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COMPARISON OF SIMULATION MODELS USED IN ASSESSING THE EFFECTS OF POWER-PLANT-INDUCED MORTALITY ON FISH POPULATIONS

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ABSTRACT

Eight models predicting the impact of power plant operation upon economically important fish species are compared. The paper focuses on the effect differences between the models have on model predictions. Generalized model simulators were developed for the young-of-the-year and life-cycle submodels. Criteria used to evaluate model predictions are percentage of reduction in young-of-the-year and annual loss in yield to the fishery due to plant operation. Major differences between the models include the life stage lengths, density-dependent or density-independent young-of-the-year mortality, density-dependent or density-independent fishing mortality, and the method for computing recruitment of young-of-the-year fish to age class 1. Major differences in parameter values include entrainment factors, total egg production, equilibrium population size, and survival probabilities for the life-cycle models. Recommendations are made regarding our preference for model approaches. Our conclusion is that no presently existing impact model can be used to make quantitative predictions due to the large year-to-year variability in young-of-the-year densities and spatial distribution and the sensitivity of results to parameters in the density-dependent mortality function which are not well estimated.

Key words: density dependence, density independence, life-cycle model, model predictive ability, model simulations, parameter values, percentage reduction, regression equation, scaling factor, striped bass, young-of-the-year model.

1.0 INTRODUCTION

This paper reviews and compares eight models developed for the expressed purpose of evaluating the impact of power plant operation on populations of commercially and recreationally important fish species spawning upriver or in the neighborhood of a power plant. Most of these models are complex computer simulations using data from ongoing sampling programs. All simulate the entrainment of fish eggs and larvae through the cooling systems of the power plants. Most of the models reviewed are part of a family of models, evolving through time and generally increasing in complexity as new data and information become available and as the issues become better defined. Many of the models have been used as part of the licensing procedures for the Nuclear Regulatory Commission (NRC).

Our objectives in this review have been:

1. to evaluate the relative predictive ability of various models;

2. to review and evaluate the various models with regard to the biological realism of model assumptions;

3. to pinpoint model similarities and differences and to ascertain how important these differences are to model prediction (this objective is important since several of the models give strikingly disparate predictions of plant impact); and

4. to look for ideas for possible general approaches to modeling power plant impact.

1.1 Models Reviewed

The three systems studied in the impact models are the Hudson River (Bowline, Indian Point, and Roseton), Chesapeake and Delaware Canal (Summit), and the Niantic River--Long Island Sound (Millstone). All three areas are estuarine in nature, all are mixed by tidal fluctuations, and all are major spawning areas for commercially and recreationally important, East Coast fish species. The systems modeled are compared in Fig. 1.1.

The following terminology is used in this report in referring to the various modeling groups and models: LMS refers to Lawler, Matusky & Skelly, Engineers; ORNL refers to Oak Ridge National Laboratory; UEC refers to United Engineers & Constructors; JHU refers to the Johns Hopkins University Applied Physics Laboratory; MPPSP refers to the Maryland Power Plant siting program; and URI refers to the University of Rhode Island.

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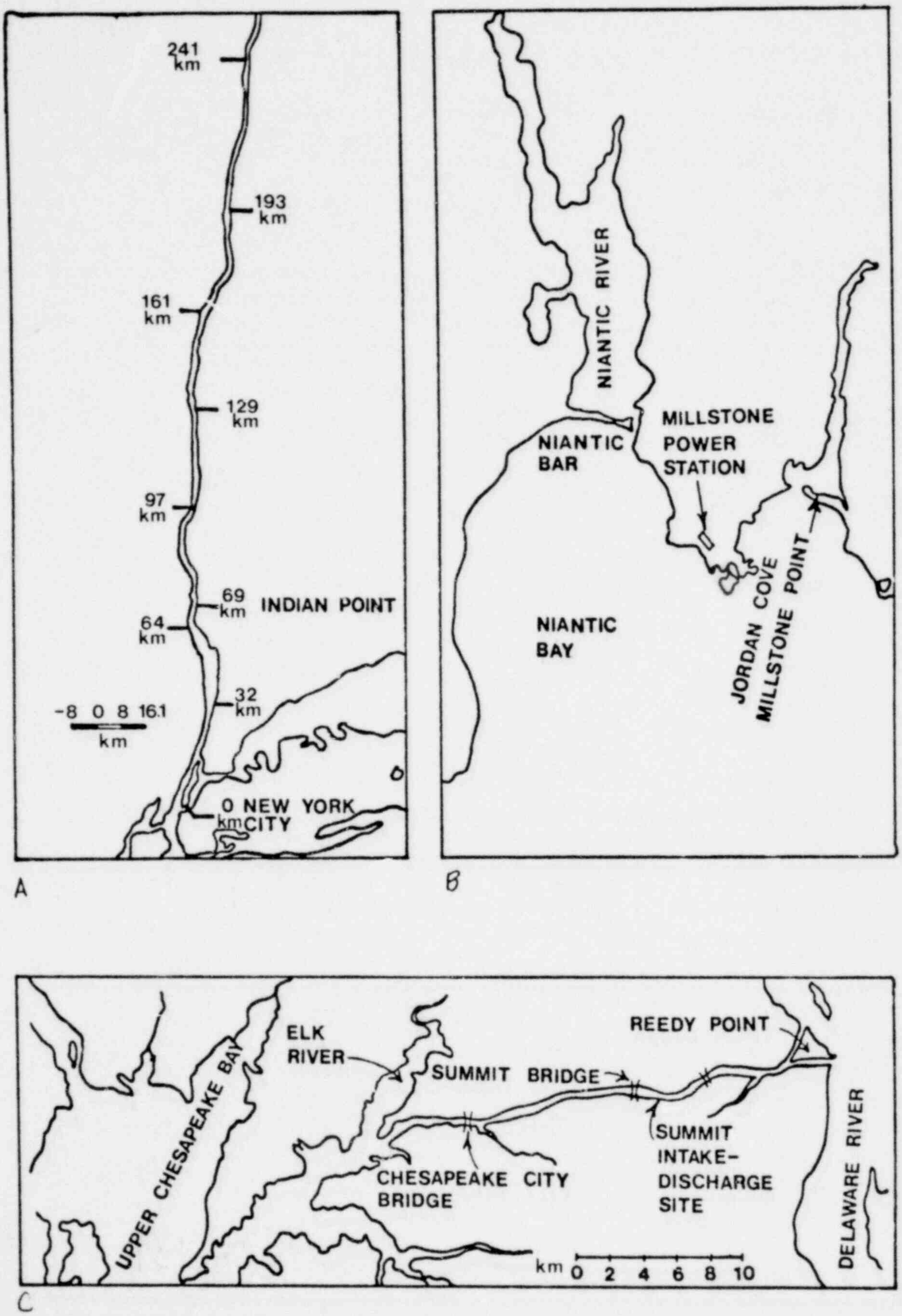

Fig. 1.1. Diagram showing power plant impacted systems modeled. A- Hudson River; B- Niantic Bay; C- C&D Canal.

Hudson River striped bass models (Bowline, Indian Point, and Roseton power stations).

1. The 1972 LMS model, developed for the applicant, involving no longitudinal segmentation or vertical stratification of the Hudson River (Lawler 1972a)--referred to as the LMS completely mixed model.

2. The 1972 LMS model, developed for the applicant, involving longitudinal segmentation but no vertical stratification of the Hudson River (Lawler 1972b)--referred to as the LMS 1-D model, the LMS 1-D(67) model with 1967 data and the LMS 1-D(73) model with 1973 data (Lawler 1974).

3. The 1973 ORNL model, developed for NRC, involving longitudinal segmentation but no vertical stratification of the Hudson River (NRC 1975, Eraslan et al. 1976, Van Winkle et al. 1974)--referred to as the ORNL 1-D model.

4. The 1975 LMS model, developed for the applicant, involving both longitudinal segmentation and vertical stratification of the Hudson River (LMS 1975)--referred to as the LMS 2-D model.

Chesapeake and Delaware (C&D) striped bass models (Summit Nuclear Power Station).

5. The UEC model, developed for the applicant (UEC 1975)--referred to as the Delmarva model.

6. The ORNL model, developed for NRC (Christensen et al. 1975)--referred to as the ORNL Summit model.

7. The JHU model, developed for MPPSP (Warsh 1975, Portner 1975)--referred to as the JHU model.

Winter flounder model (Millstone Nuclear Power Station)

8. The URI model, developed for the applicant (Sissenwine et al. 1974, Saila 1976)--also referred to as the winter flounder model.

Although other impact "models" exist besides those reviewed here, they either have been superseded by the ones we will review or are simple enough that we have put them into the category of a calculation (for example, a local entrainment calculation).

When discussing a property of the models (e.g., the life-cycle submodels) that applies to all three LMS models or both ORNL models, the designations LMS and ORNL, respectively, are used.

In general, the models are conveniently partitioned into two submodels. The first simulates the annual effect of plant entrainment

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(and in some cases plant impingement) on recruitment of young-of-the-year into the adult population and is called the young-of-the-year (y-o-y) model. The second submodel simulates the subsequent, long-term effect of reduced recruitment on the adult population and is called the life cycle model. The y-o-y models generally are based on a hydrodynamic model that determines waterflow and transport of eggs and larvae. None of the life-cycle models explicitly considers spatial phenomena.

1.2 Approach Used in this Review

Questions relevant to our goals were formulated to guide our review (Table 1). For each of the y-o-y and life cycle models, the following procedure was adopted.

1.2.1 Compare the Model Equation Forms and Underlying Model Assumptions

Graphs of model equations were lifted from model reports when available. Otherwise, they were computer generated or hand drawn. When the equations differed between models, primary literature sources were consulted to help judge the adequacy and scientific rationale of model assumptions.

1.2.2 Tabulate and Compare Parameter Values and Investigate Data Sources (when Available) Used in Obtaining Them

In most models parameter values are based on data or at least have a rationale for their selection. Parameter differences were investigated to see whether the differences could be traced to the use of different data sets. Statistical assumptions inherent in deriving some of the parameter values from data sources were also examined. Relevance of data sources was considered.

1.2.3 Compare Model Simulations

Many of the models had differing assumptions, parameter values, or both, and no prior investigation was available to test the effect of these differences on model predictions. Thus we decided to develop general simulators (models that simulate equations in the reviewed models) for the y-o-y and life-cycle models that could use equations or parameter values from many of the models. The simulators, discussed in the body of this paper, have proved invaluable in our analysis. The main reasons we chose to adapt the models to a generalized simulator framework, rather than lift the code entirely, were: 1) relative inflexibility of the code of any one model to include the formulation of another model; 2) expense of running several models at the time step and spatial resolution used by model developers; and 3) lack of portability or documentation for several of the model codes.

Table 1.1 Questions formulated to guide the review of models.

Presentation and comparison of model assumptions and systems studied

How are the systems studied similar and how are they different? What are the model assumptions in the physical and biological domains? What are the major similarities and differences in the models? What statistical assumptions are made in using data? How relevant are the data to the study site?

Simulation study and sensitivity analysis

How different are model predictions for models developed for the same system? How sensitive is model output to areas where the models are different? How sensitive are the models to changes in parameter values? What are sensitivity criteria?

Model evaluation

How do these models compare with classical fisheries models and other more mechanistic fish models? Are any of these models good predictive tools and does increased model complexity increase predictability? Is there a best model? How can we judge the relative quality of models? How close to field data are simulations? What are the relative costs of the various modeling approaches?

General conclusions and recommendations

Based on this review, what recommendation can we make about using models for decision making or for predicting the impact of a plant on an ecological system? What work on further model comparison, field research, or model development might improve the usefulness of present-generation models as decision aids or as predictors of plant impact upon ecological systems?

1.2.4 Decide Upon Model Prediction Criteria

Since the y-o-y models all predict the impact of power plant entrainment on y-o-y recruited into the adult population, we chose the percentage reduction in y-o-y with plant operation as our measure of impact, thus following the lead of most of the models. Percentage reduction (PR) is given by

$$PR = \frac{x - y}{x} \times 100 \tag{1.1}$$

where = y-o-y population without plant operation and = y-o-y population with plant operation.

Ultimately we are concerned in these models with the long-term impact of plant operation on the fish population itself and on the fishery in terms of loss of fish yield. A number of criteria are suggested in the various life-cycle models for translating PR into such a quantity.

1.2.5 Perform a Sensitivity Analysis

Since many of the models had different parameter values, even when the equation forms were the same, it was of interest to investigate the effect of changing parameter values of the various impact criteria. Many of these sensitivity studies were done by the original modeling groups, and the results from their studies are also reviewed and compared in this report.

