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The Impact of Impingement on the Hudson River White Perch Population: Final Report

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W. Van Winkle
B. L. Kirk
D. S. Vaughan

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1842

Prepared for
U.S. Nuclear Regulatory Commission
Office of Nuclear Regulatory Research
Division of Health, Siting and Environment
P. Reed Project Officer
Under Interagency Agreement No. DOE 40-550-75

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Task: Methods to Assess Impacts on Hudson River White Perch

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We thank G. F. Cada and R. B. McLean for their thoughtful reviews of this report. We also express our appreciation of the efforts of the biologists from Texas Instruments, Inc., LMS Engineers, and Ecological Analysts, Inc., who collected the data on which this report is based.

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ABSTRACT

BARNTHOUSE, L. W., W. VAN WINKLE, B. L. KIRK, and D. S. VAUGHAN. 1982. The impact of impingement on the Hudson River white perch population: Final report. ORNL/TM-7975 and NUREG/CR-2311. Oak Ridge National Laboratory, Oak Ridge, Tennessee. 60 pp.

This report summarizes a series of analyses of the magnitude and biological significance of the impingement of white perch at the Indian Point Nuclear Generating Station and other Hudson River power plants. Included in these analyses were evaluations of (a) two independent lines of evidence relating to the magnitude of impingement impacts on the Hudson River white perch population, (b) the additional impact caused by entrainment of white perch, (c) data relating to density-dependent growth among young-of-the-year white perch, (d) the feasibility of performing population-level analyses of impingement impacts on the white perch populations of Chesapeake Bay and the Delaware River, and (e) the feasibility of using simple food chain and food web models to evaluate community-level effects of impingement and entrainment.

Estimated reductions in the abundances of the 1974 and 1975 white perch year classes, caused by impingement and entrainment, were high enough that the possibility of adverse long-term effects cannot be excluded. It was not, however, possible to quantify the long-term consequences of this impact on either the white perch population or on other components of the Hudson River ecosystem. Moreover, the year-to-year variability in year-class abundance indices for white perch is so high that many additional years of data would be required to detect even very large reductions (greater than 50%) in average year-class abundance. Analyses of simple food chain and food web models, performed using a technique known as loop analysis, suggest that if power plant operation does result in a substantial decline in the abundance of white perch, this decline should be accompanied by an increase in the abundance of competitors that are relatively invulnerable to power plants. Observable changes in the age and size-composition of the white perch population should also occur.

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SUMMARY

This report summarizes a series of analyses of the magnitude and biological significance of the impingement of white perch at Hudson River power plants, performed by staff of the Environmental Sciences Division of Oak Ridge National Laboratory. This research was performed for the U.S. Nuclear Regulatory Commission (USNRC) in connection with the licensing of the Indian Point Nuclear Generating Station, units 2 and 3. Many of the results were also submitted as testimony for the U.S. Environmental Protection Agency, Region II in consolidated NPDES permit hearings for the Indian Point, Bowline, and Roseton generating stations. Included in these analyses were (a) evaluations of two independent lines of evidence relating to the magnitude of impingement impacts on the Hudson River white perch population, (b) the additional impact caused by entrainment of white perch, (c) data relating to density-dependent growth among young-of-the-year white perch, (d) the feasibility of performing population-level analyses of impingement impacts on the white perch populations of Chesapeake Bay and the Delaware River, and (e) the feasibility of using simple food chain and food web models to evaluate community-level effects of impingement and entrainment.

The impingement rate provides one possible index of year-class abundance. Impingement data collected at six Hudson River power plants during the period 1972-77 were examined to determine whether there was a decline in white perch abundance during this period. No statistically significant trend was found. However, further analysis showed that, because of the high year-to-year variability in year-class abundance indices, many additional years of data would be required to detect even very large reductions (greater than 50%) in average year-class abundance. Moreover, it was found that abundance indices computed from impingement data were not correlated with comparable indices derived from beach-seine data. It is not clear whether either data set provides a valid index of year-class abundance in white perch.

Impingement data were combined with data on the abundance and mortality of juvenile white perch in the Hudson River to obtain estimates of conditional impingement mortality rates for the 1974 and 1975 white perch classes. These rates are estimates of the fractional reduction in abundance of these two year classes caused by impingement. These estimates indicate that the abundance of the 1974 year class was reduced by at least 10%, and probably by 20% or more, because of impingement alone. The abundance of the 1975 year class was reduced by at least 8%, and probably by 15% or more, because of impingement alone. Most of the impact to both year classes was caused by impingement at Indian Point during the winter and early spring.

Conditional entrainment mortality rates were computed for both year classes. These rates indicate that reductions in abundance in excess of 10%, over and above impacts due to impingement, were imposed on the 1974 and 1975 white perch year classes by entrainment at Hudson River power plants.

Compensatory mechanisms such as density-dependent growth can, in principle, offset much of the mortality caused by impingement and entrainment. Consultants for the utilities have searched for empirical evidence for the operation of density-dependent growth in the Hudson River white perch population and have claimed to have found such evidence. Our independent evaluation indicates that the available data are insufficient for demonstrating the existence or nonexistence of density-dependent growth in this population. Our evaluation further indicates that it probably will not be possible to quantify the compensatory effects of density-dependent growth even if it can be shown to exist.

Impingement data collected at the Calvert Cliffs, Surry, and Salem plants were examined to determine the feasibility of performing analyses comparable to those performed for the Hudson River power plants. It appears that no such analyses are feasible at present. Our examination of these data indicated that too few white perch are impinged at Calvert Cliffs for any analysis to be worthwhile. The numbers of white perch impinged annually at Surry and Salem appear to be similar to the numbers impinged at Indian Point, but at neither plant was the available time series of impingement rates long enough for meaningful regression analyses to be performed. Moreover, the available data on (a) the white perch populations of Chesapeake Bay and the Delaware River, and (b) impingement collection efficiency, impingement survival, and the age composition of impingement collections at Surry and Salem were insufficient for calculating conditional impingement mortality rates.

Simple food chain and food web models, together with information on the life histories and vulnerabilities to power plants of fish and macroinvertebrate populations in th Hudson River, were used to assess (a) effects of interactions with other populations on the response of the white perch population to power plant mortality, and (b) indirect effects on other populations of mortality imposed on white perch. A technique known as loop analysis was used to derive predictions from the models about qualitative patterns of change (i.e., which populations should increase, which should decrease, and which should remain unchanged) among the model populations, and to identify the parameters that determine those patterns. Information on the life histories and vulnerabilities to power plants of Hudson River fish and invertebrate populations, when interpreted in the light of the theoretical results, suggested that the levels of power plant mortality imposed on predators, competitors, and prey of white perch are probably insufficient to offset the effects of mortality imposed on white perch. No piscivorous fish have been identified that prey preferentially on white perch, and, therefore, it does not appear that predator populations will be adversely affected by this mortality. If the operation of Hudson River power plants does cause a substantial decline in the abundance of white perch, this decline should be accompanied by an increase in the abundance of one or more competing fish populations. Observable changes in the age and size structure of the white perch population should also occur.

Although it was not possible to predict the long-term consequences of the impingement and entrainment of white perch at Indian Point and other Hudson River power plants, the estimated impacts of impingement and entrainment on individual white perch year classes are high enough that the possibility of adverse long-term effects cannot be excluded. In recognition of the anomalously high impact of the Indian Point Nuclear Generating Station, as demonstrated by the results obtained from this project, mitigating measures intended to reduce impingement of white perch at Indian Point were included in the December 1980 settlement agreement that terminated the EPA hearings and led to the May 1981 deletion of the requirement for closed-cycle cooling from the operating licenses for Indian Point units 2 and 3.

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INTRODUCTION

Large numbers of white perch, ranging in age from young-of-the-year through adult, are impinged each year at the Indian Point Nuclear Generating Station and other Hudson River power plants (Fig. 1). Concern about the magnitude of this impingement and its potential effects on the Hudson River white perch population were expressed in the U.S. Nuclear Regulatory Commission's (USNRC) Final Environmental Statement for Indian Point unit no. 3 (USNRC 1975). In response to this concern, the USNRC's Office of Nuclear Regulatory Research funded research at Oak Ridge National Laboratory (ORNL) with the goal of evaluating the biological significance of impingement losses of white perch at Hudson River power plants.

The project, which began in May of 1978, consisted of five subtasks:

1. Statistical analysis of white perch impingement data collected at Hudson River power plants,
2. Estimation of conditional impingement mortality rates for the 1974 and 1975 white perch year classes,
3. Estimation of conditional entrainment mortality rates for the 1974 and 1975 white perch year classes,
4. Evaluation of data relating to density-dependent growth in the Hudson River white perch population,
5. Assessment of the feasibility of performing population-level analyses for the white perch populations of the Delaware River and Chesapeake Bay, and
6. Assessment of the feasibility of using simple food chain and food web models to evaluate community-level effects of impingement and entrainment.

All but one of these analyses are described in detail in other reports prepared in connection with this project (Van Winkle et al. 1980, Barnthouse et al. 1980, Barnthouse in press). The section of this report entitled "The impact of impingement on the 1974 and 1975 white perch year classes" is an expansion and refinement of the analysis of conditional impingement mortality rates presented in Van Winkle et al. (1980).

The purpose of this final report is to summarize in one place all of the results obtained from this project. It consists of separate sections summarizing each of the six analyses, followed by conclusions and recommendations drawn from all of the analyses.

