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Historical overview of the efficacy of two decades of power plant fisheries impact assessment activities in Chesapeake Bay

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Abstract

The Chesapeake Bay is world renowned as an estuary that historically yielded large harvests of a wide variety of fish and shellfish species. Thirteen power plants are located on the mainstem of the Bay and its tributaries in Maryland, drawing out of and discharging into the Bay eight billion gallons per day of the Bay's waters for cooling purposes. Maryland DNR's Power Plant Research Program (PPRP) has, since 1974, funded a wide variety of fisheries assessment, entrainment and impingement studies. PPRP's Potomac River Fisheries Program (PRFP) encompassed multi-year, statistically rigorous, quantitative studies of all life stages of striped bass, from egg to adult, together with estuarine hydrodynamics modeling and water quality assessments, all yielding data integrated to project potential entrainment impacts from a proposed nuclear power plant. PPRP and utility-sponsored monitoring programs at BGE's Calvert Cliffs NPP, PEPCO's Chalk Point SES and DP&L's Vienna SES, as well as other generating facilities throughout the state have provided comprehensive data on impingement, entrainment and receiving water populations of all life stages of potentially impacted resource species. These studies have resulted in unusually complete and long term data sets being available for impact assessment applications, and provide a basis for confirming and validating impact assessment findings and conclusions based on much shorter time series. The state/federal Chesapeake Bay Program has extensively characterized the status and trends of all important resource species in the Bay. We compare and contrast impact conclusions and projections from studies conducted in the 1970s and 1980s with current data and information on the status of and trends in affected fish stocks in Chesapeake Bay. We use that comparison to establish the role that power plant impacts play as factors driving changes in species abundance over time. These comparisons and contrasts between historical and current data and information also illustrate and confirm the methodologies that have proven to be most and least useful for assessing entrainment and impingement impacts.

Keywords: Aquatic impacts; Modeling; Fisheries; Cooling water; Chesapeake Bay

1. Introduction

For centuries, Chesapeake Bay has been one of the most productive estuaries in the world for fish and shellfish. Of the more than 200 species of fish and shellfish found in the Bay during some stage of their life cycles, as many as 40 have supported widespread and economically important fisheries in both Maryland and Virginia (Richkus et al., 1992). The Chesapeake Bay region has also for centuries been home to a wide range of industries, including power generation. Eighteen power plants greater than 90 MW in size are currently present in Maryland (Fig. 1). Most of these facilities employ once-through cooling systems. The extensive use of the Bay's waters for power plant cooling has been of concern and interest to the state's environmental and resource agencies for more than 30 years.

Extensive public debate regarding the potential effects the Calvert Cliffs Nuclear Power Plant might

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have on the Chesapeake Bay arose in the late 1960s. Calvert Cliffs was a source of elevated concern because the plant uses a once-through cooling system that withdraws 3500 million gallons of water per day from the Bay and discharges the water back to the Bay with a temperature elevation of about 12°F. The magnitude and diversity of potential environmental impacts that came to light during the licensing of Calvert Cliffs prompted the creation in 1971 of the Maryland Department of Natural Resources Power Plant Research Program (PPRP). PPRP's purpose was to ensure a complete evaluation and resolution of such issues before future decisions were made regarding whether and where to build other generating facilities.

Today, PPRP continues to conduct research on power plant impacts to Maryland's natural resources, including air, water, biota, as well as to the human population and the economy. PPRP investigations into the effect of power plants on aquatic life in the Chesapeake Bay that have been conducted continuously since 1971 have complemented and augmented other intensive and extensive studies funded by the utilities that own and operate the generating facilities in the state, including BGE, PEPCO and DP&L, as has been described by Ringger (2000) and Bailey et al. (2000). The decades of PPRP study, together with data and information from utility studies, provide unusually long-term data sets useful for the evaluation of the effects power generating facilities have had on important fish stocks in the Chesapeake Bay, and the value of a wide range of types of studies for assessing power plant impacts. They also provide a sound foundation from which PPRP can work to ensure that the Chesapeake Bay and other of Maryland's outstanding natural resources will be protected and enhanced as the electric power industry moves into the era of deregulation. Here we provide a review of the range of work performed to assess entrainment and impingement in several decades of work in Maryland, and some of the lessons learned in the process.

2. Maryland power generating facilities

With the exception of Brandon Shores, Vienna, and two of the four units at Chalk Point, all of Maryland's steam-generating power plants identified in Fig. 1 use once-through cooling systems. Once-through systems require large volumes of water — a fossil fuel fired plant uses about 1.4 million gallons of cooling water per day for each megawatt of electricity produced. Nuclear power plants, such as the Calvert Cliffs plant, generate more waste heat than fossil fuel plants and therefore must use more water per megawatt for cooling. Fig. 2 shows water use rates of power plants in Maryland, given in millions of gallons per day (mgd). The Maryland Department of the Environment grants a surface water appropriation permit to each power plant based on a forecast of the plant's water needs over a period of several years. This permitted withdra-