1.2.6 Recommend Model Improvements and Evaluate a "Best" Approach

Various models had various strengths. In some cases we leaned toward one and sometimes toward another as a "best" approach. In many cases the question was one of simplicity of representation versus accuracy of model results. Simulation study is helping us to decide which is to be preferred.

2.0 YOUNG-OF-THE-YEAR MODELS: HYDRODYNAMICS

2.1 Introduction

2.1.1 General Structure

In considering how many eggs, larvae, and juveniles are entrained by power plant cooling waters, all models divided y-o-y into age classes. The choice of age classes varied between the models but individuals in each age class are assumed subject to the same mortality rates and entrainment potential if they are in the neighborhood of the plant. As they mature, the fish larvae and juveniles are seen by many of the models as increasingly able to avoid entrainment. This is modeled either by making individuals above a certain age unentrainable or by slowly increasing resistance to entrainment. Most of the models have divided the region spatially into segments using a hydrodynamic model to move the organisms between the segments. This allowed for the use of data on spatial distributions of sampled eggs, larvae, and juveniles in model development, and, if an independent data set was available, also in model validation. To our understanding, however, no independent data set was used in any of these models to validate relative location of organisms; i.e., no model validation attempted to move the organisms around according to hydrodynamic postulates based on one data set and validate this movement against an independent data set.

Entrainment calculations are given in all models as a density-independent mortality source while natural mortality is either density-dependent or -independent. (Some models use a formulation where mortality rate depends on stock density only. This is termed stock density dependence.) Entrainment was inflicted upon some fraction of populations in the neighborhood of the plant. Estimates of the size of the fish populations near the plant were obtained either from the hydrodynamic model based on the number of fish in the neighborhood of the site (which may include such factors as migration in addition to waterflow equations) or were assumed a constant fraction of the total population in the system. The y-o-y models predicted the number of individuals reaching recruitment age by escaping entrainment and natural mortality. The number is then used (in most models) in conjunction with a Leslie matrix model to predict long-term fishery yield or adult population reduction.

The principal components necessary to develop a y-o-y model are: 1) egg production (i.e., total number of eggs found or produced in the region of interest, by day and location); 2) aging and recruitment (i.e., survival history for particular life stages in the first year of life); 3) swimming ability and migratory behavior; and 4) entrainment and impingement rates (this component is discussed in Section 3).

Table 2.1 provides an overview to the relative complexity of the nine models reviewed; it ranks the nine models on a 0-5 scale based on amount of information included within a component (a score of 5 corresponding to most information). This ranking should not be confused with predictivity of the various models. The flow chart, Fig. 2.1, depicts the role a y-o-y

Table 2.1. Information contained in each of the nine models, ranked on a scale of 0-5.

Components	Egg production	Aging and recruitment	Swimming ability
Winter flounder	1	1	0
ORNL Summit	2	1	0
JHU	3	2	4
Delmarva	3	2	0
LMS completely mixed	3	3	1
LMS 1-D(67)	4	4	3
LMS 1-D(73)	4	4	3
LMS 2-D	5	4	5
ORNL 1-D	4	5	5

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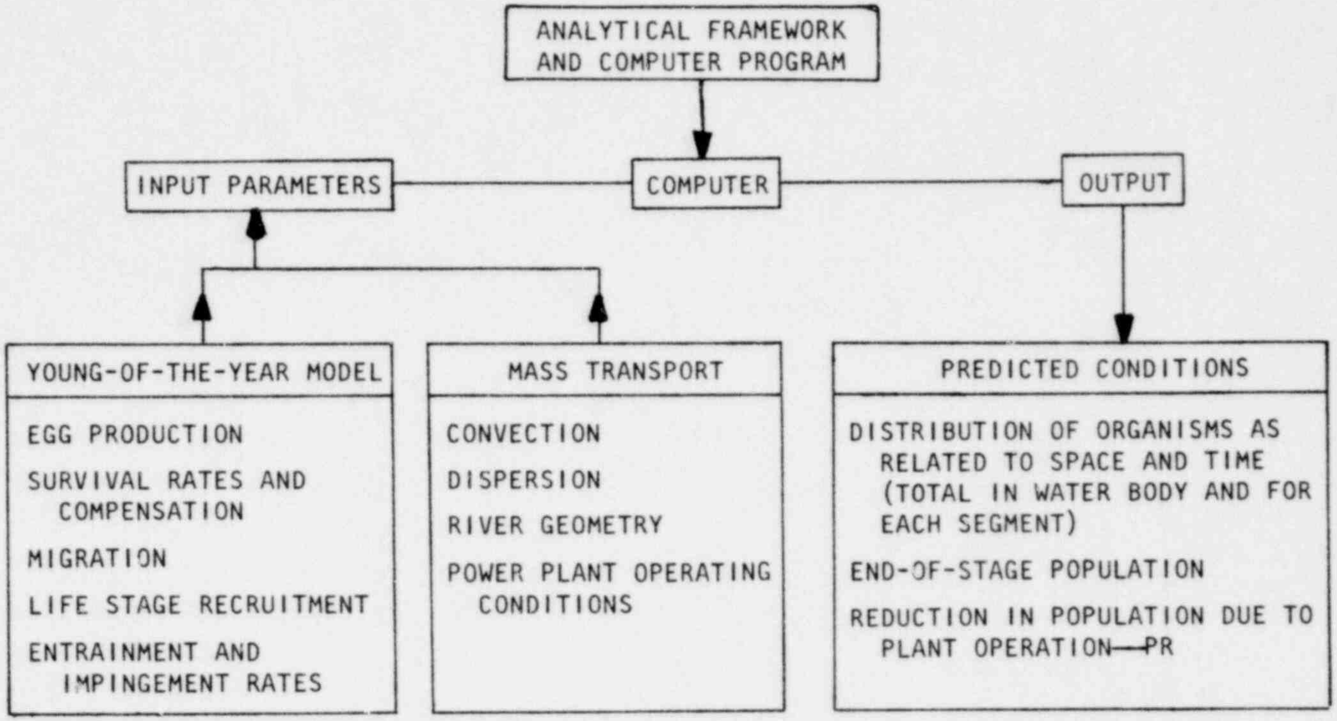

Fig. 2.1 Flowchart of a complete simulation framework for quantifying survival of young fish (modified from Lawler 1972*b*).

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model plays in the complete simulation framework for quantifying survival of young fish.

2.1.2 Biological Characteristics of Young-of-the-Year Striped Bass (Morone saxatilis)

Since eight of the nine y-o-y models consider striped bass, a summary of the biological characteristics of striped bass is included. The anadromous striped bass spawns during the spring season in the Hudson River and Chesapeake and Delaware (C&D) Canal area. The mature female produces an average of 700,000 eggs per spawn season.* Time of spawn is closely correlated to a temperature range of 12°-21° C with the majority of eggs found over a period of 1 month. The eggs are found within a salinity range of 0-0.3 percent and in deeper regions of the water body in moderate to swift currents.* Incubation times of striped bass eggs vary with temperature from about 1 to 3 days.*

The yolk-sac larvae are about 3 mm long, have self-contained food resources, and are passively transported when hatched.* Shortly thereafter the search for food, usually small zooplankton, begins. The diurnal, vertical migration of zooplankton and day/night changes in temperature result in a diurnal migration of larvae.* This migration also occurs in the fin-forming, postlarval stage, which begins at a size of about 6 mm and 6-10 days after hatching.* The major food resource for the poorly swimming, postlarval stage is considered to be large zooplankton. One reason for the variability of time to reach a particular life stage is the dependence of growth on the temperature regime of the water body.

The postlarval stage (postyolk-sac larvae) lasts for 10-22 days to a length of about 15 mm.* The next stage, juvenile age class, swimming ability improves and is well developed in another 40-60 days.* Juvenile bass tend to prefer the shallower, shoaling areas of a water body.* There is substantial mortality in the egg, larval, and early juvenile stages.

Striped bass are too large to be entrainable at an age of 70-100 days, but remain susceptible to impingement.* Juveniles subject to entrainment are termed juvenile-1 (J-I). Older juveniles are subdivided into juvenile-2 (J-II) and juvenile-3 (J-III) stages; the J-II stage is subject to impingement loss. A substantial part of the impingement kills have been attributed to the decrease in intake avoidance caused by cold temperatures and high salinity conditions.* Of course, these characteristics should be taken as approximate.

---

*Indicates that data collected for these models suggest this characteristic.

2.1.3 Comparison of Principal Components in the Young-of-the-Year Model: General Scheme

The y-o-y models all predict the impact of power plant entrainment on y-o-y recruited into the adult population. We chose the percentage reduction (PR) in y-o-y with plant operation as our measure of impact, following the lead of most of the models (see Equation 1).

Our approach in this comparison has been to list alternative formulations for each process. Within each component, the formulations are examined according to: 1) sensitivity of PR due to changes in parameter values, formulation, or both; 2) relative cost, for information and implementation of a formulation; and 3) biological realism. The comparison is process by process rather than model by model. Parameter values and data sources for parameters are also included with the discussion of the relevant processes.

Table 2.2 is included to give the reader an overview of the predictions for the various models. The PR values for the ORNL 1-D and LMS models differ greatly for similar cases. Since these models are complex and their predictions have generated much controversy, we decided to focus a large proportion of our time on analysis of them.

2.1.4 Description of the Water Bodies

Three water bodies have been modeled hydrodynamically in conjunction with biological models to estimate the effects of power plant operation on the adjacent striped bass and winter flounder populations. The Hudson River and C&D Canal contain striped bass y-o-y populations and Niantic Bay contains winter flounder larvae. The hydrodynamic assumptions are given in overview in Table 3.6.

The Hudson River (Fig. 1A), which is a spawning and nursery ground for many commercially and recreationally important East Coast fisheries, extends northward from the Battery at New York City to its headwaters in the Adirondack Mountains. An impassable dam at Troy restricts the striped bass as well as the other species approximately to the 240-km section from Troy to the Battery. An 80-km section above the Battery is estuarine (the exact extent depends on the freshwater flow rate). This estuarine section may be completely stratified, completely mixed, or partially stratified, depending on freshwater flow rates, tidal activity, and the location. For tidal amplitudes between 0.6 and 1.2 km, vertical salinity profiles indicate that the estuary is only partially mixed vertically with opposing flows occurring in the upper and lower layers. The surface layer flow is seaward representing the freshwater flow, and the lower layer flow is upriver representing the salt-wedge tidal flow. The hydrodynamics of the Hudson River is further complicated by the variations in its physical dimensions along the region of interest.

The C&D Canal between the Chesapeake and Delaware rivers (Fig. 1C) has become an important spawning and nursery area for striped bass caught

Table 2.2 Comparison of predictions of percentage reduction (PR) for various models.

Model	Compensation[a]	Entrainment factors[b]	PR	Plants operating[c]	Source
LMS 1-D 1967	High High	Best estimate Maximum	2.5 4.0	Indian Point Units 1 & 2	Table 24, Lawler (1972b)
LMS 1-D 1973	High Low	Best estimate Best estimate	2.77 4.88	Indian Point Units 1, 2, & 3 and Cornwall	Table 26, Lawler (1974)
LMS 2-D	High Low Low	Best estimate Best estimate Minimum	1.257 3.138 2.44	Indian Point Units 1, 2, & 3	Table 36, LMS (1975)
ORNL 1-D	None None None	Minimum Best estimate Maximum	18.0 34.0 42.0	Bowline Unit 2, Indian Point Units 1, 2, & 3, Roseton Units 1 & 2	Table B-34, USNRC (1975)
ORNL Summit			4.5	Summit	p. 2-1, Christensen et al. (1975)
JHU			1.0-5.0	Summit	p. 17, Portner (1975)
Delmarva			0.71-5.53	Summit	Table 1-3, Portner (1975)

[a] With reference to the LMS models: high compensation implies K_O=0.5K_E; low compensation implies K_O=0.8K_E.

[b] Values for the entrainment factors (f-factors) are given in the original sources.

[c] For each model the plants tabulated in this column were assumed to be operating in the model run with power plant mortality and were assumed to be not operating in the corresponding model run without power plant mortality.

in the Chesapeake and East Coast fisheries (Raney 1975). The canal is 27.8 km long and of uniform cross section for most of that length. Large tidal oscillations dominate the hydrodynamics; however, there is a small net eastward flow (Warsh 1975). The Delaware River, because of industrial pollution, is a poor habitat for the striped bass; therefore most of the y-o-y washed to the Delaware River are assumed to die. Striped bass y-o-y that return to Chesapeake Bay become an important part of the East Coast striped bass fishery. Vertical salinity and velocity profiles indicate that the C&D Canal is well mixed by a large and probably uniform dispersion resulting from the tidal oscillations. Little is actually known of the detailed hydrodynamics of the present canal, and the hydrodynamics after the canal dredging is completed can only be speculated upon.