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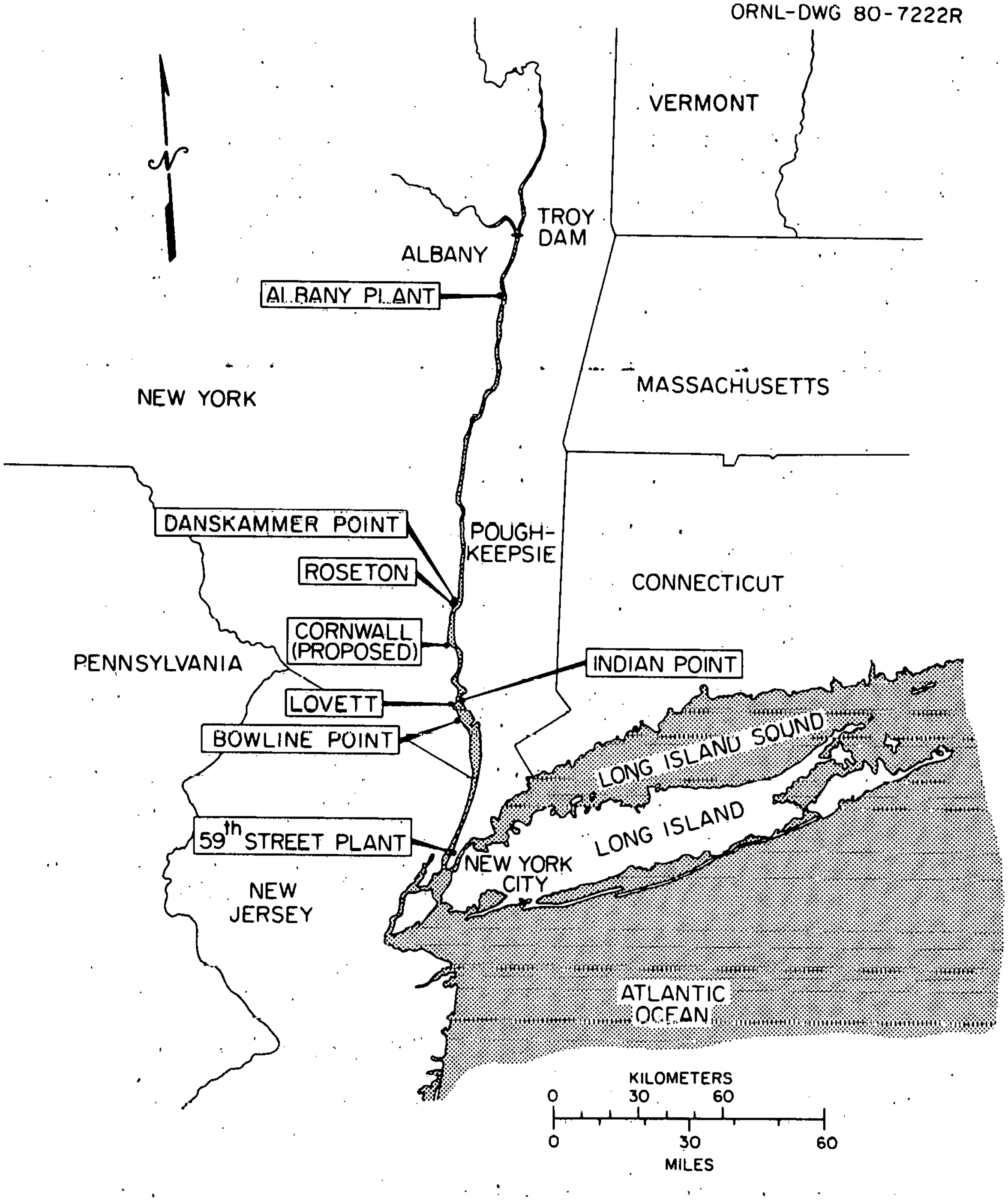

Fig. 1. Hudson River estuary showing locations of power plants.

ANALYSIS OF IMPINGEMENT RATES

The impingement rate provides one possible index of year-class strength on a relative scale. This section summarizes our evaluation of (a) whether there was a systematic decline in white perch impingement rates at Hudson River power plants over the period 1972-77, (b) whether the statistical test applied to the impingement data is powerful enough to detect a substantial decline in white perch abundance, given the variability in the data and the length of the time series, and (c) whether the impingement rate is a valid index of year-class strength in white perch.

Data on the number impinged and the impingement rate for white perch by month were compiled for all years for which data were obtainable from the utilities for each of the following power plants (moving downriver): Albany, Danskammer; Roseton; Indian Point Units 1, 2, and 3; Lovett; Bowline; and Astoria. These data are presented in Appendix A of Van Winkle et al. (1980). Collection rate is defined as the number of impinged white perch counted (Indian Point) or estimated (all other power plants) to be impinged at the intake per unit intake flow.

Except for Indian Point, where collection rates were adjusted upward to correct for less than 100% collection efficiency, collection rate is assumed to be approximately equivalent to impingement rate, which is defined as the number of white perch killed at the intake per unit intake flow. A detailed analysis of factors that influence impingement estimates at Hudson River power plants including adjustment factors, is given in Barnthouse et al. (in press).

Variation in Impingement Rate Among Years

Impingement-rate data are available on a monthly basis for a period of four to six years for Bowline, Lovett, Indian Point 2, Roseton, and Danskammer. We treated impingement rate, which is equivalent to a catch per unit effort (CPUE), as an approximate index of population size. For a CPUE index to serve as an accurate index of population size, there must be some assurance that actual variations in effort are measured. We believe that data on power plant intake flow (= effort) satisfy this condition, because the uncertainty associated with estimates of intake flow is relatively small. An analysis of the relationship between impingement and intake flow at Indian Point is presented in Appendix C of Van Winkle et al. (1980). Given this assumption, we examined the time series of impingement rates over years for trends in population size. The regression model used was $Y = a + bX$, where Y is the impingement rate for young-of-the-year white perch, X is year, a is the Y-axis intercept, and b is the slope. A slope (b) significantly greater than 0.0 ($P \leq 0.10$) suggests an increasing trend in population sizeover years, while a slope significantly less than 0.0 suggests a decreasing trend in population size. A slope not significantly different from 0.0 indicates that, although year-class strength may have varied, there was no systematic trend in year-class strength over the period 1972 (or 1973) through 1977. The regression analysis was performed for each of the above five power plants and for all five power plants combined for each month. The reason for performing individual regressions for each power plant and month was to examine the possibility that there might be consistent patterns of variation at a power plant for certain months which were masked by averaging over power plants or over months. The regression analysis was also performed using the mean annual impingement rate, which was calculated as the average of the twelve monthly impingement rates for each year. In all, 78 regressions were performed. Because the twelve monthly impingement rates are used to calculate the mean annual impingement rate for each year, however, this set of regressions cannot be treated rigorously as a set of 78 statistically independent regressions.

The results of these regression analyses are presented in Table 1. Of the 78 regressions, the slope (b) differs significantly ($P \leq 0.10$) from 0.0 in only eight cases. Of these eight cases, the slope is significantly greater than 0.0 seven times and less than 0.0 only once (Lovett, in March). In our judgment the mean annual impingement rates for each of the five power plants and for all five plants combined are likely to be more reliable indices of population size than the individual monthly impingement rates. Monthly impingement rates are more subject to variation from year to year due to temperature or salinity differences and, consequently, to differences in the spatial distribution of young-of-the-year white perch in the Hudson River, rather than due to real differences in year-class strength. None of the slopes for the six "annual" regressions differs significantly from zero. However, given the large variability in impingement rates used in these regressions, the time series are relatively short (i.e., 5 - 6 years), and thus, the statistical power of the test for a trend is not high. Based on a systematic analysis of minimum detectable differences in annual impingement rates and the number of years required to detect a specified reduction in this index of year-class strength, it was concluded that long time series of estimates of year-class strength would be required to detect even substantial reductions (e.g., 50%) (see next subsection for additional detail). In addition, based on an analysis comparing data on impingement rate and beach-seine catch per unit effort (CPUE), the accuracy of impingement rates as estimates of relative year-class strength is called into question (see subsection on comparison of alternative indices of year-class abundance for additional detail). A final point relating to the use of impingement rate as an index of year-class strength is that a systematic decrease in year-class strength due to impingement mortality would only start to manifest itself with the 1977 (or 1978) and subsequent year classes. This delay is due to the age of sexual maturity for females, the multiple age-class composition of the spawning population of females, and the appreciable increase in impingement mortality starting in 1973 and 1974.

Table 1. Summary of results from regression analyses to examine the time series of impingement rates for trends in the Hudson River young-of-the-year white perch population[a]

Month	Bowline N	Bowline r^2	Bowline b	Bowline P	Lovett N	Lovett r^2	Lovett b	Lovett P	Indian Point 2 N	Indian Point 2 r^2	Indian Point 2 b	Indian Point 2 P
January	5	0.06	-84.5	0.68	5	0.60	208	0.12	5	0.53	5810	0.16
February	5	0.17	-95.1	0.49	5	0.27	95.7	0.37	5	0.44	11539	0.22
March	5	0.21	-80.6	0.44	4	0.88	-29.8	0.06*	5	0.12	-565	0.57
April	5	0.11	-75.7	0.58	5	0.11	-39.5	0.59	5	0.02	349	0.82
May	5	0.53	-24.0	0.16	5	0.37	-23.1	0.27	4	0.21	-462	0.54
June	5	0.00	0.00	-	5	0.00	0.00	-	5	0.00	0.00	-
July	5	0.05	-1.00	0.71	5	0.00	-0.02	0.99	4	0.63	8.49	0.21
August	5	0.26	13.2	0.38	5	0.25	-8.09	0.39	4	0.14	93.2	0.63
September	5	0.03	0.52	0.79	5	0.02	-0.65	0.82	5	0.04	28.5	0.75
October	5	0.26	7.42	0.39	5	0.35	33.3	0.29	5	0.81	534	0.04*
November	5	0.16	65.2	0.51	5	0.71	93.6	0.07*	5	0.59	1795	0.13
December	5	0.06	81.1	0.70	5	0.15	45.8	0.52	4	0.63	5625	0.20
Annual	5	0.05	-16.1	0.72	4	0.67	29.9	0.18	4	0.74	2335	0.14
	Roseton N	Roseton r^2	Roseton b	Roseton P	Danskammer N	Danskammer r^2	Danskammer b	Danskammer P	All five plants N	All five plants r^2	All five plants b	All five plants P
January	4	0.83	4.65	0.09*	6	0.25	2.23	0.31	5	0.52	1149	0.17
February	4	0.24	4.05	0.51	6	0.27	2.26	0.29	5	0.42	2261	0.24
March	4	0.88	12.7	0.06*	6	0.54	13.0	0.10*	5	0.21	-216	0.44
April	4	0.21	55.7	0.54	6	0.48	121	0.13	5	0.01	33.5	0.90
May	4	0.37	77.1	0.39	6	0.08	36.0	0.58	5	0.21	-96.9	0.43
June	4	0.00	0.00	-	6	0.00	0.00	-	5	0.00	0.00	-
July	5	0.01	0.033	0.85	6	0.44	-2.82	0.15	5	0.00	-0.247	0.91
August	5	0.26	17.8	0.38	6	0.36	-14.8	0.21	5	0.06	13.4	0.68
September	5	0.42	-59.8	0.23	6	0.19	-8.83	0.39	5	0.06	-7.05	0.70
October	5	0.34	-80.8	0.30	6	0.10	25.2	0.54	5	0.84	108	0.03*
November	5	0.04	23.7	0.76	6	0.26	109	0.30	5	0.79	419	0.04*
December	5	0.01	-1.67	0.87	6	0.03	-4.01	0.73	5	0.05	255	0.73
Annual	4	0.49	14.8	0.30	6	0.40	23.2	0.18	4	0.45	402	0.33

[a]The regression model used was $Y = a + bX$, where Y is impingement rate for young-of-the-year white perch and X is year. N is the number of data points (i.e., number of years); r^2 is the coefficient of determination (i.e., the fraction of variablity in Y values accounted for by X); b is the slope of the straight line; and P is the probability of obtaining a slope this steep (either positive or negative) if the true slope is 0.0. P values $\leq$ 0.10 are indicated by an asterisk (*).

Minimum Detectable Difference in Year-class Strength

Impingement rates for young-of-the-year white perch in the Hudson River were analyzed to address two questions: (1) assuming a specified number of years of additional data, what is the minimum fractional reduction in mean year-class strength that could be detected, and (2) assuming a specified fractional reduction in mean year-class strength, how many additional years of impingement data would be required to detect the reduction.