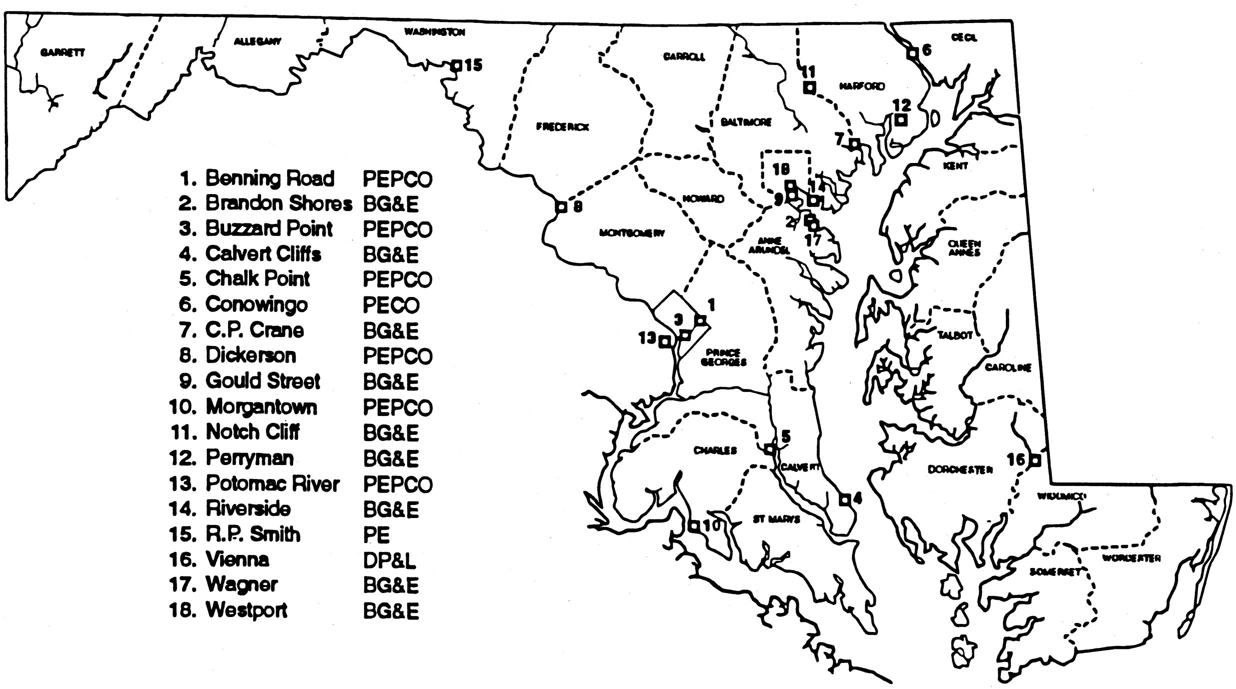

Fig. 1. Location of power plants in and around Maryland (with capacity greater than 90 MW) (Power Plant Cumulative Environmental Impact Report, 1982).

wal, also shown on Fig. 2, represents the estimated maximum amount of water that each plant could withdraw.

2.1. Modes of impact and assessment approaches

All plants using surface water for cooling have intake structures that include some type of trash rack at the entrance, to prevent large debris from disrupting cooling water flow. Nearly all plant intakes also include traveling screens, with relatively fine mesh that keeps small objects, including fish, from entering the cooling system and clogging condenser tubes. The screens are rotated at varying time intervals so that the material impinged on them can be washed off and, in most cases, be discarded into the receiving waters. Objects and biota small enough to pass through the traveling screens, such as phytoplankton, zooplankton, and ichthyoplankton are entrained in the plant's cooling system flow. Biota impinged on traveling screens are subject to stress from immobility (e.g., preventing respiration) and physical abrasion. Entrained organisms are subject to stress due to rapid temperature change, turbulence and shear forces, and biocides.

PPRP and utility impingement and entrainment impact assessments have in all cases proceeded from a first level characterization and quantification of the numbers and types of organisms being affected. Subsequent steps in assessments sometimes have consisted of a second level determination of the consequence of the effect (i.e., what percentage of the organisms entrained or impinged are killed or impaired in some way), and a third level evaluation of whether population level effects may result from the entrainment or impingement losses. Not all plants in Maryland or all species affected have been subject to these three levels of assessment. Species deemed to be of greatest value, generally because of their commercial or recreational importance, have been addressed in the greatest detail. An example of such a species in Chesapeake Bay is the striped bass (*Morone saxatilis*). For other species, less complex approaches have been employed to place within a population or ecosystem context the losses attributed to cooling water withdrawal. The results of studies of these types conducted in the 1970s and early 1980s provided a basis for the development of Maryland's regulations for cooling water intake and discharge that have ensured the protection of the state's aquatic resources. Below we provide a summary of some of the studies conducted and the manner in which the data were used to support regulatory decisions regarding Maryland's power plants.

3. Impingement

An example of annual impingement collected at power plants located on Maryland's Chesapeake Bay in the 1970s is summarized in Table 1. Similar data have been collected at nearly all plants in the 1970s and at some of these plants through the 1990s. At mesohaline facilities, a few species (Atlantic menhaden, spot, bay anchovy, hogchoker, and blue crabs) generally dominate impingement counts and the species composition of impingement is relatively similar from year to year. Year-to-year fluctuations in impingement

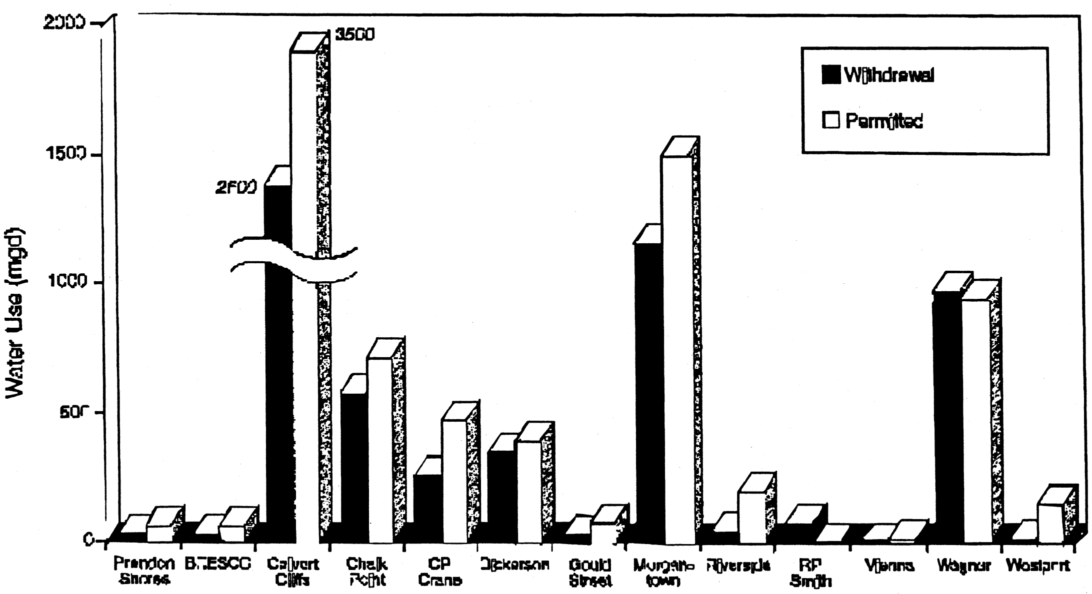

Fig. 2. Surface water withdrawals (mgd) 1991 (Power Plant Cumulative Environmental Impact Report, 1982).