Millstone Point (Fig. 1B) is located east of the outlet of the Niantic River and Niantic Bay on the Connecticut side of Long Island Sound. The flow conditions near Millstone Point are dominated by tidal flow and the hydrodynamics of adjacent Long Island Sound. Winter flounder breed in the shallow waters of the Niantic River, in Jordan Cove, and near the Niantic Bar. The currents at ebbtide sweep water from the Niantic River past Millstone Point. At flood tide the currents reverse.

2.1.5 Description of the Power Plants

The characteristics of the power plant as well as the characteristics of the fish species and the water body affect the predicted mortality. All three plants have surface level, shoreline intake structures. The Indian Point and Millstone plants have once-through cooling systems, which require the intake of large amounts of water, while the Summit power plant has proposed a cooling tower and closed-cycle cooling, and thus would draw in only enough water to replace evaporative losses. The inflow rate for the three Indian Point plants is 130 m^3/sec, and 115 m^3/sec for the three Millstone units. The proposed inflow rate for the Summit plant is 1.4 m^3/sec (Fig. 1.1). The flow rate is less in winter than in summer.

2.1.6 Description of the Models

The accuracy of the model predictions depends on the physical and temporal assumptions underlying the model. Approximations to physical and biological mechanisms involve spatial or temporal averaging, the scale of which determines the amount and type of data for model parameterization and validation as well as to some extent model results. The various parameters describing the estuarine flow in the Hudson River must be approximated. Because of the complexities of tidal flow, velocity, and dispersion, measurements in the field and accurate representations within the models are difficult to obtain. In the 1-D Hudson River models only longitudinal gradients and average tidal values are considered. The tidal averaging employed in the Hudson River models implies that the hydrodynamics of the tidal flow can be represented by some characteristic or average value. This may be a reasonable approximation physically; however, the errors introduced by this approximation in the estimates of fish population losses may be large and significantly affect the prediction of power plant operation (A. H. Eraslan, personal communication). In all the models any complexities lost by considering simple formulations or average values are theoretically included in the dispersion or other terms although they do not enter explicitly. The winter flounder model uses a very small time step, the JHU model incorporates 10 vertical layers, and the LMS 2-D model (LMS 1975) includes both vertical stratification and finer temporal scale in attempts to achieve greater accuracy in their results. Finer spatial and temporal scales in the models increase the cost of operation of the model and the amount of sample data needed for implementation and verification. We believe model development should concentrate more on refinement of the biological components based on the available sample data rather than on increasing hydrodynamic complexity.

The Hudson River models have grown in hydrodynamic complexity through the years. On the C&D Canal hydrodynamic models were not included, the researchers thinking that greater emphasis should be placed on determining the biological components and that detailed physical models with their greater number of parameters and correction factors tended to suggest a greater understanding of these processes than are present. We agree with this assessment. We suggest that a transport model similar to that used in our model simulator, where fish transport occurs according to field data rather than hydrodynamic principles (Section 3.5), is a viable alternative. The number of assumptions inherent in this formulation is few and the measure of corroboration is the same, i.e., to match the sample distributions at some points in time.

The spatial scales on which density-dependent mortality and migration rates are calculated can change the model predictions (Section 3.6). Table 2.3 gives the spatial and temporal scales for each model.

2.2 Convection-Dispersion Equation for Fish Transport

The transport of y-o-y fish is modeled by the convection-dispersion equation in all of the models considering hydrodynamic transport. The 1-D convection-dispersion equation is

$$\frac{\partial C_i}{\partial t} + U_i \frac{\partial C_i}{\partial x} = E_i \frac{\partial^2 C_i}{\partial x^2} - K(C_i) \tag{2.1}$$

where C_i is the concentration of fish in segment i, U_i is the net mean velocity, E_i is the dispersion coefficient, and $K(C_i)$ is the source-sink term that is usually a function of the fish concentration. These source-sink terms represent changes in the concentration due to causes such as death, birth, migration, entrainment, and so on. The convection-dispersion equation therefore gives the numerical change in the fish

Table 2.3. Hydrodynamic model characteristics.

Model	Water body & type	Mean velocity	Dispersion	Spatial dimensions	Time step	Total op. time
LMS 1-D(67)	Hudson R. (partially mixed estuary)	input discrete	salinity meas.	long. 8 seg. var. length, 12 seg. 16 km	3 h	1 yr
LMS 2-D(73)	Hudson R. (partially mixed estuary)	input function	Elder (1959)	long. 29 seg. var., vert., 2 equal layers	3 h	1 yr
ORNL 1-D(73)	Hudson R. (partially mixed estuary)	input discrete	Bowden (1965)	long. 76 seg., 3.2 km	4 h	1 yr
JHU (2-D)	C&D Canal (tidal, fully mixed)	input discrete	guess	long. 50 seg. 1.6 km N, vert.	1 h	90 days
Winter floun. (2-D)	Niantic R. & Bay (part. mixed estuary to ocean)	match motion equation	Bowden (1965)	287 squares, 305 m on side	1 min	75 days
LMS 1-D(73)	Hudson R. (partially mixed estuary)	input discrete	salinity meas.	long. 12 seg., 16 km	3 h	1 yr

concentration from all sources. The winter flounder model includes only an entrainment term in the $K(C_i)$; however all the other models include terms for entrainment, growth, death, and behavioral changes in the fish concentration. These terms will be discussed in their appropriate sections in the body of the report. In the application of the convection-dispersion equation, the difference form of Equation 2.1) is used to compute the concentration in each spatial segment for each time interval, through appropriate numerical methods.

The LMS and JHU models might also include terms for vertical convective transport and vertical dispersive transport analogous to terms (1) and (2). In both cases, however, these terms were not used in running the models, but were included implicitly in the vertical migration behavior term. (The transports were considered to be either too small [convection] or so large [dispersion] that their action would mask the observed vertical patterns.

2.3 Velocity

Each of the transport models includes a term representing the convective transport of the fish with the water currents, which is computed from the local mean velocity. The mean velocity for any segment in the system is calculated from the average flow rate and the average cross-sectional area for that segment. In the LMS 1-D(67,73) and ORNL 1-D(73) models the net flow rate is based on the measured freshwater flow at Green Island near Troy. Starting with the 1973 4-day averaged values (USDI Geological Survey 1974), ORNL calculates the net flow rate at point i as

$$Q_i = \overline{Q}(1 + 0.25[0.52 - i]/152) \qquad (2.2)$$

The LMS model also used average values of freshwater flow rates in (67) and (73), computing Q_i based on their long-term analysis of flows in the lower Hudson River that recognizes the various streamflows into the river. The two sets of Q_i are compared in Fig. 2.2. Both sets match reasonably well for June 1973. The LMS model has slightly higher values for May 1973 and slightly lower values in July 1973 than ORNL; however on the whole the longitudinal distribution and the monthly averages are close. The average 1967 values for LMS, also given in Fig. 2.2, are four orders of magnitude larger than both sets of 1973 values, which indicates some discrepancy in the 1967 values. The LMS 2-D model represents the flow rate at any location and time in the river by a pair of complex sinusoidal functions that represent the tidal oscillations and lag times that have been observed in the upper and lower layer flows:

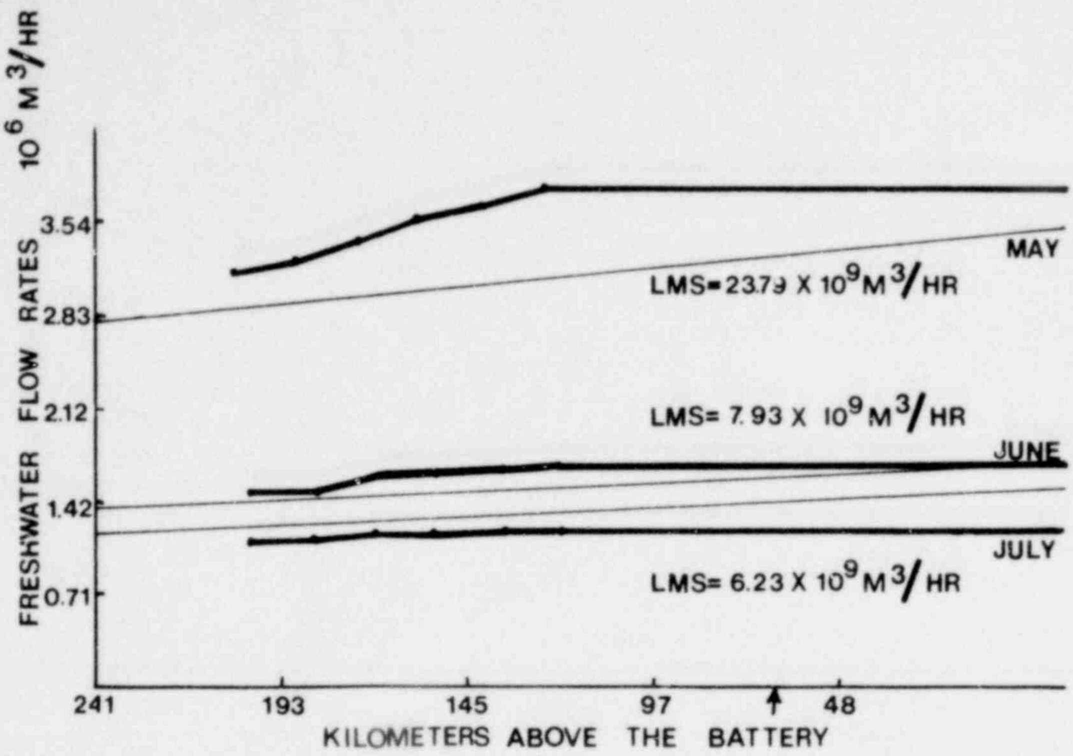

Fig. 2.2. Comparison of freshwater flow rates Q_i.

$$Q^k(x,t) = \begin{cases} q_E^k \sin\left(\pi \dfrac{t'}{T_E^k}\right) & \text{ebb} \quad 0 \leq t \leq T_E^k \\[2ex] q_F^k \sin\left(\pi + \dfrac{\pi(t - T_E^k)}{\tau - T_E^k}\right) & \text{Flood} \quad T_E^k \leq t \leq \tau \end{cases} \tag{2.3}$$

where k = (1) upper layer and (2) lower layer, $t' = t + \theta$, q_E^k = maximum flow in upper or lower layer during ebbtide, q_F^k = maximum flow in upper or lower layer during flood tide, τ = duration of tidal period (h), T_E^k = duration of ebb phase in layer k (h), $T_F^k = \tau - T_E^k$ = duration of flood phase in layer k (h), and θ = phase lag (h) from the Battery.

The various parameters necessary to apply these equations, including the local flow rate, were determined from salinity profiles using the graphical solution technique for a two- layered stratified system as given by Abood (1974). This technique has the advantage of being able to represent the temporal tidal variations in flow without an excessive amount of data input, as would be the case if the flow rate for each time interval in each layer were tabulated. The JHU model used the limited amount of data available on the C&D Canal to form a series of hourly flow rates adjusted to estimate the flow rates after the planned widening of the C&D Canal. The sets of data were combined by truncating and matching them to each other according to the tidal phase. The combined series was then repeated until a set of values was constructed on which the model was run. The winter flounder model was the only model to compute the velocities internally at each location to satisfy the equations of motion for the system:

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} = -g\frac{\partial z}{\partial x} + \rho v + \frac{1}{P(h + z)}(\tau_{sx} - \tau_{bx}) \tag{2.4}$$

$$\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} = -g\frac{\partial z}{\partial y} - fu + \frac{1}{P(h + z)}(\tau_{sy} - \tau_{by}) \tag{2.5}$$

$$\frac{\partial z}{\partial t} + \frac{\partial}{\partial_x}\{(h + z)u\} + \frac{\partial}{\partial y}\{(h + z)v\} = 0 \tag{2.6}$$

where u, v are vertically averaged velocity components, τ is the surface and bottom stress, f is Coriolis parameter, h is the mean depth, $\underline{z}$ is water surface height, g is gravitational acceleration, and P is pressure. These equations represent a vertical integration of the time-dependent equations of motion and mass conservation for the system. Therefore, u and v are vertically averaged velocity components in the x and y directions, respectively. Boundary conditions such as inflow rates from the Niantic River and tidal variation of water level along the Long Island Sound interface were used as well as local geometric movements to generate appropriate constraints. The technique is much more complicated than using tables of values for the flow rates, however, and requires extensive testing and verification. The actual calculation of the convective transport based on the local velocity values is included in Section 2.6.