Coefficients of variation over the period 1972-77 were calculated for 71 indices of white perch year-class strength constructed using the impingement rate data presented in Appendix A of Van Winkle et al. (1980). The frequency distribution of these coefficients of variation is plotted in Fig. 2. Figure 3 shows, for two values of the coefficient of variation that bracket the mode of the frequency distribution, the minimum detectable fractional reduction in year-class abundance of white perch as a function of the number of additional years (beginning in 1978) for which impingement data are available. Figure 4 shows, for the same two values of the coefficient of variation, the number of additional years of impingement data required to detect a specified reduction in year-class abundance.

Our results indicated that the variability in the baseline data is so great that more than 50 years of data would be required to detect an actual 50% reduction in mean year-class strength, given a power (1-ß) of only 50%.

Detailed results on this subtask are given in Appendix D of Van Winkle et al. (1980). A paper describing the methodology and using Hudson River white perch impingement data as an example has been published in the Canadian Journal of Fisheries and Aquatic Sciences (Van Winkle et al. 1981). Van Winkle presented a paper on this topic at the Annual Meeting of the American Fisheries Society, Louisville, Kentucky, September, 1980.

Comparison of Alternative Indices of Year-class Strength for the Hudson River White Perch Population

The validity of using impingement data in place of, or in addition to, data collected with standard fisheries sampling has not been established. Hickey (1978) correctly pointed out that intake screens at power plants represent a new type of sampling gear, the usefulness of which must be evaluated in comparison with standard gears such as beach seines, trawls, gill nets, commercial fishing gears, and acoustical techniques.

In Appendix C of Van Winkle et al. (1980) we examined the validity of the assumption that the impingement rate of young-of-the-year white perch at the Hudson River power plants is an approximate index of the size of the young-of-the-year white perch population in the Hudson

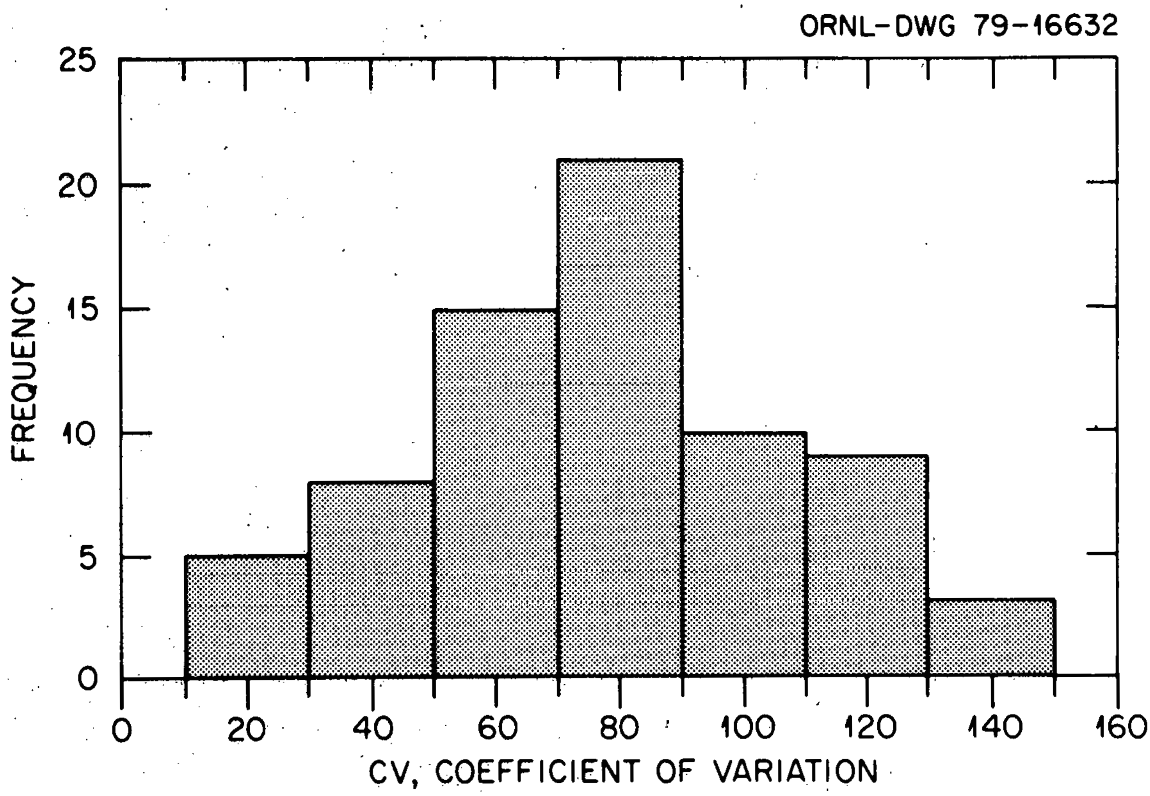

Fig. 2. Frequency distribution of the 71 values for the coefficient of variation (as a percent) given in Table D-1 of Van Winkle et al. (1980).

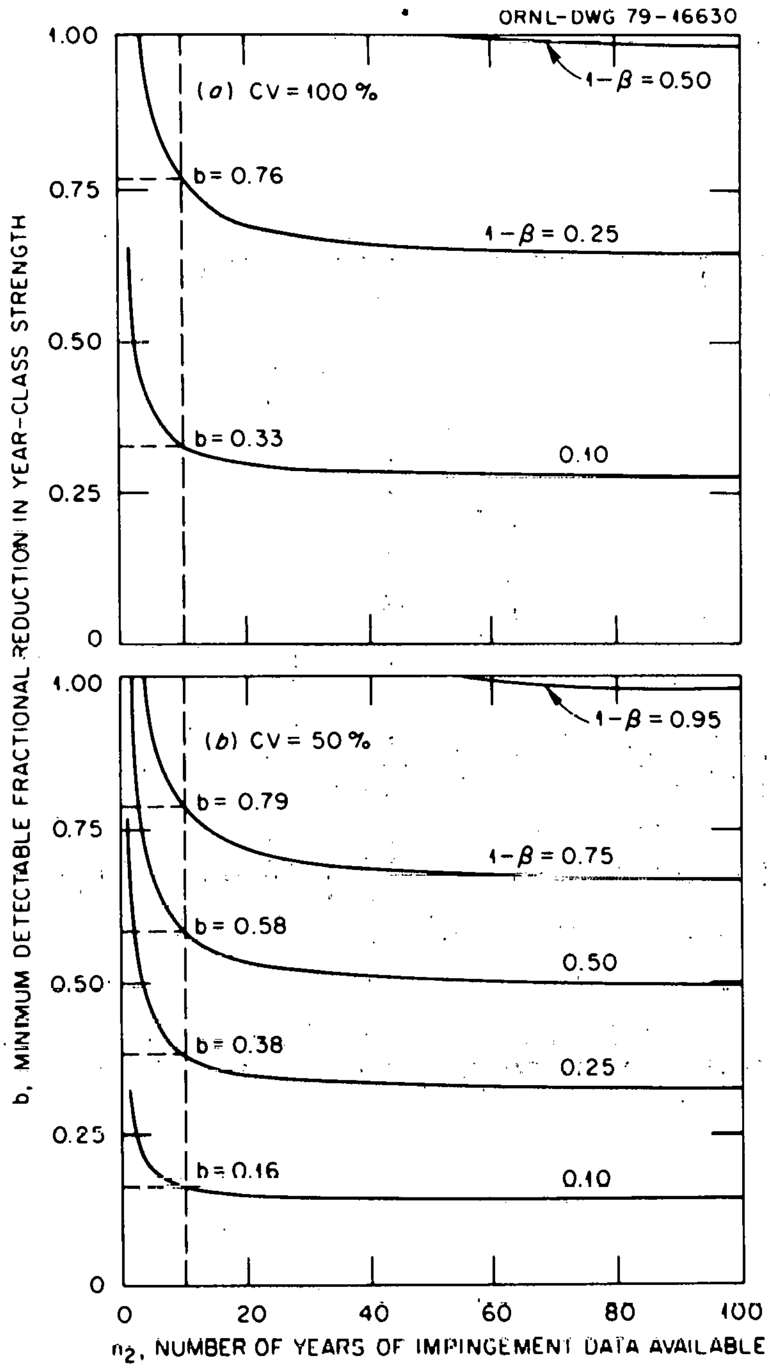

Fig. 3. Minimum detectable fractional reduction in year-class strength of young-of-the-year white perch in the Hudson River as a function of the number of years for which impingement data are available (starting in 1978).

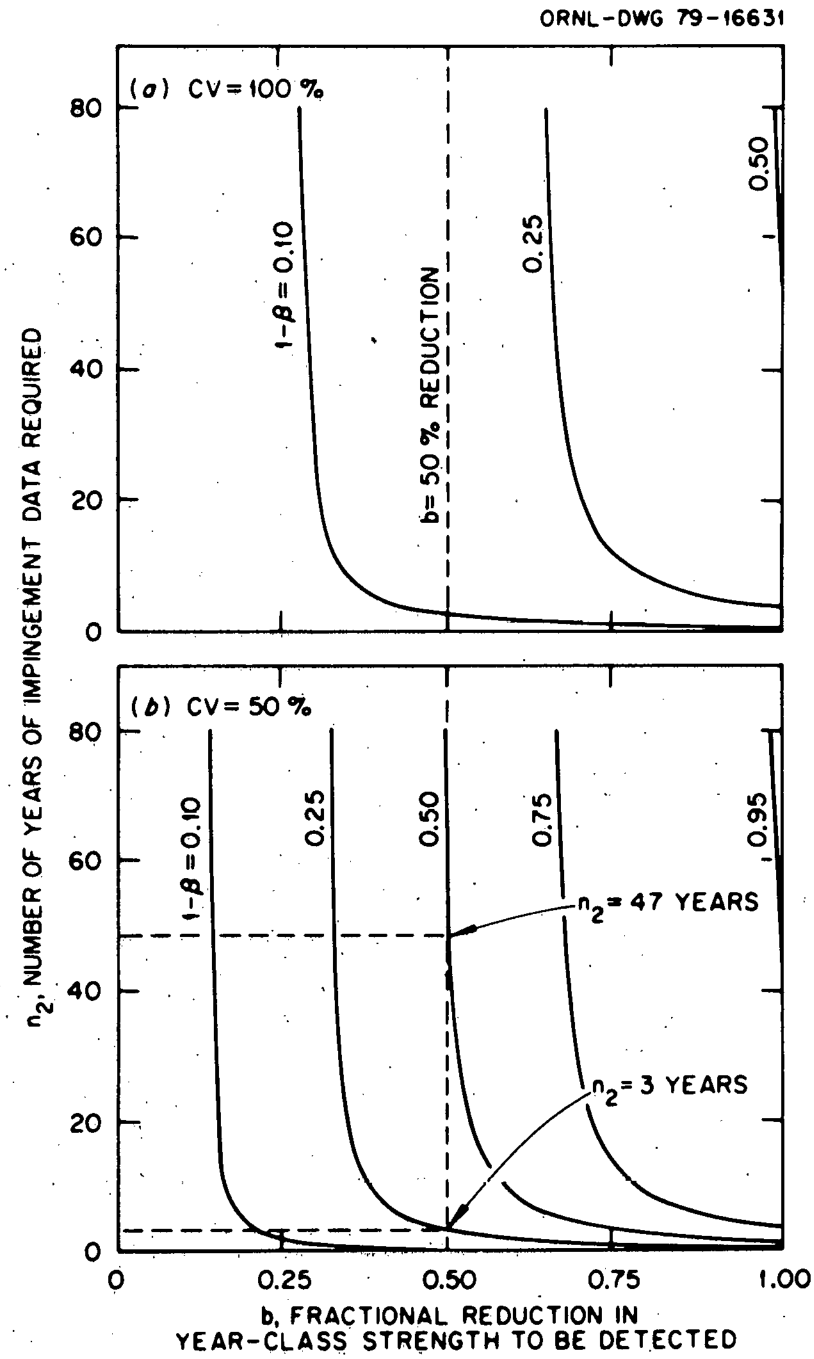

Fig. 4. Number of years of impingement data (starting in 1978) required to detect a specified fractional reduction in year-class strength of young-of-the-year white perch in the Hudson River.

