere. Each year, some 18 months after the boats returned to port and consistent with the hundreds of pages of operating procedures developed under the oversight of federal and state regulators, the consulting teams analyzed the digitized data, producing written reports for regulators on species of interest. It all happened -- like clockwork.

By the time that I arrived on the scene in 1999, the extraordinary effort that was the design and execution of the HRBMP looked to the uninitiated, if not easy, at least familiar. Nor was I alone in losing sight of the monumental effort that had been and continued to be achieved, daily. By late 2002, the Hudson River's resident advocates, including the chief prosecuting attorney for Riverkeeper and a senior attorney for the Natural Resources Defense Council, had begun to marvel aloud about the River's ecological health – back from the brink in 1966. Robert F. Kennedy, Jr. captured the public ethos in his testimony to Congress on the 30th anniversary of the Clean Water Act: "Today, as a result of their work and as a result of that Act, the Hudson River, which was a national joke in 1966--it was dead water for 20 miles stretches north of New York City, south of Albany; it turned colors sometimes two or three times a week, depending on what color they were painting the trucks at the GM plant in Tarrytown--today that waterway is an international model for ecosystem protection. It is the richest water body in the North Atlantic. It produces more pounds of fish per acre, more biomass per gallon than any other waterway in the

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[10] New York State Department of Environmental Conservation regulator William Sarbello in comments to USEPA on the proposed federal rule to regulate cooling water intake structures.

Atlantic Ocean, and it is the last major river system left on both sides of the Atlantic that still has strong spawning stocks of all of its historical species of fish." (Senate Hearing 107-1012; see also Levinton and Waldman 2006, p. 8.) What Mr. Kennedy's extraordinary statement failed to mention is that meaningful discussion – and often debate -- about the Hudson River's ecological health is possible because we possess a dataset of the HRBMP's quality, consistency and rigor.

Twenty years later, it is easy to see how very wrong my first impressions of the HRBMP were. Perhaps, it was in part because the hundreds of HRBMP scientists, led by four now graying men with approximately 150 years of collective HRBMP expertise, were understated to a person – scientists and statisticians in an older tradition of evidence first and foremost. Perhaps, the funders of the HRBMP were also disinclined to self-aggrandizement, as they continued to incur, without complaint, the unheard-of annual cost of its performance. Perhaps, it was in part that the HRBMP and regulatory teams had found a collegial groove based on candor and trust, one that is not the stuff of contemporary headlines and blogs. Perhaps, it was too easy to lose sight of the HRBMP's remarkable value in the all too noisy, headline-worthy disputes surrounding Hudson River power production, which inexplicably dwarfed not only the HRBMP, but even the reality of overfishing that the HRBMP data starkly captured.

So, as a late, largely bystander to the unprecedented achievement that is the HRBMP, I offer this brief postscript to the last or wrap-up HRBMP annual report, written and funded by the genuine, if unsung, heroes of my professional career – the men and women who quietly, rationally have given us, as we cannot but recognize, "probably the best dataset on the planet." And despite the superlatives, I am mindful that this is only the beginning. The unique resource that is the HRBMP stands ready for continued and even broader use by future generations of scientists, including those with multi-faceted, multi-disciplinary goals that we view today with awe, as they pursue questions and inquiries that we may not yet be able to foresee or at least fully appreciate. From the studies of disease, through the international trends in North Atlantic fisheries, to the workings of global Climate Change, how much we stand to learn from the HRBMP, its digitized databases and the archived specimens, about this moment in time and our shared future.

ENZ, Jones Day

April 8, 2019

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ACKNOWLEDGEMENTS

A program that has continued for more than 40 years, taken hundreds of thousands of biological tows using seines, nets, and other sampling devices, produced many millions of records of data, hundreds of technical reports, and hundreds more scientific publications, is obviously the result of the collaborative efforts of many people. The first attempt at a comprehensive report on the study (Barnthouse et al. 1988) included a list of technical personnel from 1964 to 1980, containing more than 1,900 names of scientific and technical staff, managers, regulators, utility staff, and scientific consultants. It would be impossible to produce a similar list for the last 38 years of the program, so we will not attempt it.

However, none of the results achieved by the program would have been possible without the efforts of the many individuals associated with the utility and energy companies; federal and state regulators; NGOs and environmental organizations; nationals labs, universities and medical centers; and the long list of consulting firms that performed the work and analyzed the results. These consulting organizations include Applied Biomathematics, Applied Science Associates, ASA Analysis & Communication, Alden Research Laboratory, AKRF, Coastal Environmental Services, Ecological Analysts, Ichthyological Associates, Lawler Matusky & Skelly Engineers, Pisces Conservation, Post Buckley Schuh & Jernigan, LWB Environmental, Normandeau Associates, Northeast Biologists, HydroQual, Martin Marietta, Texas Instruments, Raytheon, Cornell University, the City University of New York, New York University, and West Virginia University, with apologies to those we missed. We thank all for their efforts that led to the success of the Hudson River Biological Monitoring Program in characterizing the ecology of a magnificent estuary.