Tabulation of velocity values for the system has the advantage of assuming nothing about the characteristics of the flow but is not generally applicable when conditions change. It also necessitates the storage of a large number of values. Equations derived from assumptions about the governing characteristics of the flow, especially in a tidal situation, decrease internal storage with a small increase in computation and are generally applicable as the flow conditions change. The one limiting point is that the flows may be incorrectly represented because of the action of other factors used in determining the flow. Needless to say this can be determined only by verification of the representation versus field data, as is done with the LMS 2-D and winter flounder models. Both models fit the data fairly well.

2.4 Dispersion

Dispersion results from turbulent eddies and shear stresses caused by velocity differences. Dispersion varies as a function of the size of the water body, the velocity of the water, and the roughness of the bottom, thus it is difficult to measure in an estuary exhibiting continuous variations in local velocity. Because of the velocity's importance in transport many techniques and theories have been developed to compute appropriate values. The LMS 1-D(67,73) model used measured salinity profiles to compute the horizontal dispersion E_h within the salt reach of the Hudson River, and computer values above the point from tidal and geometric properties. Although the actual technique is not stated, it is probably similar to the methods used in ORNL 1-D(73) and winter flounder. In the LMS 2-D model (LMS 1975) the dispersion coefficient was calculated similarly to a technique proposed by Elder (1959). The resultant horizontal dispersion coefficient values for the upper and lower layers, respectively, were computed as

$$E_h = k(U_u - U_l) + D_w \qquad (2.7)$$

$$E_h = AHU_l^{0.5}/ c + D_w \qquad (2.8)$$

where U_u and U_l are the velocities of the upper and lower layers, respectively, H is the lower layer depth, c is Chezy's coefficient (which includes the effect of bottom roughness), D_w is the diffusion coefficient due to wind or bottom stresses, A is the coefficient due to shear between the layers, and k is a coefficient used for model adjustment. Both ORNL 1-D and winter flounder models calculate the horizontal dispersion coefficient using adaptations of Bowden's method (1[illegible]). The ORNL 1-D model calculated the dispersion as

$$E_h = 6(0.002)^{0.5}\bar{U}_i\bar{D}_i \tag{2.9}$$

by assuming that the velocity varies logarithmically up to 60 percent of the depth and parabolically above that. The winter flounder model used a different variation of Bowden's method (1965). Assuming a unidirectional flow with small periodic oscillations occurring at the boundaries, an equation from Lamb (1932) is employed to compute E_z, the vertical dispersion, from measured vertical velocity profiles. The dispersion is then calculated, according to Bowden, as

$$E_{h,i} = 0.00125U_i^2D_i^2 \,/\, E_{z,i} \tag{2.10}$$

which after substitution of the formulation for E_z calculated from Lamb becomes

$$E_{h,i} = 7.3U_iD_i \tag{2.11}$$

where D in both formulations is the average depth at i. Warsh (1975) assumed a constant dispersion coefficient for the C&D Canal of 13.9 x 10^5 m^2/h.

The actual dispersion coefficient values used on the Hudson River are given in Fig. 2.3. The dispersion values for LMS 2-D were not available so they could not be included in the comparison. Above the 106-km point all sets of values agree reasonably well; however, below this point the values become quite different. Such discrepancies must be investigated and the different values should be justified. That is especially true in this case because the use of salinity profiles by LMS (below 97 km) resulted in much larger values for the dispersion coefficient. Although dispersion coefficients calculated from salinity profiles are commonly used in equations calculating the transport of other substances, it does not seem correct to use salinity dispersion to represent fish dispersion when the mechanisms causing salinity dispersion may have no analogy to fish dispersion. The lower values obtained from other methods seem more suitable. For further discussion see Section 2.7.

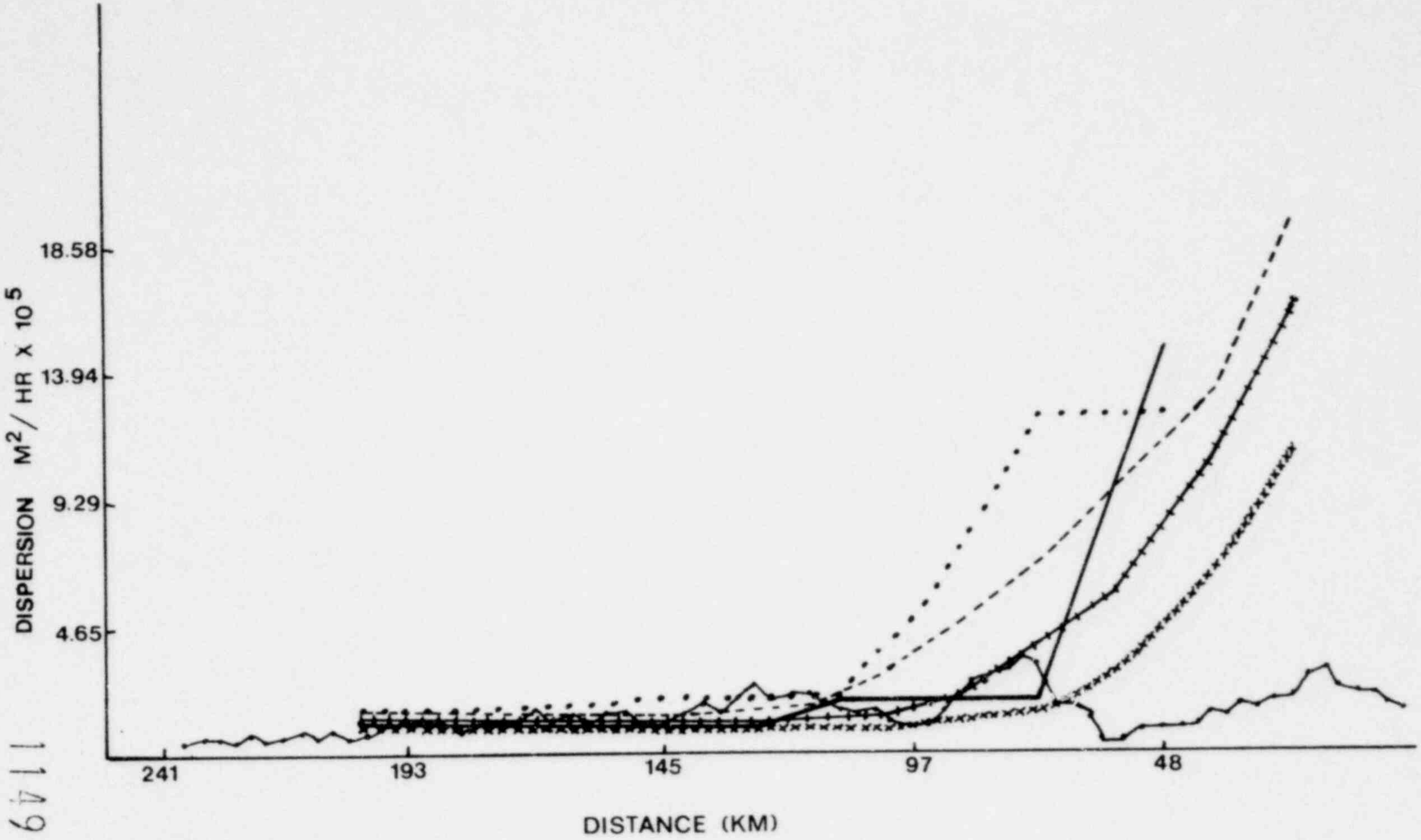

Fig. 2.3. Longitudinal variation in the dispersion coefficient $E_{h,i}$.

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2.5 Salinity and Temperature

The ORNL 1-D model calculated the longitudinal temperature and salinity distributions in order to include temperature and salinity effects on spawning, growth, survival, swimming ability, and so on. Assuming a temporal variation in temperature from data (New York Department of Environmental Conservation 1974) and a 4° C decrease in mean temperature from the Battery to Troy, the base longitudinal temperature distribution was determined. Thermal discharges from power plants were added at the corresponding locations and the overall combined distribution was determined. The salt intrusion length in the Hudson River was calculated from the freshwater flow according to an empirical formula given by:

$$\frac{\text{salt intrusion length (km)}}{254 \text{ km}} = A \left(\frac{1000 \text{ m}^3/\text{s}}{\text{flow rate (m}^3/\text{s)}} \right)^{b} \tag{2.12}$$

with A and b changing at 25,000 m^3/sec from $A = 0.885$, $b = 0.366$ (below) to $A = 6.58$, $b = 0$ (above). The longitudinal salinity distribution below the intrusion length was then calculated from a solution to the convection-diffusion equation.

2.6 Convective Transport and Advection Avoidance

Convective transport refers to the transport of material, in this case fish larvae, by the currents of the water. In the convection-dispersion equation this transport is given as

$$U_i \frac{\partial n_n(t)}{\partial x} \tag{2.13}$$

Normally velocity varies vertically, with the maximum velocity occurring just below the surface in the deepest section and declining to zero near the bottom and sides. Realistically, therefore, organisms in the region of the maximum velocity are transported faster than the mean velocity for that segment and organisms near the bottom and sides are transported more slowly. In winter flounder the computed average vertical velocity values at each location are used to compute the convective transport at that location. Any effect of vertical velocity difference is assumed to be included in the dispersion transport. The larvae are assumed to congregate near the depth having the mean velocity, and thus they are probably transported according to the given velocities. If the organisms are distributed in some other manner so that the transport calculated from the average vertical velocity is over- or underestimated the actual transport, the velocity probably could be altered by the inclusion of a parameter (Sissenwine et al. 1974) to convert the velocity values. The LMS 2-D model has different velocity functions for the upper and lower layers, thus the transport in the two layers is different, approximating the differences in transport expected due to vertical velocity differences. The 1-D models, because the transport is based on an average freshwater velocity, include an advection avoidance factor, AA_n , which represents the proportion of the y-o-y fish that are not transported by the net freshwater flow. In both models LMS 1-D and ORNL the convective transfer rate is calculated based on the freshwater flow rates for each segment. The estimate is then corrected by subtracting the net transfer rate resulting from errors introduced by tidal and vertical averaging. The LMS 1-D(73) model estimates an advection avoidance factor (they refer to it as transport defect factor, TDF) by calculating the proportion of organisms in the bottom 1.2 m of the river from sample information. Here $1 - AA_n$ represents that proportion of the organisms that is transported. The net convective transport is then $(1 - AA_n)$ times the dispersion factor. The calculated values for AA_n were 0.58 for eggs and 0.2 for larvae (Lawler 1974, LMS 73 Cornwall, page 11). The USNRC (1975) for ORNL (73) chose AA_n, called convective defect factor (CDF), such that the model matched the measured longitudinal distributions of y-o-y. A value for AA_n of 0.8 for both eggs and larvae gave the best fit.

According to data given in USNRC (1975), lower values of AA_n cause more rapid flushing of the y-o-y fish because a greater proportion of the y-o-y fish are being transported by the net freshwater flow. For the short-lived eggs, any differences probably are insignificant. For the longer-lasting larval stages, however, these differences could result in more rapid flushing in LMS 1-D(73) than that predicted by the ORNL 1-D(73) model and thus reduce their entrainment prediction because larvae remain near the plant for a shorter time. For example, USNRC (1975, Tables B-34) showed that a 15 percent increase in the PR resulted from an increase of AA_n from 0.4 to 0.8. Extrapolating from this, we would expect from differences in the AA_n values alone that LMS's PR would be somewhat less than the PR value estimated by ORNL. If, as suggested by sampling data (Rathjen and Miller 1957, Carlson and McCann 1968, TI 1973b and 1974), the eggs and larvae are avoiding transport by occurring predominantly near the bottom and shore, higher AA_n values would be justified. For juveniles, convective transport is assumed to be zero since they can control their position by swimming and their longitudinal changes in position are accounted for solely by migration.