River estuary. Two lines of evidence were presented: (1) comparison of young-of-the-year white perch impingement rates and catch per unit effort (CPUE) by beach seines and (2) comparison of the length-frequency distributions of young-of-the-year white perch in impingement collections and in beach-seine samples. Contrary to our expectation, we found that there is not a statistically significant positive correlation between the impingement rate indices and beach seine indices of year-class strength and that the two sets of length-frequency distributions tend to differ.

Our results led to the obvious question: Which data set (impingement or beach seine) provided the more accurate (less inaccurate?) indices of the year-class strength? Unfortunately, the answer to this question was not obvious. There were two major differences between the two sampling programs. The volume of water sampled (i.e., effort) and the number of fish collected were much greater for the impingement data, which argued in favor of the impingement data being the more accurate. However, the five power plants included in the analysis in Section C.1 (Van Winkle et al. 1980) represented only five sampling points, whereas there were over 100 beach seine stations located between RM 12 (George Washington Bridge) and RM 152 (Troy Dam), a difference which argued in favor of the beach-seine data being the more accurate. This side of the argument was weakened, however, by the fact that the beach-seine survey was specifically designed for young-of-the-year striped bass and not young-of-the-year white perch.

We prepared a manuscript for open literature publication, and sent it to Dr. Ronald Klauda of Texas Instruments (TI) for informal review. His comments indicated that the problem of measuring year-class strength in white perch was even more complex than we had imagined. The main problem was that year-class strength for Hudson River white perch, in contrast to striped bass, may not be fixed by early fall of the first year of life. Recent analyses by TI (Texas Instruments 1980) show that young-of-the-year beach seine indices of year-class strength in the fall and yearling beach seine indices of year-class strength the following spring and summer are not positively correlated.

Two other generic concerns were evident from this review. Primarily because of the adversarial Hudson River Power Case, ORNL does not have ready access to new data or the scientists who collect it. New data generally are not available in the public domain for one to two years after collection. For time-series data sets of the type and length of interest in this situation, the addition of two years' data can substantially change the results of the analysis. In addition, there is the risk of misinterpretation because of limitations on communication with the scientists responsible for collecting, analyzing, and interpreting the data.

Following in Klauda's review, we examined the correlations between the impingement rate time series for the various power plants. To our chagrin, only Indian Point unit 2 and Lovett were significantly positively correlated ($r_s = 0.9$; $P < 0.05$). Other Spearman correlation coefficients were as follows: Bowline and Lovett (0.7); Bowline and Indian Point unit 2 (0.60); Roseton and Danskammer in October-November (0.50); and Roseton and Danskammer in April-May (-1.2). We also compared the mid-July to August beach seine indices. For the years 1969-1976 (n = 7; no data for 1971), both the Spearman nonparametric correlation coefficient and Olmstead/Tukey corner test for association indicate that these two time series are not significantly correlated. Yet the first time series is a part (approximately 60% of the data) of the second time series. Given the problems identified above, we decided the manuscript did not merit submission for open literature publication.

The above analysis led to the following conclusions:

1. A reliable annual index of year-class strength for the Hudson River white perch population is needed.

2. Whether the present utility monitoring program can provide such an index is not clear.

3. Impingement data from the various power plants may be of value in developing this index, but further analysis is required.

THE IMPACT OF IMPINGEMENT ON THE 1974 and 1975 WHITE PERCH YEAR CLASSES

The objectives of this analysis were (1) to estimate the impacts of impingement on the 1974 and 1975 white perch year classes, (2) to identify the plants responsible for the greatest impact, and (3) to identify the seasons during which the greatest impact occurred.

Analytical Methodology

This analysis was performed using a simple model (Barnthouse et al. 1979) derived from Ricker's theory of fisheries dynamics. The measure of impact computed using this model is the conditional mortality rate (Ricker 1975, p. 9). As applied to impingement, the conditional mortality rate (M_I) is defined as the fraction of the vulnerable population that would be killed by impingement in the absence of mortality from all other sources, both natural and anthropogenic (throughout this paper we denote mortality from all other sources as "natural" mortality). The conditional impingement mortality rate has three major advantages over other quantitative estimates of impact. First, it is numerically equal to the fractional reduction in year-class abundance due to impingement, provided that density-dependent mortality is negligible during the period of vulnerability to impingement. Second, it accounts for the differential impact of impinging fish of different ages and, when properly calculated, it accounts for the effects of seasonal variations in impingement. Third, the only data required are estimates of the abundance of each year class at the time juveniles become vulnerable to impingement, counts of the number of fish impinged, and estimates of the rate of total mortality during the period of vulnerability.

We did not attempt to extrapolate estimates of the direct impact of impingement on single year classes to estimates of the long-term impact on the white perch population as a whole. Such extrapolations would have little value because the effects of compensatory processes, which undoubtedly operate in this population, cannot be validly quantified from any existing data.

Abundance, Mortality, and Impingement Estimates

Ranges of estimates of the abundance of young-of-the-year white perch on July 16 of 1974 and 1975 (assumed to be the beginning of the period of vulnerability to impingement), obtained from mark-recapture data, were presented in Table 6 of Van Winkle et al. (1980). Van Winkle et al. (1980) concluded that natural mortality among yearling and older white perch is approximately 50% per year; natural mortality among impingeable young-of-the-year is probably between 50 and 80% per year.

Estimates of the number of white perch impinged and killed by Hudson River power plants during 1974-77 were calculated by Van Winkle et al. (1980) from data obtained from the Hudson River utilities. It was assumed that, for all plants except Indian Point (where all impinged fish are collected), factors promoting overestimates (principally the survival of impinged fish) and underestimates (principally collection efficiency) of impingement are roughly equal in magnitude. It appears from data on the length-frequency distribution of impinged white perch that relatively few fish older than age II are impinged. Young-of-the-year white perch are readily distinguished from older fish on the basis of length, but yearlings can be clearly distinguished from two-year-olds. Therefore, we employed two alternative assumptions about the age distribution of the impingement "catch." First, we assumed that all impinged white perch older than age 0 are yearlings, resulting in two years of vulnerability to impingement. Alternatively, we assumed that one-half of these fish are yearlings and half are two-years-olds, resulting in three years of vulnerability to impingement. It is likely that the true split between yearlings and two-year-olds lies between these extremes.

Results

We applied the empirical model described by Barnthouse et al. (1979) using all combinations of estimates of initial abundance, mortality, and period of vulnerability of the 1974 and 1975 white perch year classes. Because no age-frequency distributions were available for impingement collections beyond December 1977, we could not compute

m_I for the 1975 year class under the assumption of three years of vulnerability to impingement. Table 2 contains the ranges of estimates of m_I, for both year classes, for all plants combined. These estimates indicate that under the most optimistic assumptions, i.e., high abundance, low natural mortality, and two years of vulnerability, impingement at Hudson River power plants reduced the size of the 1974 white perch year class by about 10% and the 1975 year class by about 8%. Under the most pessimistic assumptions, the size of the 1974 year class was reduced by 59%. Overall, the estimates of m_I indicate a probable 20% or larger reduction in the size of the 1974 year class because of impingement. Given that we could compute m_I for the 1975 year class only under the optimistic assumption of two years of vulnerability, our results indicate a probable 15% or larger reduction in the abundance of this year class.

The reproductive value of a sexually immature fish increases with its age, because its probability of surviving to maturity increases. For this reason, the impact to a population of killing an immature fish increases with its age (Barnthouse et al. 1979). Thus, the impingement of yearling and two-year-old white perch has substantially greater impact on the white perch population than is indicated by their contribution to the impingement counts. In Table 3 we have tabulated the contributions of yearling and older white perch to m_I, under assumptions yielding low (low young-of-the-year natural mortality and two years of vulnerability) and high (high young-of-the-year natural mortality and three years of vulnerability) contributions for these fish. Assuming two years of vulnerability and low young-of-the-year mortality, yearling and older white perch accounted for only 8% of the total impingement count for the 1974 year class. Yet the contribution of these fish to m_I is about 20% (0.028/0.153) as high as the contribution of young-of-the-year. Under the assumption of three years of vulnerability, the contribution of yearling and older fish is about 75% as high as the contribution of young-of-the-year. The contribution of yearling and older fish to m_I for the 1975 year class is even higher than that for 1974.

Table 4 contains an analysis of the contribution of each of six power stations to m_I for each year class. Because these results are relatively insensitive to assumptions about abundance, mortality, and length of the period of vulnerability, we present the analysis for a single reference case: best estimate of initial population size, high natural mortality, and two years of vulnerability. These results show that the impact of the Indian Point Nuclear Station (units 1, 2, and 3 combined) was, for both year classes, greater than the combined impact of the other five plants. Interestingly, the contributions of Bowline and Lovett were smaller in comparison to those of Roseton, Danskammer, and Albany than would be expected based on their contributions to the impingement counts. The explanation for this result is that relatively more yearling and older white perch are impinged at the latter three plants (Van Winkle et al. 1980).

Table 2. Estimates of total conditional impingement mortality rates (m_I) and impingement exploitation rates (in parentheses) for the 1974 and 1975 year classes of the Hudson River white perch population. Estimates were computed using all combinations of assumptions about initial population size, natural mortality, and number of years of vulnerability.[a,b]

Number of years of vulnerability	Year class	Initial Population Size: Low — Natural mortality rate: Low	Low — High	Best estimate — Natural mortality rate: Low	Best estimate — High	High — Natural mortality rate: Low	High — High
2	1974	0.309	0.446	0.177	0.255	0.095	0.137
		(0.165)	(0.200)	(0.094)	(0.114)	(0.051)	(0.061)
	1975	0.166	0.245	0.116	0.172	0.077	0.115
		(0.082	(0.099)	(0.057)	(0.069)	(0.038)	(0.046)
3	1974	0.387	0.583	0.221	0.336	0.119	0.181
		(0.172)	(0.209)	(0.099)	(0.119)	(0.053)	(0.064)
	1975	--	--	--	--	--	--

[a]Total conditional impingement mortality rates are equal to fractional (or percent) reductions in year-class strength due to impingement, assuming no compensation.

[b]Exploitation rate calculated by dividing the total number of white perch impinged in a year class during the entire period of vulnerability by the initial size of the young-of-the-year population at the start of the period of vulnerability.