Table 1
Estimated annual impingement (number of individuals) at the Chalk Point and Morgantown plants[a]

Species	Chalk Point 1976–1977		Morgantown			
	Number	Percent	1975		1976–1977	
			Number	Percent	Number	Percent
Atlantic menhaden	1,347,490	31	414,376	57	793,168	45
Spot	647,016	15	200,972	28	312,665	18
Hogchoker	191,926	5	2,510	0.3	38,095	2
White perch	41,910	1	60,648	8	91,525	5
Bay anchovy	Included with other fish		30,969	4	52,201	3
Other fish species	139,928	3	22,645	3	162,390	10
Total fish	2,368,324	55	732,081	100	1,450,044	82
Blue crabs	1,948,132	45	Not available		307,051	17
Total impinged organisms	4,316,456	100	Not available	1	1,757,101	100

[a] We note that subsequent studies suggested that these impingement figures were overestimates, and monitoring in later years yielded much lower impingement totals (Richkus et al., 1992).

catch generally reflected year-to-year fluctuations in fish and crab abundances in the intake area. The highest impingement generally occurred in late summer and fall, and the lowest values occurred in winter and spring. Juveniles dominated impingement catches, and the number of fish impinged usually was greatest at night. Mortality of the impinged fish varies from species to species. About 90% of impinged spot and hogchoker survive, whereas only about 25% of impinged menhaden and other clupeids survive (Table 2). Blue crabs had essentially no post-impingement mortality. Thus, losses of fish and crabs as a result of impingement are much less than the number impinged (Power Plant Cumulative Environmental Impact Report A, 1984). Mortality rates to impinged organisms generally were highest under intermittent screen rotation schedules (three times per day), rather than when screens were rotated frequently (once per hour) (Power Plant Cumulative Environmental Impact Report A, 1984). However, more organisms were impinged by frequent rotation schedules, and as a result, overall losses to local populations were lower if infrequent screen rotation schedules were used.

Although rigorous estimates are not available for all species, post-impingement mortalities were highest at plants where impinged organisms were returned to the receiving body along with other plant discharges which included chlorine residuals (Power Plant Cumulative Environmental Impact Report A, 1984). Subsequent changes in state discharge regulations have eliminated this additional potential source of mortality. A number of other steps were taken in the 1980s to reduce impingement mortality at some plants. A new screen wash discharge system that returned impinged organisms to the nearfield area rather than into the heated discharge canal was installed at PEPCO's Morgantown SES. A barrier net was installed across the intake canal at PEPCO's Chalk Point SES that reduced the numbers of fish and other organisms approaching the intake screens, substantially reducing the amount of impingement.

All studies demonstrated that high impingement episodes account for a large proportion of annual impingement at mesohaline facilities. As a result, impingement levels are not directly related to the volume of water pumped but are more a function of fish and crab abundance, as well as the behavior of the organisms and variable water quality in the vicinity of intake screens, thus reflecting its site-specific nature. At Calvert Cliffs and Morgantown, high impingement episodes were related to low dissolved oxygen (DO) levels in the intake embayment (Power Plant Cumulative Environmental Impact Report A, 1984). Removal of panels from curtain walls during periods when low DO typically occurred provided entrapped organisms with an escape route and reduced impingement levels. At Chalk Point, high impingement episodes are related to normal seasonal migration.

The six species that dominate the impingement estimates are all abundant, ubiquitous species that occur throughout mesohaline regions of the Bay and its

Table 2
Percent survival and percent loss of equilibrium (LOE) of major fish species impinged at Calvert Cliffs in 1979 (Richkus et al., 1992)

Species	Percent survival	Percent LOE
Atlantic menhaden	49.27	1.41
Spot	87.34	0.14
Hogchoker	> 99.00	0.0
Bay anchovy	66.82	2.66
Atlantic croaker	3.81	1.04
White perch	73.08	11.54
Blue crab	> 99.00	0.0

tributaries. These species also dominate net catches made during surveys conducted at these sites, confirming the non-selective nature of cropping by power plants (Power Plant Cumulative Environmental Impact Report B, 1986). The plants appear to have impinged fish at a rate proportional to their abundance in the plant vicinity. There is insufficient knowledge of population size and dynamics of all of the listed species to predict the exact consequence of plant-induced losses, but no changes in fish density or community composition in the vicinity of these plants were observed during the 10 to 15 years over which data were collected most intensively. A relatively recent assessment of trends in important aquatic resources in different segments of the Bay found various long-term trends in the abundance of some of the major species impinged (Richkus et al., 1994), but none that could be linked to impingement effects. Figs. 3 and 4 provide summary presentations for the Patuxent River basin and the Middle Mainstem basin. In both, under finfish, it can be seen that bay anchovies, spot and menhaden, three of the species appearing in greatest numbers in entrainment and impingement estimates for the Chalk Point and Calvert Cliffs power plants over the last several decades, are characterized as being at or above the long-term reference levels established to characterize status. This information further supports the view that power plant effects are not a dominant factor in establishing the status of basin-specific fish stocks.

In lieu of complex and costly population level modeling of individual species, one simple way used by PPRP to place impingement losses in perspective was to compare them to other population losses (i.e., due to predation, fishing, natural die-offs, etc.). Such data were available for several major impinged species, and we presented the following discussion in Power Plant Cumulative Environmental Impact Report B (1986).