The JHU model includes two sets of correction factors when computing the convective transport. Recognizing that vertical differences in velocity result in differences in transport, the mean velocities are apportioned to the 10 layers according to parameter G^j (Warsh 1975), which decreases from 0.1205 to 0.0544 from the top layer to the bottom layer of the canal. The transport in each layer is then calculated from these velocities. The G^j value is calculated from vertical velocity profiles and represents the fraction of the total transport expected in each layer j. As the fish get older and gain swimming ability, they are no longer transported passively. Thus, larvae-2 are able to avoid convection in proportion to their ability to swim (Fig. 2.4). This swimming ability factor for larvae-2 is multiplied by the convective transport factor, reducing it with fish aging. When the fish are juveniles, convective

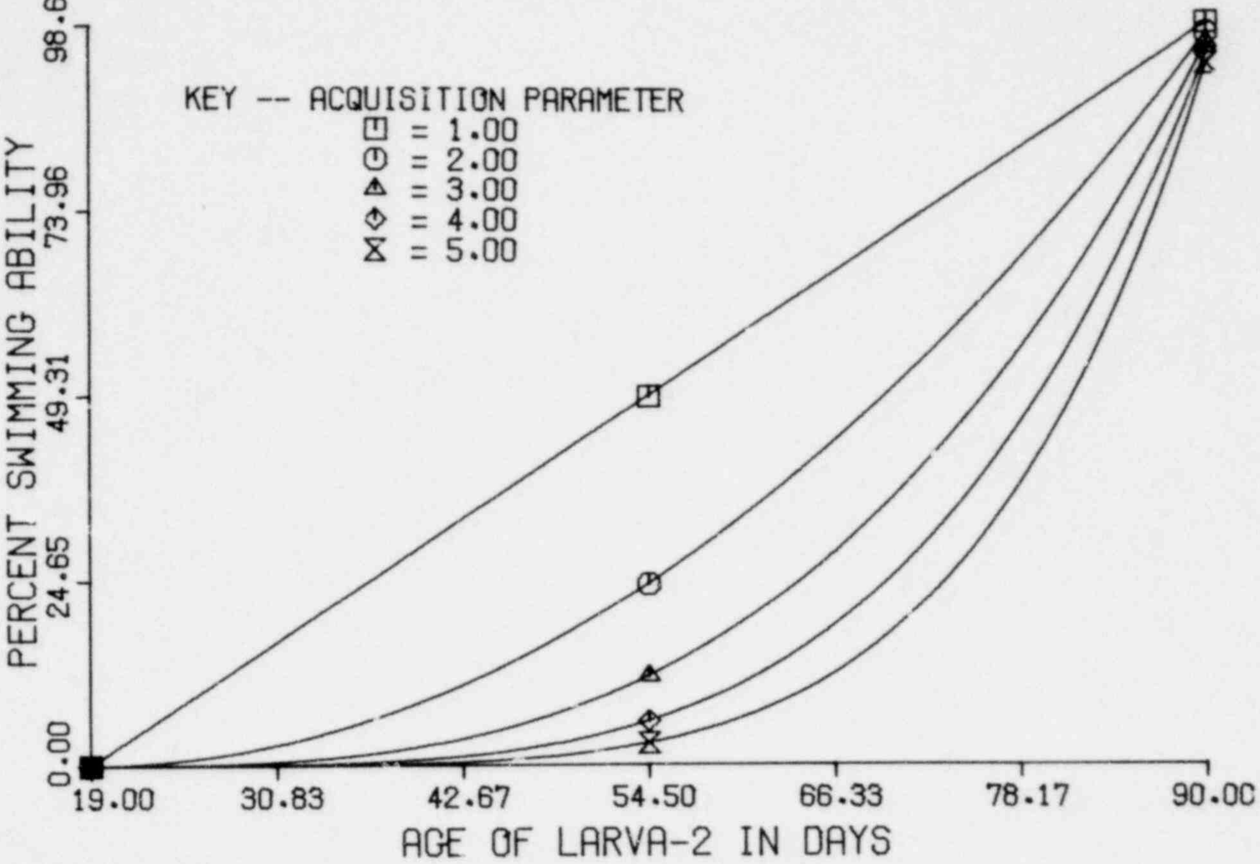

Fig. 2.4. Acquisition of swimming ability after Warsh (1975).

transport becomes 0, because of increased swimming ability. The use of a swimming ability factor has the advantage that AA values are based on flow and behavioral characteristics of fish at each age (day cohort), and not a discrete step function, as in LMS 1-D and ORNL. The swimming ability function, in the JHU model, however, is not based on data or laboratory information about acquisition of swimming ability. For further discussion see Section 2.9.

All these methods use the flow information to duplicate the sample distribution of the fish. The most important component of this process is the convective transport because the predicted PR is sensitive to the choices of the flow velocity and AA values, especially in the vicinity of the plant intake.

2.7 Dispersive Transport

The horizontal dispersive transport is represented by the first term on the right in the convection-dispersion equation (2.1). In all of the models except LMS 1-D(73), the local dispersive transport is calculated from the values of the horizontal dispersion coefficient E_h at that location. The JHU model apportions the dispersive transport to the 10 layers according to the Q^j since dispersion is proportional to the local velocity. In the LMS 1-D(73) model the dispersive transport is modified by $(1 - AA_n)$ in the same manner as the convective transport was modified. This results in much lower effective dispersion coefficients for eggs and only slightly lower values for larvae. The LMS 1-D(67) dispersion coefficients are much larger in June and July than the ORNL 1-D values near the Indian Point nuclear plant which would result in the fish being transported back and forth in front of the plant faster than predicted by ORNL 1-D(73). This difference is especially large when one considers that in 1966 and 1967 over 50 percent of the larval striped bass were sampled below the 96.5-km point. We do not know the exact effect that this difference will have on the resultant PR; however, the insensitivity to dispersion coefficient suggests the effect on PR is probably minor. For example, sensitivity analysis (Lawler 1973) on the LMS 1-D(67) model suggests that a reduction of the dispersion coefficient from 12.95×10^5 m^2/h to 9.1×10^5 m^2/h in the vicinity of the power plant causes no significant or predictable change in the estimated PR. Although the lowest value used in the sensitivity analysis is still 163 percent larger than the value used in the ORNL 1-D model at the 72-km point, this analysis suggests that reducing the dispersion further would still result in no change.

The combined physical transport at the 72-km point shows that with the addition of the advection avoidance the LMS dispersive transport is more variable than the values used in the ORNL models.

2.8 Swimming

The acquisition of swimming ability and the increased ability of the larvae to avoid passive transport either within the water body itself or in the intake flow can be important in reducing the entrainment loss predictions. Juvenile I striped bass in the ORNL 1-D model, are assumed to swim at a speed of 0.15 m/sec and the J-II and J-III can swim at 0.3 m/sec. The intake avoidance factor is calculated as

$$f_{10} = 1 - \lambda \frac{\upsilon_{\text{mob}}}{\upsilon_{\text{int}}} \tag{2.14}$$

where υ_{mob} is the swimming velocity of the fish, υ_{int} is the maximum intake velocity (0.3 m/sec) and λ is some weighting factor. Neither justification for the choice of the λ values nor for its use in equation (2.13) are not given. It may, however, represent that only fraction of the fish have acquired swimming velocity υ_{mob} since not all fish grow or gain strength at the same rate. Here $_{\text{mob}}$ is modified by the local temperature and salinity conditions (USNRC 1975), resulting in increased entrainment and impingement in very cold and very hot water as well as when the salt front is located near the plant intake.

The JHU model uses a much more complex but more intuitively appealing formulation than that given above. Little information exists on striped bass swimming ability (Kerr 1953). Bainbridge (1960) calculated swimming speed as body lengths per second (LB/sec), and found that for a wide variety of fish the normal cruising speed was about 3-4 LB/sec, and the burst speed was up to 10 LB/sec but most around 7-8 LB/sec. For a 5-cm J-I (about the size at the beginning of this life stage) cruising speed could be about 15-20 cm and burst speed over 30 cm/sec, which is at the lower end of the range in the ORNL models (about 3 LB/sec). Houde (1969) measured the acquisition of swimming ability in larval fish (yellow perch and walleye). His results suggest that swimming ability increases rapidly over the post-yolk-sac stage so that the juvenile has nearly the same swimming ability as the adult in LB/sec. This increase corresponds to the development of fins and the adult shape. Houde's data were converted to cm per second by multiplying the body by body length obtained from an exponential growth curve (Fig. 2.5). JHU assumes that larvae acquire swimming ability over J-I period, reaching adult ability at the end of J-I (called larva-2 in JHU, see Section 2.6). The functional form is

$$\left(\frac{t - 19}{72}\right)^{n} \tag{2.15}$$

where n is a parameter representing the swimming ability increase rate. The form (Fig. 2.4) with $n = 2$ closely corresponds to the data from Houde (1969). Increasing n from 1 to 5 changes PR predictions from 1.2 to 1.7 (Warsh 1975) for the Summit plant.

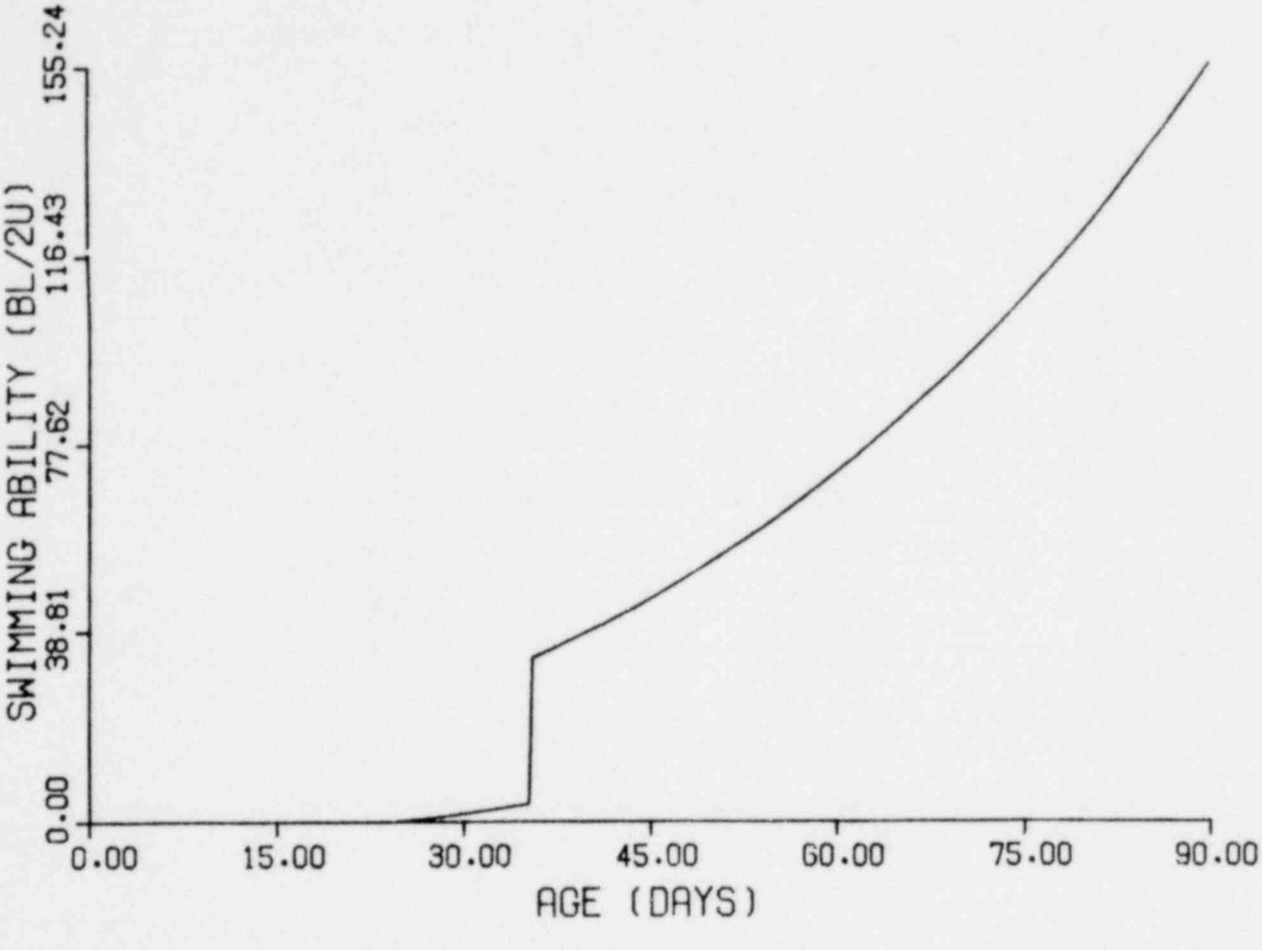

Fig. 2.5. Swimming ability of larval striped bass. Derived from acquisition of swimming ability according to Houdi (1969) growth data from USNRC IP-III.

The absolute increase in PR as the swimming ability increase rate decreases (i.e., as n increases) is small at Summit because most fish have left the canal by the end of the J-I stage. Nevertheless, for power plants where the larva-2 are present near the intake, the increase in PR would be significant.

2.9 Migratory Behavior

The approach LMS (1-D, 2-D) have used to incorporate migratory ability of J-I in their model is as follows:

1. From sampling data, estimate the fractional distribution, by segment, of J-I near the end of their stage. The fraction in segment j is the migration preference of segment j. This distribution will be approached in model runs (see Table 2.4 for a typical calculation).