Table 3. Contributions of age 0 versus age 1+ white perch to impingement counts and to conditional impingement mortality rates for representative cases yielding low and high contributions of older fish to m_I.[a]

Year Class	Case	Age 0: Fraction of impingement count	Age 0: m_0	Age 1+: Fraction of impingement count	Age 1+: m_{1+}
1974	Low natural mortality 2 years of vulnerability[b]	0.917	0.153	0.083	0.028
1975	Low natural mortality 2 years of vulnerability[b]	0.801	0.077	0.199	0.043
1974	High natural mortality 3 years of vulnerability[c]	0.878	0.211	0.122	0.158

[a]All cases use the best estimates of population size (Table 6 of Van Winkle et al. 1980).

[b]Assumptions yielding low contributions of age 1+ impingement to the conditional impingement mortality rate are low age 0 mortality and 2 years of vulnerability to impingement.

[c]Assumptions yielding high contributions of age 1+ impingement to conditional impingement mortality rate are high age 0 mortality and 3 years of vulnerability to impingement.

Table 4. Relative contributions of six power plants to impingement counts and plant-specific conditional impingement mortality rates ($m_{i.}$) for the 1974 and 1975 white perch year classes.[a]

Plant[b]	1974 year class		1975 year class	
	Fraction of impingement count	$m_{i.}$	Fraction of impingement count	$m_{i.}$
Bowline	0.134	0.033	0.066	0.013
Lovett	0.034	0.008	0.020	0.003
Indian Point	0.771	0.197	0.764	0.124
Roseton	0.023	0.011	0.067	0.016
Danskammer	0.025	0.011	0.058	0.016
Albany	0.017	0.011	0.025	0.008

[a]Analysis for reference case (best estimate of initial population, high age 0 natural mortality, 2 years of vulnerability).

[b]All units combined.

Figure 5 shows an analysis of the above reference case by season. For both year classes, substantial impacts occurred only during winter (December-February) and spring (March-May). Not surprisingly, the seasonal pattern of impacts for all plants combined is closely matched by the seasonal pattern at Indian Point. The combined impact of the other five plants is spread relatively evenly over the year.

Discussion

Our analysis shows that the abundance of the 1974 white perch year class in the Hudson River was reduced by at least 10%, and probably by 20% or more, because of impingement. The abundance of the 1975 year class was reduced by at least 8%, and probably by 15% or more. These impact estimates do not include consideration of entrainment, so that the total impact of power plants on these year classes was even greater than is indicated by our analysis.

The fact that yearling and older white perch are vulnerable to impingement contributes to the surprisingly high impact of impingement on this population. However, it is the seasonal distribution of white perch that is primarily responsible for their vulnerability. These fish migrate to the lower and middle estuary, where the Bowline, Lovett, and Indian Point plants are located, during the late fall and remain there through the winter (Consolidated Edison 1977). Studies conducted by Texas Instruments (1974, 1975a) suggest that the high levels of winter impingement of white perch at Indian Point may be related to their preference for deep areas of the Hudson River channel. In the vicinity of Indian Point the channel is located along the east shore of the Hudson, adjacent to the Indian Point intakes. Impingement "events" at Indian Point are also related to the presence of high concentrations of white perch in the vicinity of the salt front, which fluctuates above and below the plant during the winter. The mobility of these overwintering fish, and consequently their ability to avoid intake structures, is probably reduced because of near-freezing water temperatures.

Given the information currently available, it is our judgment that the level of impingement impact on the Hudson River white perch population is high enough to warrant mitigation. because the Indian Point Generating Station is responsbile for most of the impact, mitigating impingement at Indian Point is the most effective way to protect this population. This could be accomplished either by reducing the number of fish impinged or by increasing the survival rate of impinged fish. Since impingement at Indian Point occurs primarily during winter and early spring, any mitigating devices installed must be effective at low temperatures in order for the impact to be substantially reduced.

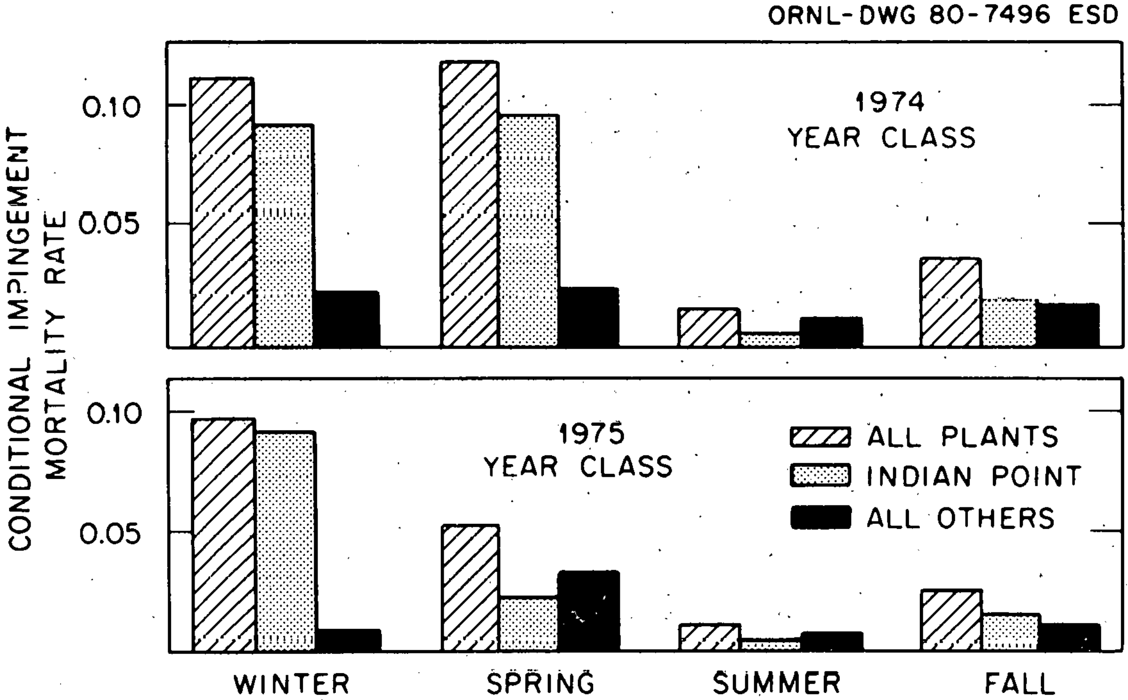

Fig. 5. Seasonal comparison of conditional impingement mortality rates for all plants combined, for Indian Point (all units combined) and for all other plants combined.

THE IMPACT OF ENTRAINMENT ON THE 1974 AND 1975 WHITE PERCH YEAR CLASSES

The purpose of this analysis was the estimation of conditional entrainment mortality rates for the 1974 and 1975 white perch year classes. The model used for this purpose (Boreman et al. 1979), known as the Empirical Transport Model (ETM), was developed in cooperation with the U.S. Fish and Wildlife Service's National Power Plant Team. ORNL's work was funded by NRC (Methods to Assess Impacts on Hudson River Striped Bass, NRC FIN No. B0165). To use the ETM, the following data are required:

(1) morphometric data for the Hudson River estuary,

(2) power-plant withdrawal rates,

(3) spatial and temporal distributions of entrainable white perch life stages during 1974 and 1975,

(4) estimates of the probability of entrainment mortality for entrained white perch eggs, yolk-sac larvae, post yolk-sac larvae, and juveniles, and

(5) estimates of W-factors for the four entrainable life-stages (these parameters are estimates of the density of organisms in power-plant cooling water relative to their density in the river cross section from which cooling water is drawn).

The morphometric and power-plant withdrawal data were obtained directly from the utilities. Our estimates of the biological input data (items 3-5) required by the ETM were discussed in the Annual Report for the period October 1, 1978 - September 30, 1979 (Barnthouse et al. 1980). Detailed descriptions of the data and methods used are contained in the testimony of Boreman et al. (in press), prepared for the Hudson River Power Case.

Table 5 contains estimated conditional entrainment mortality rates for the 1974 and 1975 white perch year classes. These year-specific values were calculated from the spatial distributions, temporal distributions, and power-plant flows observed during these years. A range of estimates of the conditional entrainment mortality rate for each year class was obtained by using two alternate sets of W-factors as inputs to the ETM. Although the impact estimates presented in Table 5 represent fractional reductions in abundance of greater than 10% for both year classes, they are smaller than the corresponding impingement impact estimates (Van Winkle et al. 1980, Table 8).

Table 5. Conditional entrainment mortality rate estimates, expressed as percentages, for the 1974 and 1975 white perch classes[a]

Year	GBC[b]	MU[c]
All plants:		
1974	10.9	11.7
1975	13.0	13.6
Roseton, Indian Point unit 2, and Bowline only:		
1974	6.9	7.8
1975	9.6	8.7

[a]From Table VIII-1 of Boreman et al. (in press).

[b]W-factors computed using the Gear-Bias Cancelling (GBC) method, explained in Section V of Boreman et al. (in press).

[c]W-factors computed using the Modified Utility (MU) method, explained in Section V of Boreman et al. (in press).

EVALUATION OF DATA RELATING TO THE EXISTENCE OF DENSITY-DEPENDENT GROWTH IN THE HUDSON RIVER WHITE PERCH POPULATION

Although we estimated the impact of impingement and entrainment (measured as fractional reductions in year-class abundance in the absence of compensation) on the 1974 and 1975 white perch year classes, we were unable to project these impacts into the future in order to estimate the effects of power plants on the long-term abundance of the Hudson River white perch population. Long-term projections were impossible because the operation of compensatory mechanisms, such as density-dependent growth can, in principle, offset much of the mortality caused by impingement and entrainment. Two consultants for the utilities, Texas Instruments (TI) and Lawler, Matusky, and Skelly Engineers (LMS), searched for empirical evidence for the operations of density-dependent growth in the Hudson River white perch population. On two occasions, LMS claimed to have found such evidence. We conducted an independent evaluation of both the raw data and the analyses of those data performed by LMS and TI, and concluded that the data available are not sufficient for demonstrating the occurrence or nonoccurrence of density-dependent growth in the Hudson River white perch population.

Although LMS has twice reported finding inverse correlations between growth and abundance in white perch (Orange and Rockland Utilities, Inc. 1977; Lawler, Matusky, and Skelly 1978), TI twice reported looking for, but not finding such correlations (Texas Instruments 1975b, 1978). Moreover, an examination of LMS' two analyses revealed serious deficiencies, most of which were shared by TI's work. The length data used by LMS contained unevaluated biases caused by the pooling of fish collected from different stations with different gears. It is quite possible that the results reported by LMS were no more than artifacts introduced by the pooling procedure. In both reports the correlation set forth as empirical evidence of density-dependent growth was obtained from a multiple regression in which an environmental variable (freshwater flow) was included. In each case, the particular variable selected was chosen from a large number of alternative formulations, at least partly because a good fit could be obtained with it. We believe that, aside from any problems with the data, results derived in this way cannot be accepted as empirical confirmation for the reality of density-dependent growth.