Menhaden is one of the major commercial finfish species in the Bay, usually accounting for over 40% of total landed weight in the 1970s. Populations are mobile, and they are distributed throughout mesohaline and oligohaline regions of the Bay. Impingement mortality for menhaden is considered to be 100%. As an approximation of a single year's impingement

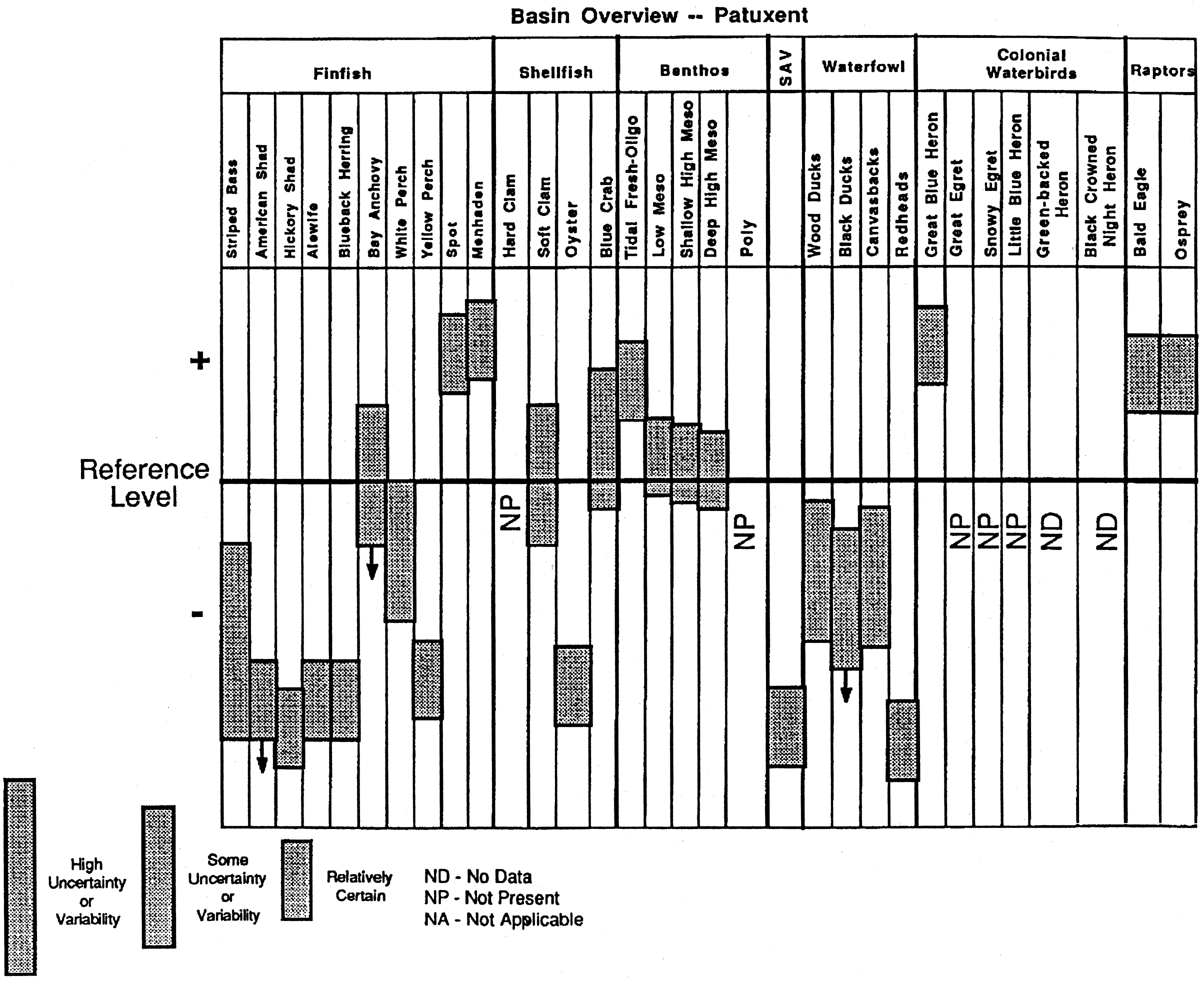

Fig. 3. Status of key species in the Patuxent basin relative to each species' respective reference level (Richkus et al., 1994).

weight total of menhaden for the three mesohaline plants, the 1976 number totals were multiplied by the average weight of menhaden impinged at Calvert Cliffs (20 g = 0.043 lbs) to give total impinged weight estimates of 76,000 lbs. This was about 1.25% of the 1976 Maryland landings of 6 million lbs. Although the mean weight of commercially harvested menhaden is not known, they are larger (older) than the juveniles being impinged. The number of juvenile menhaden impinged is, therefore, much more than 1% of the number of adult menhaden commercially caught. However, since these juveniles would have suffered considerable natural mortality (typically 90%) before reaching harvestable size, the plant-related losses would probably cause a much smaller decline in subsequent years.

Menhaden experience large natural die-offs throughout the Bay during summer months. Many of these kills are unreported or unquantified. Reported kills of menhaden in 1974 and 1975 totaled 100 million and 1.9 million individuals, respectively (Power Plant Cumulative Environmental Impact Report B, 1986). The 1976 impingement total for the three plants is estimated to be 1.8 million individuals.