2. Compute the fractional distribution of J-I at any time t in the model.

3. Use the difference between the model distribution and the sampled distribution to compute the number of J-I that must migrate into or out of each segment. Define the difference in time between t and the end of J-I appearance. This is the time span over which migration occur to achieve the end of stage distribution and determines the proportion of migration for the next time step.

4. Continually update steps (2) and (3) with increasing t. The same approach is used for J-II and J-III. For the latest LMS 2-D model, diurnal vertical migration of larvae was incorporated in a similar manner.

The ORNL 1-D claim the following approach to J-I migration (J-II and J-III were done similarly) is more realistic than that of LMS:

1. Determine shoal parameter values (SP_j) for all segments (e.g., for the j^{th} segment). This value represents the amount of shoaling area within each segment.

2. Define the shoaling potential for migration from an element to an adjacent element as

$$(\mathrm{SP}_j - \mathrm{SP}_{j\pm1}) \;/\; \tfrac{1}{2}(\mathrm{SP}_j + \mathrm{SP}_{j\pm1}) = S_{j\pm1} \qquad (2.15)$$

3. Define the "Crowding potential" for migration from an element to an adjacent element as

[(J-I density in the element) - (J-I density in the adjacent element)] / (adjacent J-I density in for the two elements) = $c_j \pm 1$

Table 2.4 Typical computation of index of relative abundance of juveniles (after Lawler 1972b).

Segment number	Location	Number of fish/tow[a]	Segment volume ($km^3 \times 10^2$)	Water volume in segment (%)[b]	Index of relative abundance[c]	Fish in each segment (%)[d]	Migration preference[e]
1	Coxsackie	0	12.4471	5.9	0	0	0
2	Saugerties	0.2	21.3537	10.12	2	0.08	0.0008
3	Kingston	0.5	17.0800	8.10	4	0.17	0.0017
4	Hyde Park	1.7	20.2741	9.61	16	0.68	0.0068
5	Marlboro	4.2	25.5369	12.11	51	2.17	0.0217
6	Cornwall	48.5	26.8165	12.71	616	26.15	0.2615
7	Peekskill	47.4	24.6699	11.69	554	23.51	0.2351
8	Croton Point	37.4	62.7956	29.76	1113	47.24	0.4724
			210.9738	100.00	2356	100.00	1.0000

[a] Carlson & McCann (1968) egg sampling data for 1967. [b] Relative to volume of all segments. [c] Column 4 times column 5. [d] Column 6 divided by sum of indexes of relative abundance and multiplied by 100%. [e] Column 7 divided by 100.

4. Define the "driving potential" as $SE_{J-I} \cdot S_{j+1} + CE_{J-I} \cdot C_{j+1}$, where SE_{J-I} and CE_{J-I} are parameters to fit the predicted to observed distributions. This "driving potential" determines migration in the J-I stage. For J-I through J-III, the shoaling effect parameter (SE) = 0.4 and the crowding effect parameter (CE) = 0.2.

Basically, this approach attempts to recognize the ability of bass to move considerable distances in an effort to obtain an "optimal" shoaling area. Operationally, however, there appears to be little difference between the ORNL and LMS approaches. It is interesting that the ORNL 1-D model was able to replicate, to some degree, observed spatial distributions with a migration equation based on the biological characteristic of shoaling in juvenile striped bass. The LMS and ORNL models are the only models reviewed that consider migration explicitly.

3.0 YOUNG-OF-THE-YEAR MODELS: PRODUCTION AND SURVIVAL

3.1 Egg Production

The number of eggs spawned per location and time may be approximated by information on the number and fecundity of mature females, or directly from egg sampling data.

3.1.1 Egg Production Based on Adult Stock

The winter flounder modelers based their winter flounder spawn estimate on scanty data about the fecundity and number of mature females. In fact, the following excerpt from their documentation (Sissenwine et al. 1974) illustrates the weakness of their estimation: ". . . at present, there is no information available concerning the size of the resident winter flounder population in the Millstone bight." Their final estimate is 1.469×10^8 hatched eggs. It appears that these eggs are input in their model in a single day and located in the Niantic River, Niantic Bar, and Jordan Cove (see Fig. 1.1C). This type of estimation should be used only when more complete data are unavailable.

The ORNL 1-D model combines information on adult stock and sampling data for its egg production estimates. The total spawn size is based on both adult stock and sampling studies; temporal and spatial distribution of the spawn in based on T.I. (1973a) sampling studies.

3.1.2 Egg Production Based on Sampling Studies

For many of the models, sampling programs were conducted to measure the number of eggs per unit volume as a function of time and location. The use of egg production as an input for a location and time is often desired. The typical data reduction step to accomplish this may be done in two basically different ways:

1. Estimate the total eggs spawned for a year (per unit volume), then approximate the temporal and spatial distribution of the eggs directly from normalized sampled distributions. This method was used in the JHU model. The technique and rationale follow:

Let

E_i = total number of eggs found in sampling on day i of the spawning season (per unit volume)

$\boldsymbol{E}_i$ = total number of eggs spawned on day (per unit volume)

S_e = egg survival proportion for 1 day

Assume eggs that remain after 3 days become larvae, then

$$
\begin{aligned}
\hat{E}_1 &\cong E_1 \\
\hat{E}_2 &\cong S_e \cdot E_1 + E_2 \\
\hat{E}_3 &\cong S_e^2 \cdot E_1 + S_e \cdot E_2 + E_3 \\
\hat{E}_4 &\cong S_e^3 \cdot E_1 + S_e^2 \cdot E_2 + S_e \cdot E_3 + E_4 \\
\hat{E}_5 &\cong S_e^3 \cdot E_2 + S_e^2 \cdot E_3 + S_e \cdot E_4 + E_5
\end{aligned}
\tag{3.1}
$$

Summing over all samples for the days of spawning:

$$\sum_{i=1}^{N} \hat{E} \cong (1 + S_e + S_e^2 + S_e^3) \sum_{i=1}^{N} E_i \tag{3.2}$$

so that the estimate of total eggs spawned in

$$\text{eggs} = \sum_{i=1}^{N} E_i = \frac{1}{(1 + S_e + S_e^2 + S_e^3)} \sum_{i=1}^{N} \hat{E}_i \tag{3.3}$$

The estimate is then proportioned among river segments and time.

Since the temporal distribution of egg production is a function of temperature, the JHU model considers two cases of temporal distribution, a long spawn season and a short spawn season.

2. Estimate the total number of eggs spawned in a particular location per day. In most models reviewed, the estuaries were divided into a number of segments and egg production was an input per segment. The conceptual framework for estimation of egg production per day can be derived from the previous way of egg estimation. Let E_i and E_i now be for a particular segment. Then with a 3-day duration for the egg stage and assuming no transport of eggs in or out of segments occur for the duration of the egg stage, the first day's estimate of egg production $E_1 \simeq E_1$; since $E_2 \simeq S_e E_1 + E_2$, the second day's production is estimated as and so on, sequentially by day solve for the one unknown E_i. It is

straightforward to extend this iterative technique to an egg stage duration of any length.

The Delmarva model uses a simplified version of this approach. It assumes the inverse of the egg stage duration $(\Delta t_e)^{-1}$ (in days) will approximate the fraction of egg concentration sampled that was produced that day, i.e., $E_i \approx (\Delta t_e)^{-1} \cdot E_i$. The egg stage duration (Δt_e) is treated as a parameter and two cases of egg production $(\Delta t_e = 3,2)$ are considered. The model uses a single average day of spawn. The estimated yearly production is averaged over a 20-day spawn season to obtain an estimate of the average day's spawn. The major problem with this estimation technique is that it ignores egg survival and temporal variation in egg production, thus the technique is not recommended for use in y-o-y models.

A conceptually equivalent technique to (3.4), capable of handling samples at finer than daily time resolution, is as follows: egg production during time interval $(t,\ t + \Delta t)$ is given as

$$P'(t)\Delta t = \underbrace{\hat{E}(t+\Delta t)-\hat{E}(t)}_{(A)} + \underbrace{K_e \int_t^{t+\Delta t} \hat{E}(t)dt}_{(B)}$$

$$+ \underbrace{\exp(-K_e \cdot \Delta t_e) \cdot \int_t^{t+\Delta t} P'(t - \Delta t_e)\, dt}_{(C)} \qquad (3.5)$$

where $P'(t)$ = spawning rate in a particular segment, in units of eggs per unit volume per unit time; $E(t)$ = estimated concentration of eggs in the same segment at time t (eggs/unit volume); Δt_e = egg stage duration time; K_e is the mortality rate for eggs. Term (A) is the measured concentration difference in eggs between (t) and $(t + \Delta t)$; term (B) is the mortality occurring over the time interval (Δt); and term (C) is the hatching of live eggs occurring over the time interval (Δt).

The last technique is used in all LMS and ORNL 1-D models. Table 3.1 compares the estimates of total egg production per year used in the various model runs. Figure 3.1 shows the distribution of y-o-y Hudson River striped bass by location for several years. Clearly, the spatial distribution of y-o-y and egg production are quite variable from year to year, hence the fraction of y-o-y entrained per year is variable. This variability is a major factor in reducing the predictivity of PR for future years, since egg production spatial distribution is not known for future cases.

Table 3.1 Egg production comparison.

Hudson River models	Eggs spawned per year $(\times 10)^9$	Spawn duration (days)	Source
LMS completely mixed			
LMS 1-D(67)	2.1575	49	LMS (1975), Table 8
LMS 1-D(73)	2.81275	49	LMS (1975), Table 8
LMS 2-D	1,594[1] to 3.184	49	LMS (1975), Table 8
ORNL 1-D, 67 data	0.36		ORNL 1-D, Carlson and McCann (1969)
ORNL 1-D, 68 data	2.03		ORNL 1-D , Carlson and McCann (1969)
ORNL 1-D, 73 data	4.6[2]		ORNL 1-D, Carlson and McCann (1969)
C&D models			
JHU	[3]	21-56	Warsh (1975:25)
Delmarva	[3]	1	Portner (1975)
Winter flounder	0.1469	1	Sissenwine et al. (1974)

[1] Several cases are considered with hatching times variable (1.5-3 days).

[2] Approximate value.

[3] Not given in their documentation.

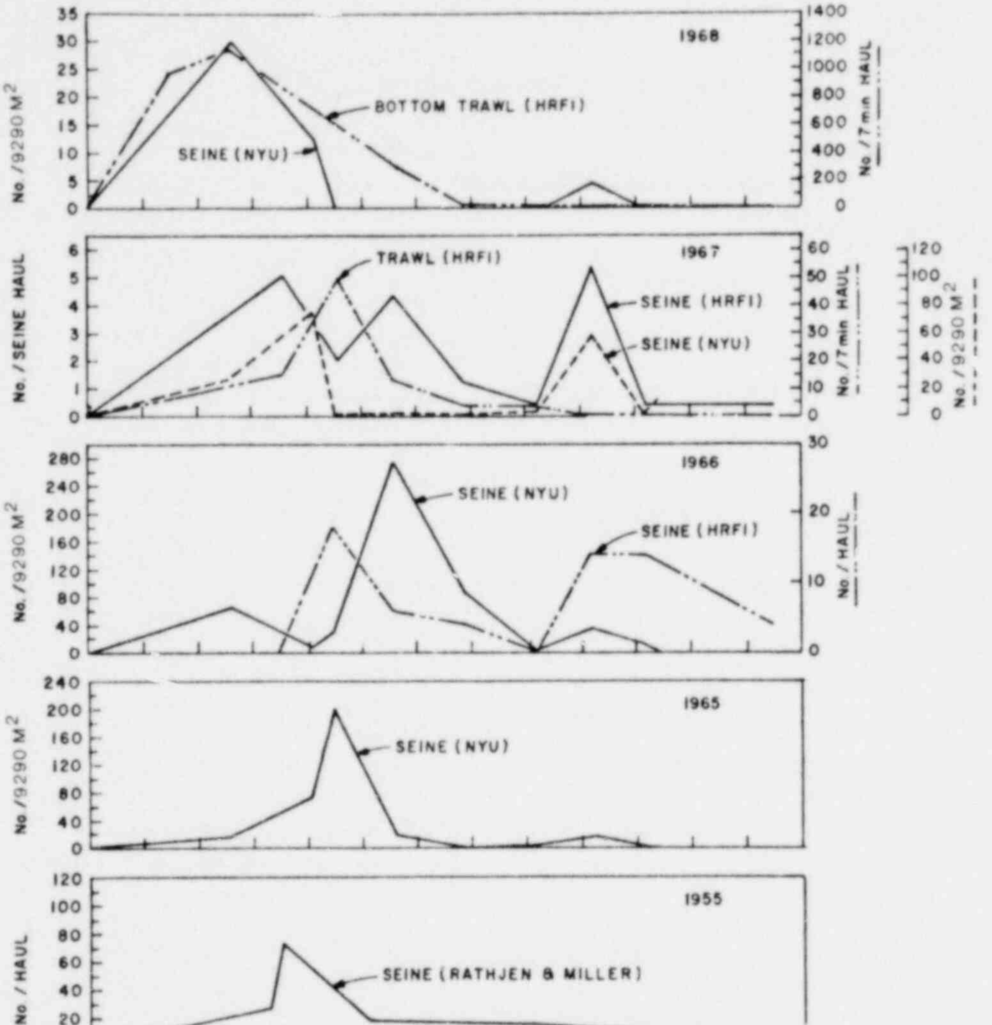

Fig. 3.1. Annual estimates of longitudinal distribution of y-o-y striped bass in Hudson River (adapted from Eraslan et al.)(1976: fig. B-10).