Our comparisons of the TI and LMS growth and abundance indices for white perch suggested that the correlations presented by LMS may have been spurious. Both sets of indices purported to be measures of the growth and abundance of juvenile white perch in the Hudson River. However, when the LMS and TI growth (Table 6) and abundance (Table 7) indices for the same years were compared, only the growth indices were positively correlated.

Even if a correlation did exist between growth and density in white perch, the discovery of this correlation would not be proof that growth is functionally related to density. Alternative explanations

Table 6. Correlation between TI and LMS white perch growth indices over the period 1972-75

Year	LMS growth (mm)[a]	TI growth (mm/d)[b]
1972	57.1	0.034
1973	76.5	0.0222
1974	69.3	0.0204
1975	75.7	0.0177

$$TI = -0.04453 + 0.00086\ LMS$$

$r^2 = 0.83$ $F = 9.64$ $P = 0.09$

[a]Lawler, Matusky, and Skelly (1978, Table 3).

[b]1975 year-class report (Texas Instruments 1978, Table B-116).

Table 7. Correlations between LMS and TI white perch density indices

	LMS unadjusted density (CPUE)[a]	LMS adjusted density (CPUE)[b]	TI density (CPUE)[c]
1972	117.5	8.143	4.3
1973	38.8	-33.927	20.1
1974	100.4	37.955	6.8
1975	53.0	-12.170	26.0

LMS (unadjusted) vs TI

$LMS = 124.81 - 3.31\ TI$

$r^2 = 0.85 \quad F = 11.32 \quad P = 0.08$

LMS (adjusted) vs TI

$LMS = 30.86 - 2.16\ TI$

$r^2 = 0.54 \quad F = 2.37 \quad P = 0.26$

[a]Lawler, Matusky, and Skelly (1978, Table 3).

[b]Table 11 of Barnthouse et al. (1980).

[c]1975 year-class report (Texas Instrument 1978, Table B-116).

for such a correlation are clearly possible. The hypothesis of density-dependent growth cannot be accepted until it has survived independent tests designed to refute it.

Finally, the existence or nonexistence of density-dependent growth is entirely irrelevant to a rational assessment of the impact of powerplants on the Hudson River white perch population. We do believe that some form (or forms) of compensatory mechanisms must operate in this population under certain conditions. Once this is conceded, the mere demonstration that some particular mechanism exists or does not exist is useless for predictive purposes. Studies of density-dependent growth would be useful if it were possible to quantify its compensatory effects. However, these effects cannot be quantified (they could be either substantial or negligible) in the absence of precise quantitative information on the relationship between size and mortality in juvenile white perch. No such information now exists, and we doubt that it can ever be obtained.

A complete account of our analysis was presented in the Annual Report for the period October 1, 1978 - September 30, 1979 (Barnthouse et al. 1980).

DATA AND INFORMATION FROM OTHER WATER BODIES

We examined the available data on the white perch populations of the Delaware River and Chesapeake Bay. We concluded that analyses similar to those performed for the Hudson River population (Van Winkle et al. 1980) are not possible for these other systems.

Although estimates of annual mortality were obtained for both Delaware (Wallace 1971) and Chesapeake (Mansueti 1960) white perch populations, no absolute abundance estimates exist, either for adults or for young-of-the-year (T. Polgar, Maryland Power Plant Siting Program, personal communication). Consequently, conditional impingement mortality rates could not be computed.

Impingement data collected at the Calvert Cliffs, Surry, and Salem plants were examined to determine the feasibility of performing regression analyses analogous to those in Section II of the topical report (Van Winkle et al. 1980). No such analyses were feasible. Our examination of the 1977 Environmental Monitoring Report (nonradiological) for Calvert Cliffs (Baltimore Gas and Electric Co. 1978) indicated that too few white perch are impinged at this plant for any analysis to be worthwhile. From the data in Tables 11-1, 11-11, and 11-13 of the above report, we estimated that only about 1200 white perch were impinged at Calvert Cliffs during all of 1977.

Enough white perch are impinged at both Surry and Salem so that analyses would be useful, but at neither plant was the available time series of impingement rates long enough for meaningful results to be obtained. Even with no correction for collection efficiency, more than 500,000 white perch were estimated to have been impinged at Salem between April and December of 1977 (Public Service Electric and Gas Company 1978, Section 3.1.2.2). Similarly, the unadjusted impingement estimates for Surry indicate that at least 300,000 white perch were impinged between May and December of 1977 (Virginia Electric Power Co. 1978, Section 3.0). If the seasonal impingement patterns at Salem and Surry are similar to the pattern observed at Indian Point, then, allowing for less-than-100% collection efficiency and for the lack of winter impingement collections, as manyy as one million white perch may have been impinged at each plant during 1977. By comparison, one to two million white perch are impinged annually at Indian Point, and two to three million are impinged annually at all Hudson River Power Plants combined.

We believe that the five-year time series analyzed in the topical report is the minimum length required for a meaningful analysis. Five years of comparable data were not available for either Salem or Surry. The first year of operation at Salem was 1977; therefore, only two years of data existed for this plant at the time we performed our evaluation. Impingement data have been collected since 1973 at Surry. However, because of a change in intake design, the data collected prior to May 1974 are not comparable to later data. Moreover, the sampling intensity at Surry, 50 min per week (Adams et al. 1977, p. 2-215), is only about 4% of that at the Hudson River plants (at least 24 h/week). Consequently, the data that do exist for Surry are probably low in precision compared to the Hudson River data, so that an even longer time series might be required to detect a significant trend in the rate of impingement of white perch. Given the magnitude of white perch impingement at Salem and Surry, we believe that a requirement for more extensive impingement monitoring at these plants should be considered. Special studies of collection efficiency and of long-term survival of impinged fish, such as those conducted at the Hudson River plants, would be extremely valuable.

MULTIPOPULATION MODELING

Assessments of the impacts of power plants on aquatic ecosystems, including the work described in the other sections of this report, generally focus on single populations. Quantitative studies of the impacts of power-plant-related stresses on individual organisms (e.g., thermal tolerance studies) are conducted. Data on individual organisms are then extrapolated, using a population model, to impact on populations. However, in many cases, studies of single populations may be inadequate for assessing power plant impacts, because they cannot account for the effects of interactions among populations. For example, interactions with food organisms, competitors, and predators may magnify or offset the direct effects of mortality caused by power plants on a population. It is also possible for direct impacts on one population to cause indirect impacts on others. The effects of these interactions on the responses of populations to power plant mortality can be quantified using multipopulation models: simple food chain and food web models that incorporate the dynamics of several interacting populations.

Although many theoretical studies were performed using these models, there have been few attempts to apply them to resource management or impact assessment problems. This report describes exploratory research intended to investigate the utility of simple multipopulation models, analyzed using a method known as loop analysis (Levins 1974, 1975) in power plant impact assessment and monitoring. The assessment of direct and indirect effects of impingement and entrainment of white perch at Hudson River power plants is an especially appropriate test problem for this investigation. Previous work (Van Winkle et al. 1980) showed that this population suffers unusually high levels of entrainment and impingement mortality. In addition, a great deal of information is available concerning the biology of the white perch and its role in the Hudson River ecosystem.

This research had three major objectives:

(1) Identify the theoretical effects of inter- and intrapopulation interactions on the responses of populations to power plant mortality,

(2) Use the results to assess the likely consequences of the entrainment and impingement of white perch on Hudson River fish populations, and

(3) Evaluate the potential uses of multipopulation models and loop analysis in assessing potential impacts, designing ecological monitoring programs to detect those impacts, and interpreting monitoring data.

Modeling Strategy

Even for an intensively studied ecosystem such as the Hudson River, there are many gaps in our knowledge about interpopulation interactions. The many limitations on our knowledge of ecosystem structure and function have important implications for the kinds of strategies that are appropriate for modeling multipopulation systems. The strategy taken in this study has three essential components: (a) studying several simple, alternative models of the system of interest, (b) employing highly generalized functional forms in the model equations, and (c) drawing only qualitative conclusions from the analyses. As noted above, there is considerable uncertainty about the actual patterns of interaction among Hudson River fish populations. In addition, the number of species occurring in any ecosystem, including fish, invertebrates, phytoplankton, microbes, etc., is so enormous that the lumping of similar populations, and of life-stages within populations, is necessary in every modeling study. The use of multiple, alternative models, each constructed using different simplifying assumptions, aids in identifying artifacts of simplification and in ensuring the robustness of conclusions drawn from the study.

Aside from the above considerations, the information needed to formulate realistic and precise mathematical representations of interactions betweeen the white perch and any of its prey, competitors, or predators is unavailable and probably unobtainable. For this reason, methods of model formulation and analysis were chosen that involve specifying neither the exact functional forms of these interactions nor the values of any of the parameters. The key to this approach is an analytical method known as loop analysis (Levins 1974, 1975; Lane and Levins 1977). Loop analysis is a simple method of studying the behavior of systems of coupled differential equations in the neighborhoods of equilibrium points. To perform loop analysis, it is necessary to specify only the signs of the partial derivatives of the equations. Any available information about the magnitudes or relative magnitudes of the partial derivatives can be used to increase the power of the analysis. It is possible, using loop analysis, to study the effects of a stress imposed on one or more of the model populations on the equilibrium abundances of all populations. It is frequently possible to determine which populations will decrease, which will increase, and which will be unaffected without specifying a single parameter value.

In addition to determining directions of change, loop analysis can be used to identify critical parameters that are especially important in determining the responses of the model populations to the stress being studied.

In order to obtain generality and robustness, the strategy employed in this study sacrifices numerical precision. The only predictions generated are qualitative patterns of change among populations resulting from power plant mortality. Given the limited state of our understanding of the Hudson River ecosystem, the absence of quantitative predictions is no great sacrifice. Swartzman et al. (1978) convincingly argued that, despite years of developmental work and large expenditures of research funds, the striped bass population models developed by ORNL for NRC and by LMS engineers for the Hudson River utilities cannot make reliable quantitative predictions about the effects of power plant mortality on the Hudson River striped bass population. Attempting to make quantitative predictions about multipopulation responses would surely be a futile exercise.

Model Description

The primary source of energy for the biota of the Hudson River is organic detritus. According to Consolidated Edison (1977), more than

90% of the energy budget of the tidal portion of the Hudson River (the habitat occupied by the white perch population) is derived from three sources: the watershed upstream from Troy Dam, terrestrial runoff from the lower watershed, and organic pollution. Less than 9% of the total available energy is derived from primary production in the river itself.