Menhaden are also a favorite prey of the two major predatory fish in the Bay: bluefish, and striped bass. Daily rations for these species are about 3–5% of their body weight/day. Total stock of bluefish and striped bass in the Bay is unknown, but the amount harvested can be used to give some insight into the amounts of forage fish consumed by predators. From May to October 1976, sport fishermen landed 535,800 lbs of striped bass and 2,915,179 lbs of bluefish in the upper Bay (Power Plant Cumulative Environmental Impact Report B, 1986). If these totals are combined with commercial landings over the entire Bay during the same period, total weight of both species landed was 5,246,000 lbs. Assuming 4% of body weight consumed each day for a five-month period, total forage which would have been utilized by these landed fish is 32,525,000 lbs, much of which would have been menhaden. The estimated impinged total of 76,000 lbs is

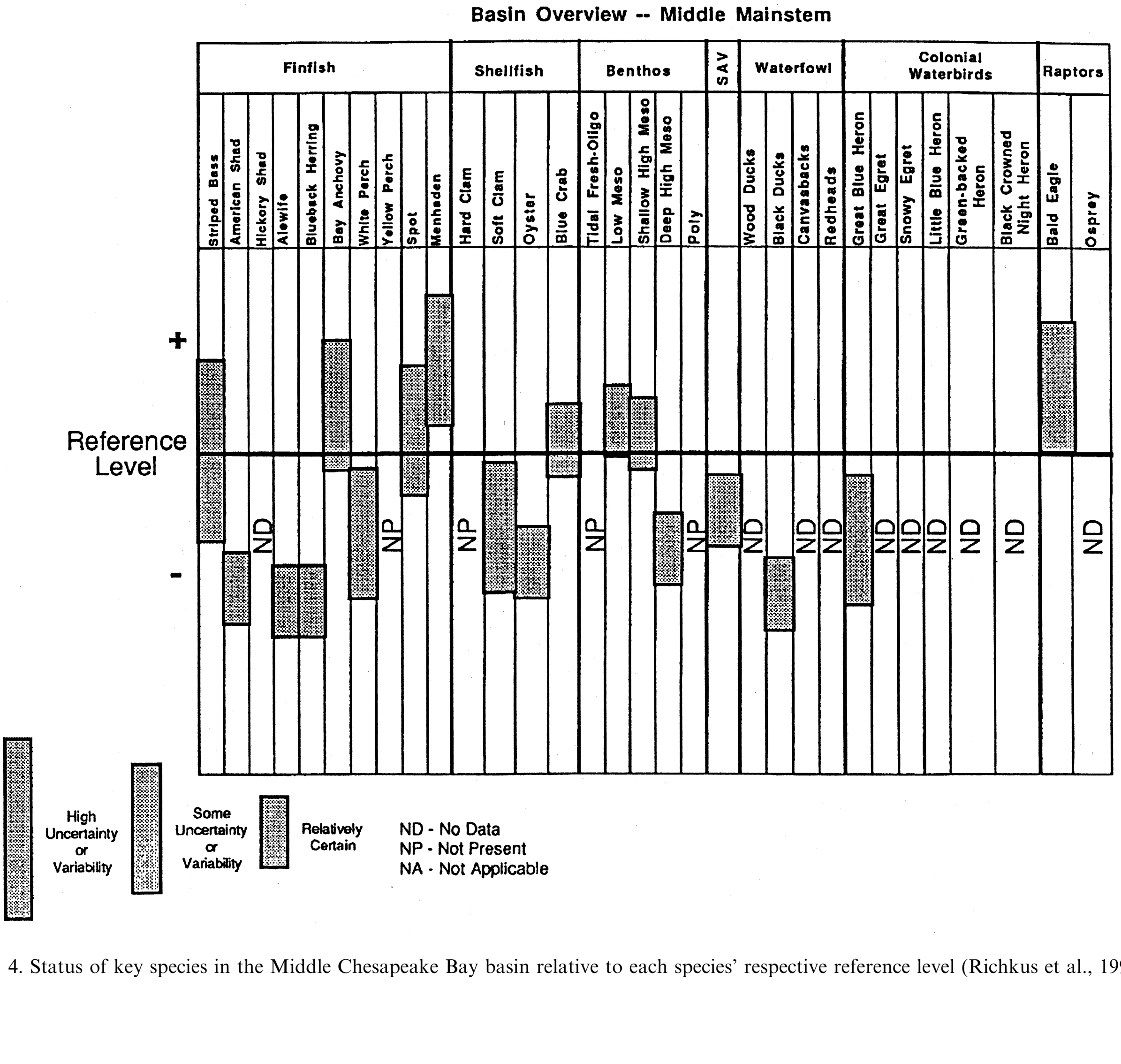

Fig. 4. Status of key species in the Middle Chesapeake Bay basin relative to each species' respective reference level (Richkus et al., 1994).

about 0.23% of that total. All of the above comparisons suggest that menhaden impingement kills represent a small perturbation on the Bay.

Crabs — in 1976, Morgantown impinged about 281,000 crabs. From June to December 1976, Chalk Point impinged approximately 1 million crabs, which was three times the commercial catch in the Patuxent and equal to the estimated sport harvest. In 1976, Calvert Cliffs impinged approximately 440,000 crabs. Mortality studies have demonstrated that crabs suffer less than 1% mortality from impingement. Thus, unless the crabs should suffer delayed mortality as a result of the impingement episode (and there is no evidence of this), no impact would result from the mechanical effects of impingement. Post-impingement mortalities could occur where crabs are washed into a discharge canal (such as at Chalk Point or Morgantown) where they are exposed to chlorinated and heated effluent. This possibility was addressed at these plants and led to reorientation of the screen wash discharge point.

These conclusions are presented in PPRP's Cumulative Environmental Impact Reports (CEIR) which are issued every two years by the Maryland Department of Natural Resources. Subsequent to these findings, the state's focus on impingement was substantially reduced, although on-going data gathering by utilities was tracked and reviewed. No impingement data or information obtained in the intervening 15 years revived concern regarding the effects of impingement on Chesapeake Bay fish stocks or prompted the state to take additional measures to reduce the magnitude of those impacts.

4. Entrainment

Phytoplankton and zooplankton entrainment effects were intensively studied at a number of Maryland power plants in the 1970s and early 1980s, in particular at Calvert Cliffs, Morgantown and Chalk Point. The early results of these studies suggested that losses of phytoplankton and zooplankton were very variable, with greatest reductions found in the summer and at plants where chlorine was used as a biocide to keep condenser tubing from being fouled. We found that phytoplankton and zooplankton populations recovered rapidly from power plant related mortalities and stresses, such that nearfield effects could not be detected except in special circumstances (Power Plant Cumulative Environmental Impact Report B, 1986). The findings from over 15 years of study at more than six plants led to no state actions, other than constraints on the use of biocides such as chlorine, to alter power plant operations to alleviate the minimal observed effects on these plankton community elements.