3.1.3 Discussion

In general, egg production is known with much more certainty than are the other principal components. Since eggs do not avoid the biologists sampling nets, the degree of accuracy in estimates of egg production is approximately proportional to sampling effort (within reasonable bounds). The principal errors in estimation stem from: 1) spatial distributions that are highly clumped and heterogeneous (sampling problem); 2) violation of the "transport in or out of segments during egg stage duration" assumption; and 3) variability of egg stage duration and survival. The recommended technique for estimation of egg population is Equation (3.5) since it uses more information than technique (3.4). If data about fecundity and the number of mature females is available, however, then egg production based on the adult stock in conjunction with the technique (Equation 3.5) is recommended. See Table 3.2 for the egg formulation comparison.

An alternative model formulation applicable to all d-i (or stock d-d) mortality and transport equations does not require egg production estimates. What is required are estimates of the average normalized spatial and temporal distributions for each life stage in y-o-y; these data are necessary to (realistically) estimate and validate the parameter values of any hydrodynamic model. Christensen et al. (1975) use a simplified version of this approach in their entrainment calculations. In this model, only estimates for the proportion of individual within an age class are in the C&D Canal and in front of the Summit plant are required. This type of approach relies very heavily on sample data, but with good data, it is quite accurate for short-term (PR) predictions.

3.2 Aging and Recruitment

3.2.1 Life Stages in the Models

The biological characteristics of y-o-y change with age. The first step in quantifying age-specific characteristics is to divide the first year of life into a number of life stages (classes). These life stages are usually chosen to coincide with the major phases of life for y-o-y. The age classes used by the various models are given in Table 3.3. As seen in the table, there is a considerable variability in age class duration between the striped bass models. Variability in growth of striped bass is a major reason for the difference between models (e.g., field studies in Table 3 of Lawler (1972a).

Usually, different life stages of y-o-y are not equally susceptible to entrainment. Also, the longer a fish is in a particular life stage, the longer the fish is exposed to that life stage's entrainment probability, which gives impact predictions greater sensitivity to parameter changes in longer life stages.

Table 3.2. Egg production[1] formulation ranking.

	Probable error in estimate of total egg production	Probable error in temporal and spatial distribution	Relative cost	Biological realism
Egg production based on adults	Low to high	High	Low	Low to moderate
Egg production per year from samples	Low	Moderate	Moderate	Low to moderate
Egg production per day from samples (Eq. 3.4)	Low	Low	High	Moderate
Egg production per day from samples (Eq. 3.5)	Low	Low	High	Moderate
Normalized distributions	Low	Low	High	Moderate

[1] Rankings based on models reviewed.

Table 3.3. Comparison of values used for the life stage duration and equilibrium survival fraction[a].

Model	Eggs	Yolk-sac larvae	Post-yolk-sac larvae	Juvenile			Source
				I	II	III	
LMS Completely Mixed	1.5 (0.01-0.1)	21 (0.005-0.1)	[b]	30 (0.2)	137.45[c] (0.4-0.6)	159 (0.184-0.4)	Table 3, Lawler (1972a)
LMS 1-D 1967	1.5 (0.1)	28 (0.15-0.5)	[b]	30 (0.2)	123[d] (0.5)	158 (0.1898)	Table 4, Lawler (1972b)
LMS 1-D 1973	1.5 (0.1)	28 (0.15)	[b]	30 (0.2)	123[d] (0.53)	158 (0.186)	TI(1973a)
LMS 2-D	1.5,2.25,3 (0.1)	6 (0.15)	22 (0.15)	30 (0.2)	123[d] (0.53)	158 (0.186)	Table 8, LMS (1975)
ORNL 1-D[e]	2[f]	6	22	40	123	172	Table B-23, USNRC (1975)
JHU[g]	3	10	[b]	67	275	275	Clark(1972) and Table 1-2, Portner (1975)
Delmarva[h]	2-3 (0.1)	10-15 (0.1)	78-72 (0.1)	[i]	275	275	Mansueti(1961) and Portner (1975)

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3.2.2 Equations for Survival and Recruitment

Equations for survival and transfer between life stages have used three approaches. There are: 1) not dividing the y-o-y into life stages; 2) treating the population as a group of cohorts, where a cohort represents individuals hatched at the same time; and 3) treating individuals in each age class as indistinguishable by cohort but uniformly distributed in age within the life stage.

3.2.2.1 Equations for Survival in which Y-O-Y are not Separated into Life Stages. Approach 1) is used in the winter flounder model. Here the survival of the hatched eggs N_1 into 1-year-old fish N_1 is modeled using the Ricker spawner-recruit relationship (Ricker 1954),

$$N_1\ (t + 1) = N_0(t)\ \exp\ [(a - b)N_0(t)] \qquad (3.6)$$

where a and b are parameters estimated, in theory, from data on hatched eggs and age-1 adults, but in lieu of this with information derived from properties of the Ricker curve and of the adult population (Sissenwine et al. 1974). Their documentation states, "Recruitment to year-class 1 is a function of the number of eggs produced during the previous year multiplied by $1 - M_{p1}$, where M_{p1} is the reduction in recruitment resulting from entrainment." This suggests that all entrainment mortality occurs first and that all compensation mortality occurs (via the Ricker curve) within age class 0 after entrainment mortality. Sissenwine (personal communication), however, indicated that reduction in model (winter flounder) y-o-y from entrainment occurs after compensation (i.e., applied to $N_1[t + 1]$ rather than $N_0[t]$). This is a good example of the problems we have had with documentation of the models reviewed.

Parameters a and b are estimated as -9.66 and 7.54×10^{-11}, respectively. Survival of y-o-y for their equilibrium case is estimated as 0.55×10^{-4} and is based on studies by Saila (1961) and Pearcy (1962). This approach has the benefit of simplicity and relative data independence. There is, however, scanty supporting evidence for the estimated parameters or for the applicability of the Ricker formulation to this species.

3.2.2.2 Equations for Survival Based on the Cohort Approach. Approach 2), the cohort model, represents the fish by cohorts based on time of spawning. This approach is used by the LMS, JHU, and Delmarva models. The time step ranges from daily (Delmarva) to 0.1 day (LMS 1-D). The equation for change in numbers of individuals per time step is given by

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$$\frac{dn_i^{(k)}}{dt} = -m_i n_i^{(k)} \qquad (3.7)$$

where $n_i^{(k)}$ = the number of individuals in the ith life stage that are in the kth cohort (e.g., k days old).

The age-class-specific mortality parameter m_i may be either a constant, termed density-independent (d-i) mortality (Delmarva, JHU), or a function of density of fish in that life stage, termed density-dependent (d-d) mortality (LMS 1-D, 2-D). One important feature about the cohort model is that fish mature into a new age class when they have reached the exact age for the start of that age class. This also means that there is no ambiguity about the age distribution of individuals in an age class--they are all aged to within one time step. The cohort method accurately represents the mechanics of aging, assuming all fish within a cohort mature at the same rate, but can be expensive in computer storage and time.

There are several advantages to assuming the parameter m_i is constant; most important, the resulting estimates of PR will be conservative (i.e., upper bound). JHU elect to use a constant m_i because of the uncertainty of formulation and existence of d-d survival in y-o-y. JHU discuss other advantages for d-i survival equations and show that PR is independent of: 1) total number of eggs spawned per season; and 2) survival rates for any age class. These properties of d-i survival form the basis for the ORNL Summit model (<u>see</u> Section 3.3). Our simulation results suggest a minor sensitivity, to 1) and 2) for d-i survival in cases with d-d physical transport (e.g., migration to shoaling areas). For example, a change of 16.0 to 17.7 in PR occurred in simulations with no migration (i.e., passive transport) to medium strength migration.

The following example is a simple illustration of the independence of d-i survival to 1) and 2). Let N_0 be the number of eggs spawned per season, S the d-i natural survival fraction for y-o-y, and F the d-i survival fraction from entrainment. Then,

$$\text{PR} = \frac{N_0 S - N_0 S F}{N_0 S} \cdot 100 = (1 - F)100 \tag{3.8}$$

and the PR is seen to be independent of 1) and 2). We should also note that independence of 1) and 2) implies the PR is independent of sampling gear avoidance ability for any age class, as long as the avoidance is the same within a class and gear cannot be completely avoided.

The LMS (1-D, 2-D) models use a d-d survival equation (Fig. 3.2) for the m_i term:

$$m_i = k_{e,i} + (k_{e,i} - k_{o,i}) \left(\frac{n_i - n_{s,i}}{n_{s,i}} \right)^3 \tag{3.9}$$

where $K_{e,i}$ is the equilibrium mortality, $K_{o,i}$ is a compensation parameter, and $n_{s,i}$ is the equilibrium density for the ith life stage. Since mortality increases with increasing density, the mortality is termed <u>compensatory</u> <u>mortality</u>. Parameter values for the K_e and n_s terms in the studies (Lawler 1972<u>b</u>, their Table 22) are: 1.5, .068, .054, .005, and

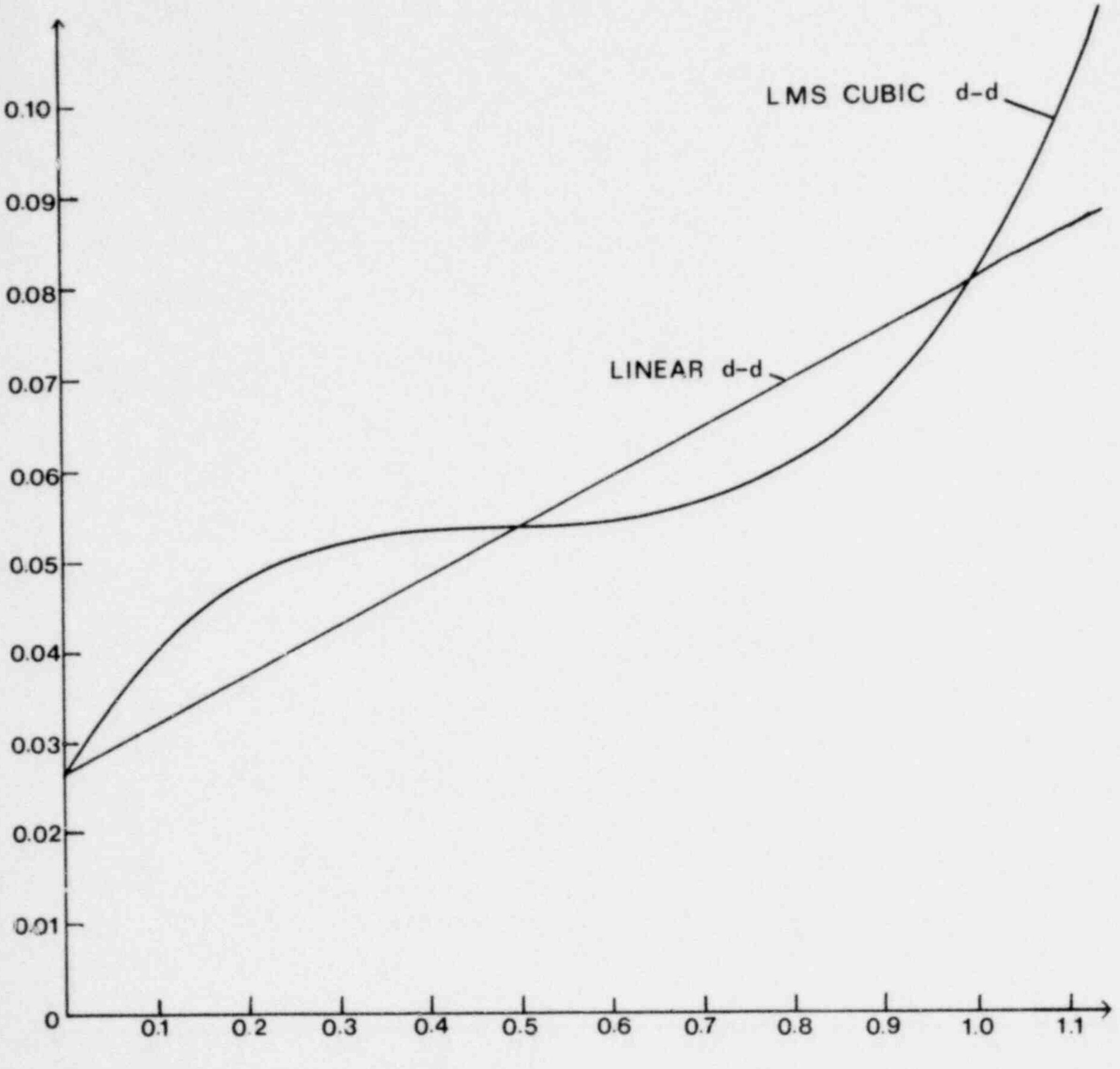

Fig. 3.2. Comparison of d-d mortality rate used by LMS and linear d-d mortality rate.