Macroinvertebrates such as chironomids, Neomysis, and Gammarus feed on the detritus, and these organisms are fed on by white perch. The simplest possible model of this system is a three-compartment model consisting of white perch, macroinvertebrates, and detritus. Figure 6 depicts the kinds of biomass flows that occur in such a food chain. Fish and invertebrate populations gain biomass through predation or grazing and lose biomass through mortality, defecation, and respiration. The detritus pool gains biomass through import, mortality to organisms, and defecation; it loses biomass through export and grazing by invertebrates. Power plants constitute a source of density-independent mortality, converting fish and invertebrates into detritus. In model 1, these flows are formalized as the following three equations:

(white perch)

$$\frac{dX_3}{dt} = X_3 \, [F_{32} \, (X_2,X_3) - G_{33} \, (X_3) - R_F - Q_3 - C_3 \, P], \qquad (1)$$

(invertebrates)

$$\frac{dX_2}{dt} = X_2 \, [F_{21} \, (X_1,X_2) - G_{23} \, (X_2, X_3) - R_I - Q_2 - C_2 \, P] \qquad (2)$$

and (detritus)

$$\frac{dX_1}{dt} = I - X_1 \, T - X_2 \, F_{21} \, (X_1, X_2) + [X_2 \, (G_{23}(X_2,X_3) - X_3 \, F_{32} \, (X_2,X_3)]$$

$$+ X_3 \, G_{33} \, (X_3) + \sum_{i=2}^{3} X_i \, (Q_i + C_i \, P) \qquad (3)$$

Table 8 presents the definitions of the variables and parameters employed in this model. Two important features of model 1 that are common to all of the models merit discussion here. First, the functional forms of equations 1 to 3 are only partially specified. Some processes, namely detritus import (I), detritus export (X_1T), density-independent mortality (Q_i), power plant mortality (C_iP), and respiration (R_I, R_F), can be reasonably assumed to be density-independent. These processes are modeled as linear functions. Predation and assimilation are undoubtedly nonlinear and density-dependent. Explicit functional forms are not specified for

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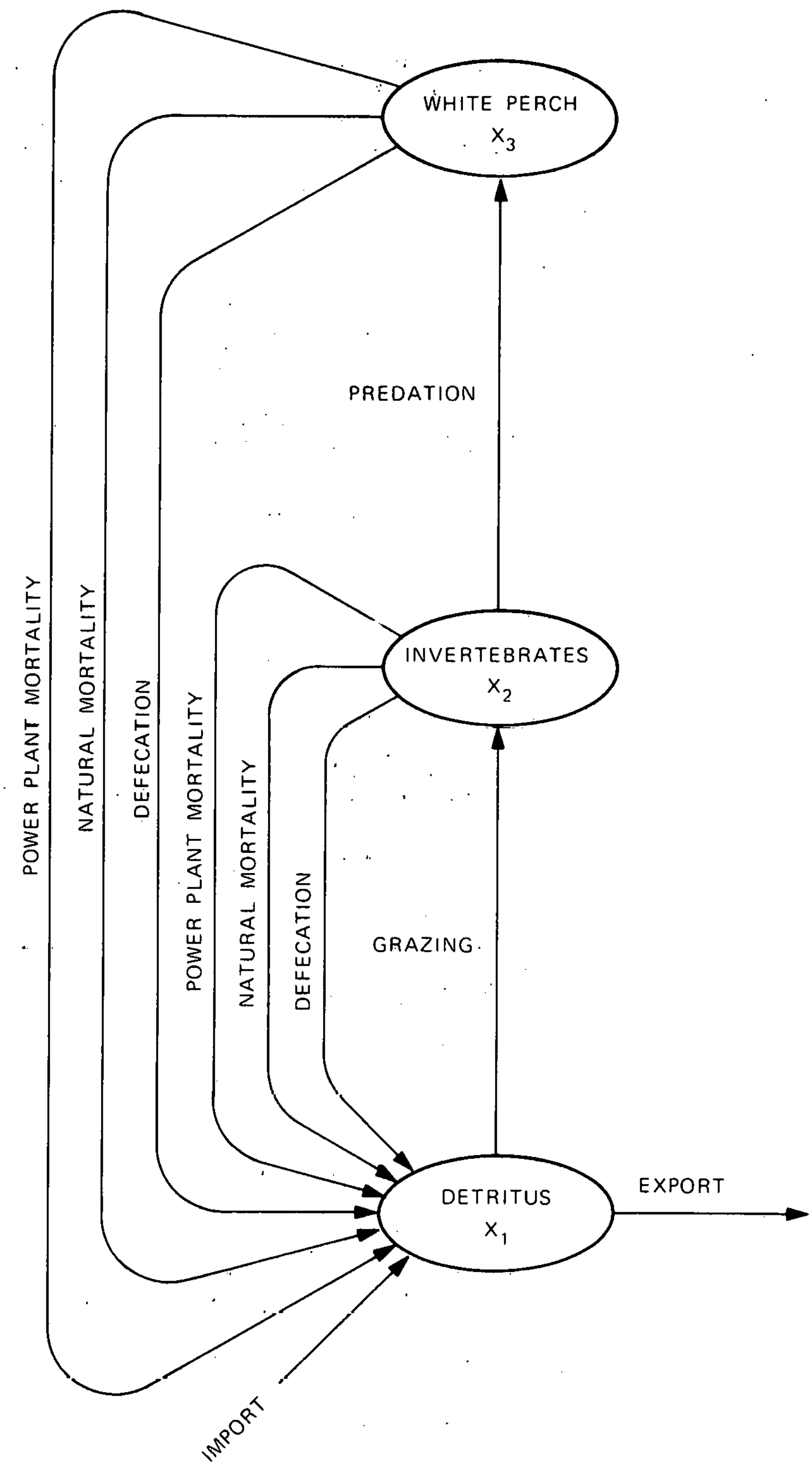

Fig. 6. Biomass flows in a three-compartment food chain.

Table 8. Definitions of variables, rate functions, and parameters for model 1

Variable, rate function, or parameter	Definition (units)
	Variables
X_1	Detritus biomass (mass)
X_2	Invertebrate biomass (mass)
X_3	White perch biomass (mass)
	Rate functions
$F_{ji}(X_i,X_j)$	Per capita assimilation rate for predator j feeding on prey i (1/time)
$G_{ij}(X_i,X_j)$	Per capita exploitation rate for prey i being fed on by predator j (1/time)
$G_{33}(X_3)$	Per capita cannibalism rate (1/time) for white perch
	Parameters
I	Detritus import rate (mass/time)
T	Detritus export rate (1/time)
R_I	Invertebrate respiration rate (1/time)
R_F	Fish respiration rate (1/time)
Q_i	Density-independent death rate (1/time)
C_i	Vulnerability coefficient (1/volume)
P	Power plant withdrawal rate (volume/time)

these processes. It is assumed only that each rate of loss or gain of invertebrate or fish biomass due to predation, cannibalism, or assimilation can be expressed as a product of the biomass of the population (X_i) times a per capita rate function ($F_{ji}(X_i,X_j)$, $G_{ij}(X_i,X_j)$, or $G_{33}(X_3)$). In addition, it is assumed that the partial derivatives of the rate functions are, with one exception, positive at equilibrium. To allow for feeding inhibition due to intraspecific crowding, the partial derivatives of the assimilation functions (F_{ij}) are assumed to be negative with respect to consumer abundance (X_i). The results obtained from analyzing the models hold for any explicitly defined process functions that have these properties.

The second important feature of the models is that biomass accounting is complete. Biomass can enter the system only as detritus import (I) and can leave only through downstream transport (X_1T) or respiration (R_I or R_F). Immigration and emigration terms for invertebrates and fish could have been included in the models, but, unless these processes are affected by power plant operation, their inclusion would needlessly complicate the equations and would not change the results of the analysis. Except for respiration, each term describing a flow of biomass out of the invertebrate or fish compartments is matched by a term describing an inflow of biomass to the detritus compartment. For the flows due to power plant mortality, density-independent mortality, and cannibalism, the inputs to the detritus compartment are equal to the outflows from the organism compartments. For flows due to predation, the input to the detritus compartment (defecation) is equal to the deficit between the outflow from the prey compartment and the input to the predator compartment.

Figure 7 presents a second graphical representation of model 1, using the notation of Levins (1974). The large closed ellipses represent the three system variables. Inter- and intrapopulation interactions are represented by lines (paths) connecting the ellipses. Positive interactions are denoted by lines ending in arrows; negative interactions by lines ending in small circles. A path from a variable to itself represents an intrapopulation interaction, such as intraspecific competition or cannibalism

Three additional models were developed by adding different combinations of competitors and predators to the three-compartment food chain (model 1). Model 2 contains two fish populations; white perch and a competing fish that also feeds on benthic invertebrates. Model 3 was obtained from model 1 by adding a predator rather than a competitor. Model 4 contains three fish populations: white perch, a competitor, and a predator that feeds on both white perch and its competitor.

Two more models were developed from model 1 by subdividing the white perch population into life stages. The purposes of studying these models were (1) to characterize the effects of power plant operation on the relative abundances of young-of-the-year versus yearling and older white perch, and (2) to discover whether, and under what conditions, the lumping of all life stages into a single

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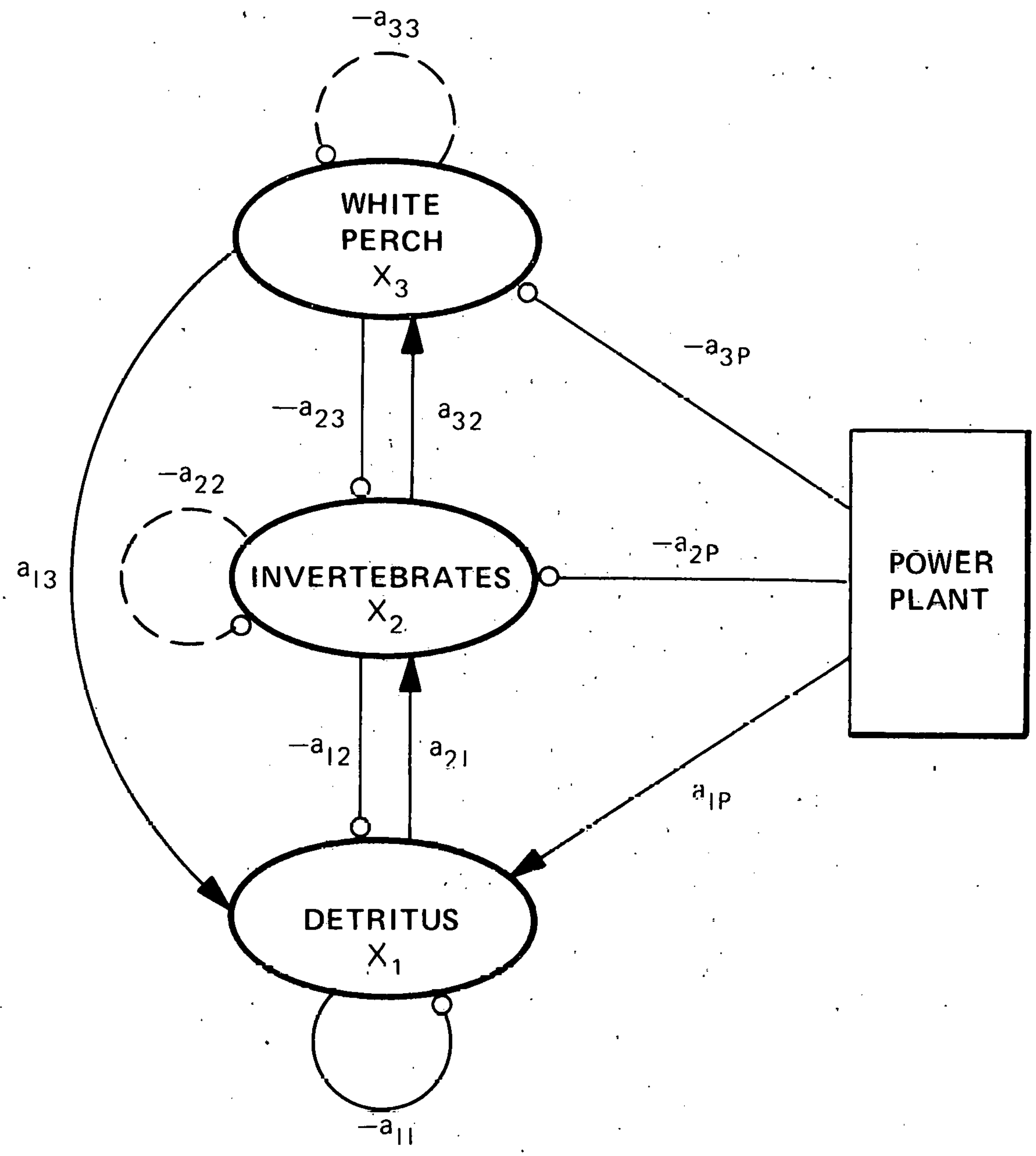

Fig. 7. Loop diagram for model one.

compartment leads to erroneous conclusions about the effects of power plant operation. Yearling and older white perch were lumped into the category "adults." Because young-of-the-year white perch (at least those beyond the early juvenile life-stage), like adults, feed on invertebrates (Texas Instruments 1980), these two age groups are competitors. In model 5, young-of-the-year white perch are vulnerable to cannibalism by adults. In model 6, it is the eggs that are vulnerable. In both models, eggs and young-of-the-year, but not adults, are vulnerable to power plant mortality.