One major PPRP program that was solely devoted to the issue of potential power plant impacts via entrainment of eggs and larvae was the Potomac River Fisheries Program (PRFP). This program, which was implemented over a six year period, was initiated as a result of a PEPCO proposal in the 1970s to construct a large nuclear power plant at Douglas Point on the Potomac River, a location at the center of striped bass spawning in that river. PRFP was the most comprehensive fisheries program of its kind at that time, with statistically rigorous survey designs for every aspect of life history and the estuarine environment that would play a role in ultimate impact to the striped bass stock. Hydrodynamics studies, including dye studies and modeling, were performed to characterize water circulation patterns that established the proportion of the ichthyoplankton exposed to power plant entrainment. Gill net and bioacoustic studies of the spawning stock were performed to establish the age and sex composition of the stock, the abundance of the spawning stock, the location of spawning, and the factors contributing to timing and location of spawning. Extensive ichthyoplankton sampling was conducted, ultimately resulting in a stratified random sampling design over the entire river segment in which eggs and larvae could be found, using oblique bottom-to-surface tows conducted at night to minimize effects of net avoidance on density estimates. These data sets were integrated into a complex population dynamics model, with the aim of assessing the potential impacts to the adult population from entrainment-induced losses of eggs and larvae. Because the proposal to construct the Douglas Point plant was put on hold and ultimately canceled, studies to establish the accuracy and precision of estimates of impacts were not possible. However, the PRFP data did play a key role in much of the population modeling later performed to support striped bass interstate management planning by the Atlantic States Marine Fisheries Commission.

In the early 1980s, Versar, Inc. developed a population-effects model for PPRP to be used as a tool to evaluate whether Maryland power plants were in compliance with water quality regulations requiring an assessment of whether cooling water entrainment of aquatic organisms adversely affects spawning and nursery areas of consequence (SNAC) for representative important species (RIS) that are specified in those regulations. The general computational scheme for the SNAC model is shown in Fig. 5 (Polgar et al., 1979; Summers, 1989). Potential adult population losses due to the entrainment of early life stages were initially estimated for 24 RIS populations in the Potomac River, and the model was, in later years, applied to many of those same species populations in other portions of the Chesapeake Bay on which power plants were sited. The calculations were based on local and regional life stage densities, larval behavioral characteristics, estuarine transport rates, and plant cooling water withdrawal rates. The impacts of population losses were evaluated in terms of regional economics as potential relative dollar value lost to the regional fishery, and in terms of ecosystem dynamics as a potential increase in "unutilized" system net production due to the computed population losses. Table 3 presents the results of the SNAC model application for the Potomac River ecosystem, taking into account the entrainment impacts of the Morgantown and Possum Point power plants. We concluded from these analyses that while several species showed potentially significant population losses (>3%), the ecological impact of these losses on the Potomac River system was insignificant. While the SNAC model proved to be a useful tool for evaluating the entrainment effects of power plants, it was also data intensive, requiring a diverse and large amount of data and information for its application. Its application illustrates that the determination of "adverse impact" that would trigger some action on the part of the plant owner remains a societal judgment on the part of the regulatory agency. Substantial differences among estimates of impacts of the different plants also illustrate the site-specific nature of entrainment impacts.

In the various applications of the SNAC model since its initial development, only in the case of PEPCO's Chalk Point SES were entrainment impacts considered to be sufficiently significant to warrant some action being taken by the state. Utility and state agency estimates of the entrainment effects differed to some degree, but there was agreement that the most important fish population experiencing the greatest potential impact was the Bay anchovy, an important forage species in the Bay. While a complete consensus on the magnitude of the loss and its potential consequences to the population was not reached, there was sufficient agreement to achieve resolution. In this instance, following state water intake and discharge regulatory procedures, this issue was resolved by having PEPCO undertake mitigation aimed at assisting the state in the restoration of several important fish stocks in the Patuxent River, in essence an out-of-kind mitigation agreement. Such an agreement was reached in this instance because the potential costs of cooling