Summary of Results

The loop expansion algorithm, explained in Appendix A of Barnthouse (in press) was used to derive equations that express the change in equilibrium abundance of each model population or age group in response to a unit increase in power plant withdrawal rate (P). On the basis of biological intuition alone, the following predictions could be made about the effects of power plant mortality on the white perch population and its prey, competitors, and predators:

1. Mortality imposed directly on white perch should cause a decrease in white perch abundance.

2. Mortality imposed on the invertebrate prey of white perch should cause an additional decrease in white perch abundance over and above the decrease resulting from mortality imposed directly on white perch.

3. Mortality imposed on either competitors or predators should offset the effects of mortality imposed directly on white perch.

4. Mortality imposed on white perch should cause an increase in the abundance of a competitor and should cause a decrease in the abundance of a predator.

The analyses of models 1-6 show that, although these interacting populations frequently respond to power plant mortality in the intuitively expected ways, counterintuitive responses are possible under some conditions:

5. If (a) a predator or a competitor, but not both, is present, and (b) no self-regulatory processes (cannibalism, territoriality, or feeding interference) are operating in the predator or competitor, then mortality imposed on invertebrates has no effect on white perch abundance.

6. If (a) a predator, but no competitors, is present, and (b) no self-regulatory processes are operating in the predator population, then neither mortality imposed on invertebrates nor mortality imposed on white perch can affect white perch abundance.

7. If both a competitor and a predator are present, then mortality imposed on invertebrates may increase, rather than decrease, white perch abundance. Moreover, mortality imposed on white perch may increase, rather than decrease, predator abundance.

8. Young-of-the-year and adult white perch respond differently to power plant mortality. Mortality imposed on invertebrates always decreases adult abundance, but may increase young-of-the-year abundance. Conversely, mortality imposed on young-of-the-year always decreases young-of-the-year abundance, but may increase adult abundance. If, and only if, adult white perch are cannibalize their eggs, it is possible for mortality imposed on eggs to increase the abundance of young-of-the-year.

9. Analyses of models 5 and 6 show that there are conditions in which, contrary to both intuitive expectation and to the predictions of model 1, mortality imposed on young-of-the-year white perch can increase, rather than decrease, the total abundance of white perch, even though neither predators nor competitors are present.

Discussion

The responses of the model populations to power plant mortality are, in most cases, in accord with intuition. Mortality imposed on white perch alone usually decreases the abundance of white perch, regardless of the presence or absence of predators and competitors. Mortality imposed on invertebrates usually decreases white perch abundance over and above the decrease caused by direct mortality; mortality imposed on competitors and predators generally offsets direct mortality. Most of the exceptions to these rules are special cases that probably do not apply to the Hudson River ecosystem. However, competitive interactions within the white perch population can markedly affect the response of this population to power plant mortality. Competition between younger age groups that are vulnerable to power plants and older age groups that are invulnerable shifts the distribution of biomass within the population toward the older age groups. At least in theory, it is possible for the total biomass of the population to increase in response to power plant mortality.

As would be intuitively expected, power plant mortality imposed on white perch increases the abundance of a competitor that is itself invulnerable to power plants. However, the effects on a predator of mortality imposed on white perch cannot be predicted from food web structure alone. A predator that feeds preferentially on white perch may be adversely affected, even if alternate prey are available. A predator that feeds preferentially on a competitor of white perch may benefit from the mortality imposed on white perch.

Information on the life histories and vulnerabilities to power plants of Hudson River fish populations, discussed in detail by Barnthouse (in press), suggests that the levels of power plant mortality imposed on predators, competitors, and prey of white perch are probably insufficient to offset the effects of mortality imposed on white perch. No piscivorous fish have been identified that prey preferentially on white perch in the Hudson River. According to Scott and Crossman (1973), the white perch is not important as a forage fish. Therefore, it does not appear that predator populations will be adversely affected by this mortality.

If the operation of Hudson River power plants does cause a substantial decline in the abundance of white perch, this decline should be accompanied by an increase in the abundance of one or more competing fish populations. Existing information is insufficient for predicting which competitor should increase. Observable changes in the age and size structure of the white perch population should also occur. The models predict that older white perch should increase in size (because of reduced competition with younger fish) and should comprise a larger fraction of the total biomass of the population.

Multipopulation models and loop analysis appear to be ideally suited for two major uses of mathematical models: deriving hypotheses and interpreting the results of experiments. Barnthouse (1976) and Lane and Levins (1977) used this strategy to interpret results of predator manipulation and nutrient enrichment experiments. The same methods can be used to formulate "impact hypotheses" that can be tested using data from a suitably designed postoperational monitoring program. The use of impact hypotheses as organizing tools in monitoring program design was advocated by Fritz et al. (1980) and by Sanders et al. (1980) as a means of ensuring cost-effective allocation of monitoring effort. Because the only data needed to derive such hypotheses using loop analysis can be readily obtained from synoptic survey data, supplemented by additional life-history data on important species, the method seems ideally suited for this purpose.

For example, this study suggests that, in designing ecological monitoring programs for detecting impacts of power plants, it would be useful to focus on detecting patterns of change among populations and age groups rather than on changes in abundance of individual populations. For example, models 2 and 4 both predict that if power plant mortality <u>does</u> lead to a substantial decrease in the abundance of white perch, this decrease should be accompanied by a complementary increase in the abundance of competitors that are themselves relatively invulnerable to power plants. This complementary increase could serve to distinguish impacts of power plant operation from changes related to qualitatively different causes, e.g., a reduction in organic carbon import (perhaps due to improved sewage treatment or to upstream water diversions) that might reduce the abundance of both white perch and its competitors. The necessary data could be obtained from the same kinds of fish surveys that are currently performed, provided that reliable abundance indices can be developed. Changes in predator populations are less useful for assessment unless information on the diet composition of the predator and the competitive relationships among its prey are available.

The age-structured models suggest that, at least for fish such as the white perch in which vulnerable and invulnerable age groups compete, data on the age-compositions and length-frequency distributions of vulnerable fish populations would aid in detecting effects of power plant operation. Provided that juvenile and adult white perch are to some extent food-limited, power plant mortality imposed on two-year-old and younger fish should result in (a) an increase in the size of older fish, and (b) an increase in the population biomass of age 3 and older fish relative to that of the vulnerable younger age classes.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

1. No statistically significant trend toward decreasing abundance of young-of-the-year white perch is evident in the available time series of impingement data. However, variation in impingement rates among years is so great that an excessive number of years (greater than the expected lifetime of any currently operating generating unit) of additional data would be required to detect an actual 50% reduction in abundance. Moreover, it is not clear whether the impingement collection rate is, in fact, a valid index of year-class abundance.

2. The abundance of the 1974 white perch year class, as estimated by the conditional impingement mortality rate, was reduced by at least 10%, and probably by 20% or more, because of impingement alone. The abundance of the 1975 year class was reduced by at least 8%, and probably by 15% or more, because of impingementalone. The impact of the Indian Point Generating Station greatly exceeded the combined impacts of all other Hudson River power plants, with most of the impact occurring during the winter and early spring.

3. Additional reductions in abundance in excess of 10%, over and above impacts due to impingement, were imposed on the 1974 and 1975 white perch year classes by entrainment at Hudson River power plants.

4. Available data are insufficient for demonstrating the operation of density-dependent growth among young-of-the-year white perch in the Hudson River. Even if the existence of this compensatory mechanism were conclusively demonstrated, its compensatory effects could not be quantified from any data that can be realistically obtained.

5. The numbers of white perch impinged annually at the Surry and Salem plants appear to be comparable to the numbers impinged at Indian Point, but at neither plant is the available time series of impingement rates long enough for meaningful regression analyses to be performed. Moreover, there is insufficient information on (a) the white perch populations of Chesapeake Bay and the Delaware River, and (b) impingement collection efficiency, impingement survival, and the age composition of impingement collections at Surry and Salem for calculating conditional impingement mortality rates.

6. Entrainment and impingement mortality imposed on white perch probably will not cause adverse effects on piscivore populations in the Hudson River. If, however, mortality at power plants causes a substantial decline in the abundance of white perch, a complementary increase in the abundance of one or more competitors that are relatively invulnerable to power plants should occur. Changes in the age and size structure of the white perch population should also occur. Older fish should increase in size and should comprise a larger fraction of the total biomass of the population.

7. Because of the impossibility of quantifying (a) compensatory mechanisms within the white perch population and (b) interactions between the white perch population and its competitors, predators, and prey, it is not possible to quantify long-term consequences of the entrainment and impingement of white perch at Hudson River power plants. Nonetheless, the estimated reductions in white perch year-class abundance are high enough that the possibility of adverse long-term effects cannot be excluded.

Recommendations

1. Impingement impacts on the Hudson River white perch population should be reduced. Because of the anomalously high impact of the Indian Point Generating Station, mitigation efforts should focus on this plant. (In part because of the results obtained from this research project, mitigating measures intended to reduce impingement of white perch at Indian Point were included in the December 1980 settlement agreement between the U.S. Environmental Protection Agency and the Hudson River utility companies.)

2. If a long-term monitoring progam intended to detect changes in the abundance of the Hudson River white perch population is implemented, an improved index of year-class abundance will be needed.

3. Any monitoring program intended to detect impacts of power plant operation on the Hudson River white perch population should include collection of abundance data for competing fish populations and of size-frequency data for the white perch population.

4. More extensive impingement monitoring at the Surry and Salem plants would be valuable. Special studies of (a) collection efficiency and (b) long-term survival of impinged white perch, similar to the studies conducted at the Hudson River plants, would be particularly valuable.

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