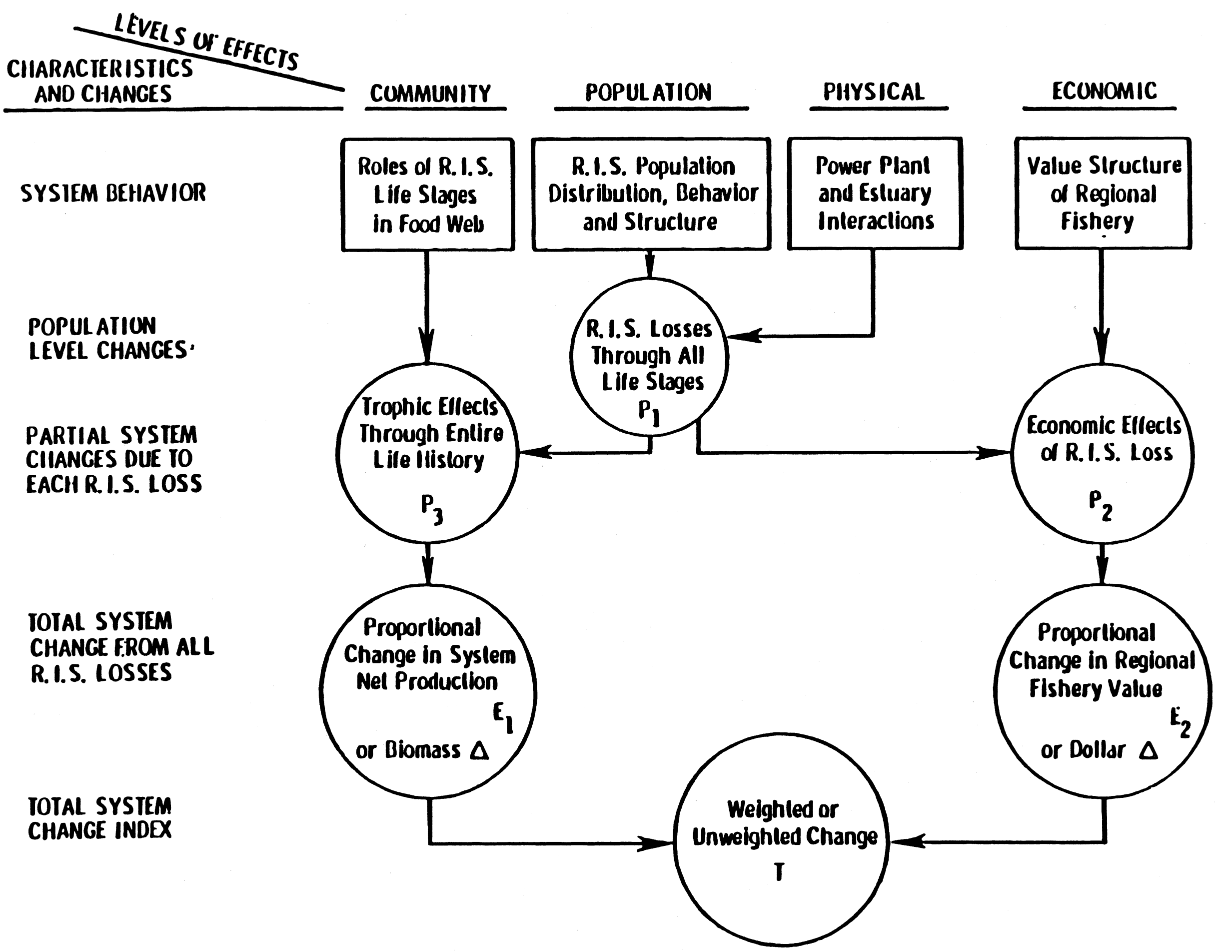

Fig. 5. The general computational scheme (Polgar et al., 1979).

alternatives, including the use of wedge-wire screens on the intake or the installation of cooling towers and reduction in water withdrawal rates, were deemed to be not commensurate with the magnitude and nature of the loss of aquatic resources.

5. Power plant impacts within the context of Chesapeake Bay fisheries management

Because of the economic and recreational value of many Bay species, declines in fish stocks in recent decades triggered both public concern and also remedial action by state and federal agencies starting in the early 1980s. One key outcome of that response was the establishment of the Chesapeake Bay Program, a multijurisdictional effort run by the US Environmental Protection Agency (EPA) and operating at both the federal and state levels. As part of the overall Bay restoration effort, state and federal resource managers developed stock assessment recommendations for the 1987 Chesapeake Bay Agreement. The agreement's purpose was to implement programs to restore depressed fish and shellfish stocks and to prevent the decline of currently abundant stocks (Richkus et al., 1992).

The assumption underlying most fisheries management is that stock abundance (population size) is regulated by internal feedback mechanisms; such that when stock abundance decreases as a result of fishing activity or any other source of mortality, the species responds with increased growth and reproduction. Theoretically, this response allows a certain level of annual harvest to be sustained indefinitely (Richkus et al., 1992). It is a complex task, however, to identify all of the factors that affect the status of exploited, or harvested, stocks and to quantitatively classify the relative impact of these factors. Fig. 6 schematically illustrates the myriad interacting natural and anthropogenic factors that bear on the size of a fish or shellfish stock. When setting harvest regulations, managers must take into account not only the biological factors but also various social, political, economic, and jurisdictional factors. These non-biological factors, many of which are not based on science, often play a major role in management decisions.

It is worth noting in Fig. 6 that cooling water withdrawal-induced mortality of various life stages of any fish population, captured in the figure as life stages "killed by man", is simply one of a large number of mortalities experienced by those life stages. As such, it has no lesser or greater importance to the ultimate fate of the affected population than any other source of mortality, and it can only be taken into account within the context of all of the other factors affecting the population. It is also notable that the Bay management plans intended to preserve and restore major fish stocks focus on environmental restoration and protection and harvest regulation, with no specific attention called to the consequences of cooling water withdrawal.

6. Conclusions

We have briefly reviewed examples drawn from more than 25 years of PPRP research conducted in the Chesapeake Bay to evaluate the effects of power plant water withdrawal on Chesapeake Bay aquatic resources. The huge volume of work performed over this time period has increased the breadth and depth of knowledge concerning how power plant cooling

Table 3
Percentage losses of Potomac RIS due to operations at Morgantown and Possum Pt, SES and their economic and ecological effects[a]

Species	Population		Economic		Ecological	
Striped bass	6.4	(1)	3.1	(1)	0.16	(7)
Alewife	6.0	(2)	0.15	(2)	0.091	(3)
White perch	5.1	(3)	0.07	(3)	0.078	(4)
Naked goby	4.4	(4)	0		0.024	(6)
Silverside	3.3	(5)	0		0.035	(5)
Bay anchovy	2.3	(6)	0		0.14	(1)
Atlantic menhaden	0.95	(7)	0.036	(4)	0.12	(2)
Atlantic croaker	0.28	(8)	4.2×10^{-4}	(5)	5.6×10^{-5}	(8)
Spot	0.073	(9)	3.8×10^{-4}	(6)	1.6×10^{-5}	(9)
Weakfish	4×10^{-4}	(10)	0		1.5×10^{-7}	(13)
Rangia cuneata	3×10^{-4}	(11)	0		1×10^{-5}	(11)
Macoma balthica	2.1×10^{-4}	(12)	0		1.5×10^{-5}	(10)
Macoma balthica Oyster	8×10^{-5}	(13)	2.7×10^{-5}	(7)	5.4×10^{-6}	(12)

[a] Rankings of losses are in parentheses; percentage of population is of equilibrium stock abundance; percentage of economic value is of the dollar value of projected annual harvest; percentage of ecological value is of contribution of biomass to higher trophic levels (Polgar et al., 1979). $E_2 = 3.4\%$ (\$174,404), $E_1 = 0.51\%$ (0.57 gm/100 gm NPP).

water withdrawal impacts fish stocks, how to quantify those impacts, and how to analyze and interpret them. We have learned a number of important lessons:

- A rigorous statistical design of sampling programs to measure impingement and entrainment rates must take into account all important site specific factors (e.g., water quality fluctuations, fish behavior, seasonal migrations, spawning period) in order to accurately characterize the quantities of organisms affected.
- Some relatively simple modifications of intake operations and structures (e.g., changing screen rotation schedules; removing skimmer wall panels during periods of low DO) can result in very large reductions in the magnitude of impingement.
- The location of a water intake (e.g., relative to spawning locations) in large part establishes the potential magnitude of entrainment.
- Assessments of population level and ecosystem level impacts require that entrainment and impingement mortalities be considered within the context of all other sources of mortality, both natural and anthropogenic.
- The large number of factors that must be taken into account in population level or ecosystem level impact assessments and the large degree of uncertainty associated with quantitative estimates of many of these factors severely limits the degree of precision and reliability that can be achieved by even the most elaborate impact assessment model constructs (Richkus, 1980).

This knowledge has provided the foundation for im-

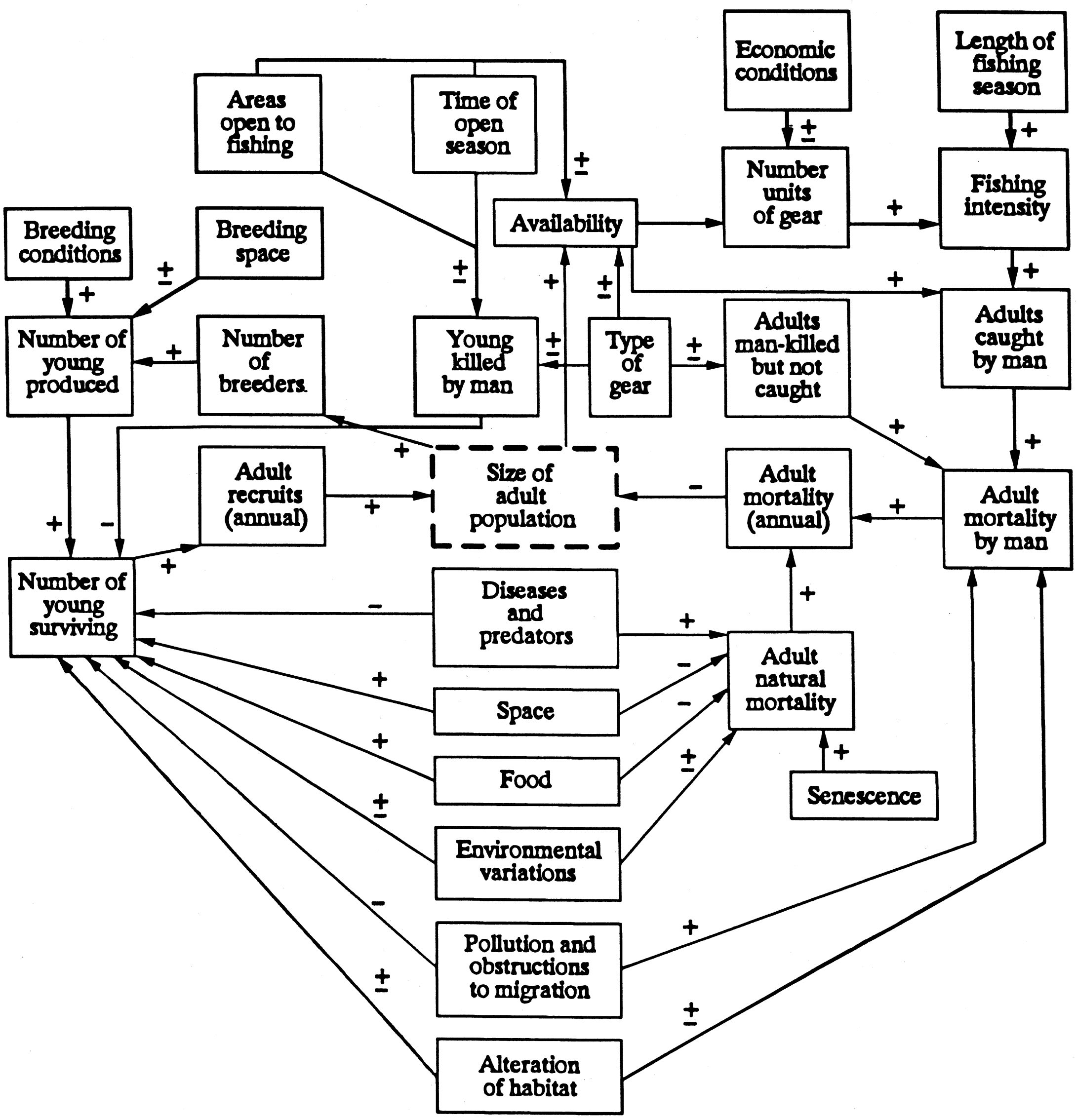

Fig. 6. Factors involved in determining population size of exploited fish or shellfish stocks. The (+) and (–) signs refer to a positive or negative effect, respectively, of one factor or another.

plementation of Maryland's regulations regarding cooling water withdrawal. In all cases, implementation can be characterized as occurring in a series of phases or stages, starting with quantifying the impacts, proceeding to the determination of the significance of those impacts, and ending with the determination of measures to be implemented by the utility to reduce impact to an extent commensurate with the significance of that impact or to mitigate for that impact. The absence of power plant water withdrawal impact issues in Maryland for more than a decade, concurrent with the intense state/federal effort to restore Chesapeake Bay and its resources, is evidence that the approaches developed and applied by PPRP have satisfied the state's needs and requirements. However, a critical point to be made regarding the regulation of power plants in Maryland is that the regulatory procedures successfully employed to protect the living resources of Maryland's Chesapeake Bay and to allow for the generation of electricity essential to the state's citizens and industry clearly allows for cooling water withdrawal as a valid use of the state's water resources, so long as the consequences of this use is balanced against other related sources of impacts and the state's overall environmental and social objectives.

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