.01 are the k_e values for the life stages of egg, larvae, J-I, J-II, and J-III, respectively; and 70.62, 17.66, 3.532, and 2.649 are the n_s values for the life stages of larvae, J-I, J-II, and J-III, respectively. Egg survival is m_i in their model. The cubic survival equation has been criticized by ORNL (USNRC 1975). The main criticisms have been: 1) no attempt to relate the m_i function to mechanisms in the y-o-y population; 2) use of a cubic function over the usual linear d-d function (e.g., in a logistic equation); 3) use of d-d survival for all y-o-y life stages; and 4) use of a constant k_i value for each life stage and each river segment.

3.2.2.3 Equations for Survival Based on the Dynamic Pool Approach

Approach 3) to survival views each life stage as containing individuals who are not distinguishable by age. In the case of the ORNL 1-D model, which illustrates one form of approach 3), the fish are assumed to be uniformly distributed by age within a life stage, no matter what pattern of recruitment into that life stage has actually occurred in the model. Their survival equation is:

$$\frac{dn_i(t)}{dt} = \underset{\text{survivors enter}}{g_{i-1}s_{i-1}n_{i-1}} - \underset{\text{survivors leave}}{g_i s_i n_i} - \underset{\text{sink term}}{(1 - s_i)m_i n_i} \tag{3.10}$$

where s_i is the survival rate through the ith life stage, g_i is the rate at which survivors in the ith stage grow into the i - first stage, and m_i is the rate of death for those which do not survive into the i - first stage. For $i - 1 = 0$, replace $g_{i-1}s_{i-1}n_{i-1}$ by the egg deposition rate. Parameter values used in the ORNL runs appear in Table 3.4.

Density-dependent survival is incorporated in the ORNL 1-D equations by modifying s_i to

$$s_i = \begin{cases} s_i^* \text{ (constant)}, n_i < n_{i,\text{crit}} \\ s_i^* \cdot (n_i - n_{i,\text{max}})/(n_{i,\text{crit}} - n_{i,\text{max}}), \quad n_{i,\text{crit}} < n_i < n_{i,\text{max}} \\ 0, \; n_i > n_{i,\text{max}} \end{cases} \tag{3.11}$$

where $n_{i,\text{crt}}$ is the critical population density for the ith stage and $n_{i,max}$ is the maximum population density for the ith stage. Table 3.4 includes the parameter values used in later ORNL 1-D runs. The original ORNL 1-D runs used parameter values for $n_{i,\text{crt}}$ that were higher than n_i values encountered in their ORNL 1-D(73) runs. Thus, survival was always density-independent. Consequently, much higher PR values were given for their runs (see Table 2.2).

Table 3.4. Parameter values used in ORNL 1-D model[1]

Life stage	g_i (/hr) for d-i runs and d-d runs	s_i (/hr) for d-i runs	s_i (/hr) for d-d runs[2]	n_i,crt (/TCM)	n_i, max (/TCM)
Egg	0.035	0.36	0.36	No compensation	
Yolk-sac larvae	0.0069	0.40	0.58	12.50	250.03
Post-yolk-sac larvae	0.0019	0.64	0.75	9.82	196.35
Juvenile 1	0.001	0.90	0.93	3.25	64.98
Juvenile 2	0.00034	0.90	0.93	2.01	40.26
Juvenile 3	0.00024	0.95	0.97	0.78	15.54

[1] Eraslan et al. (1976).

[2] Actually s_i is a function of density, and these values are applicable for densities below critical population levels (refer to text).

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The ORNL survival formulation is fraught with conceptual problems. The assumption of uniform age distribution is rarely satisfied since there are generally fewer individuals as age increases and the age distribution of individuals is highly dependent on physical distribution and the number of segments chosen to represent the Hudson River.

A second conceptual disadvantage of their formulation is that three independent parameters (apparent survival probability, growth rate coefficient, and mortality rate coefficient) are used to represent two biological phenomena (time required to pass through a life stage and mortality rate within a life stage). Eraslan et al. (1976) point out that their particular formulation is not intended to imply that the three parameters for each life stage reflect three independent biological phenomena: There is an implicit overlap or redundancy among the three parameters. Their argument is that this redundancy allows flexibility in terms of adjusting parameter values to fit the simulated temporal distributions of the various life stages to the observed temporal distributions. A third conceptual disadvantage is that s_i represents survival through the life stage, rather than per day.

3.2.3 Comparison of Evidence for LMS versus ORNL Density-Dependent Survival Function

It is difficult to realistically quantify the survival history for y-o-y fish. Even if the number of young fish entrained is known, considerable variation in predicted PR has been reported. One reason for this is the degree of d-d incorporated in survival equations. If survival of a fish is independent (dependent) of the density of other fish, then survival is d-i (d-d). As an example of this sensitivity, Lawler (1973, reference sensitivity, 73, case 17) reports a reduction of PR from 13.16 to 3.36 within a single juvenile life state due solely to d-d rather than d-i survival within that juvenile life stage.

In the development of survival equations, it is important to consider the notion of d-d survival somewhere in the life history of fish. The persistence of populations, over time, in the face of environmental stochasticity is direct evidence supporting the notion. However, the life stage or life stages on which and manner in which compensatory mortality acts is poorly understood. It is thought that some d-d survival occurs in the y-o-y population. Our simulation results indicate the PR is sensitive to the manner in which and time over which compensation occurs. For y-o-y striped bass, there are currently two hypotheses for the manner in which d-d survival occurs. Hypothesis one (supported by ORNL) is: For densities of y-o-y fish below an age-specific critical density, survival is d-i, whereas above the critical density survival is d-d and lowered (from the d-i value). Hypothesis two (supported by LMS): The survival is always d-d with a plateau of approximate d-i survival centered about an age-specific equilibrium density. Survival is higher for low densities than for high densities. Both of these hypotheses reflect the notion of d-d mortality, consistent with long-term persistence of populations. In Fig. 3.3, graphs of survival versus density for both hypotheses are presented. The general shape of a spawner-recruit curve can be inferred

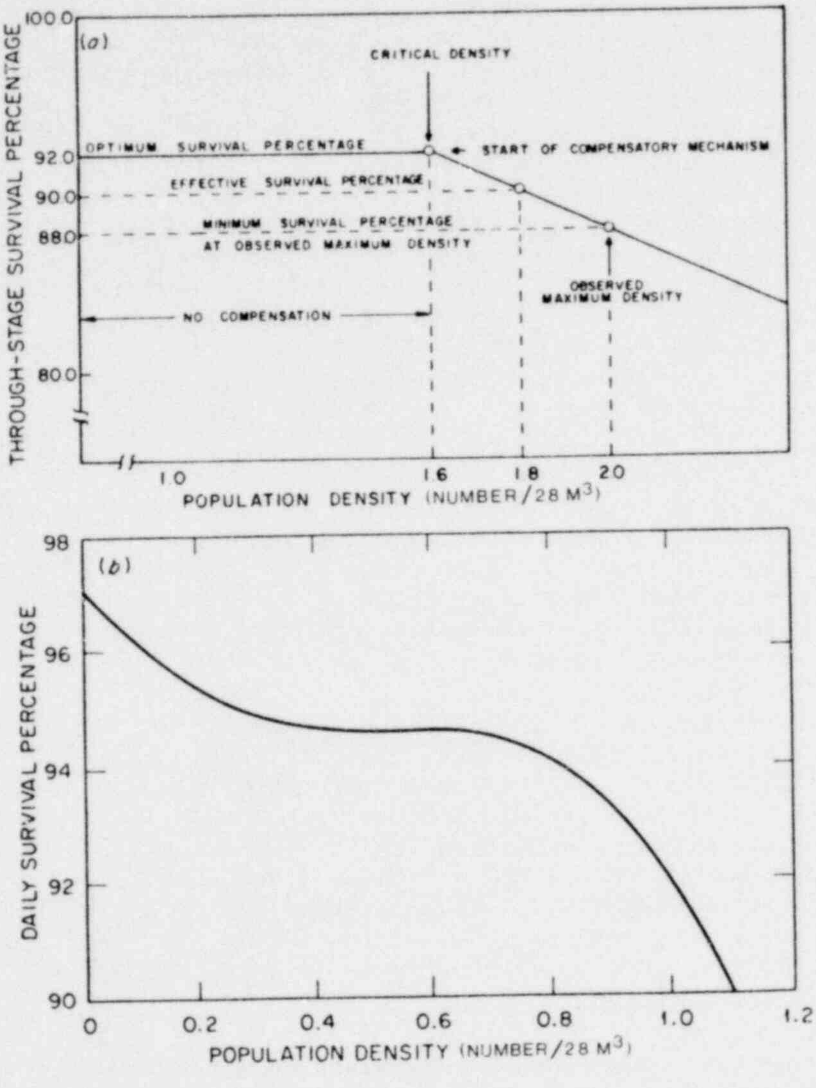


Fig. 3.3. Comparison of instantaneous survival percentage for juveniles in y-o-y model computed using density-dependent mortality hypothesis of a. ORNL 1-D model and b. LMS models. Figures are adapted from USNRC (1975) and Lawler 1972b.

for each hypothesis and is illustrated in Fig. 3.4. The major difference in the shape of these spawner-recruit curves is the linearly increasing portion of the curve, below the critical density, for hypothesis one, versus the nonlinear shape predicted by hypothesis two.

In an attempt to decide which of the two hypotheses is more representative of the Hudson River striped bass population, a literature review was conducted. Our objective was to examine spawner-recruit data for anadromous fish populations, and see which hypothesis is supported. The studies of striped bass in the San Francisco area (e.g., Stevens 1977) appear to be the only ones with data over enough years and of decent quality to infer a spawner-recruit relation for striped bass. Chadwick et al. (1977), however, have shown empirically that outflow and water diversion are highly correlated with San Francisco striped bass recruitment. The predictive ability of long-term simulations that vary only egg production from year to year (e.g., in all models compared) is questionable, owing to this recent result.

Quite good information on spawner-recruit relations in (anadromous) salmon is available. A summary of studies by Larkin and McDonald (1968) states:

> "Shepard and Withler (1958) and Shepard et al. (1964), describe for Skeena (river in British Columbia) sockeye (salmon) of ages 4 and 5 (major spawning class) a reproductive curve (spawner recruit curve with recruits being mature adults) with an almost linear ascending limb and a very precipitous descending limb generally after the Ricker type (Ricker 19[illegible]."

The study indicated that, perhaps, for some stocks high environmental stochasticity would not mask a spawner-recruit relation. Further, the study favors an S-R curve with a linear left limb. In order to examine other S-R relationships, we decided to analyze the spawner-recruit data for eight sockeye salmon stocks presented in Cushing (1971). Sockeye salmon, unlike pink or chum salmon, remain in the streams and estuaries for 1-3 yr after birth and hence seem to be closer to striped bass in early life history characteristics. Inspection of Fig. 3.5, however, reveals that a great deal of stochasticity is apparent in their spawner-recruit relations.

As an exercise, we decided to calculate Cushing's index of d-d (b) for the eight sockeye stocks. This index, b, arises from the simple spawner-recruit relation $R = kP^b$ where R is recruitment and P is parent stock in some units, and where k and b are constants. If $b = 1$, then survival is d-i, $b < 1$ implies survival is d-d, decreasing as P increases (i.e., compensatory survival). Here $b > 1$ implies survival is d-d with survival increasing as P increases (i.e., depensatory survival).

Since our main interest was in the left limb of spawner-recruit curves, we arranged the data for each stock in increasing P values. The spawner or stock domain was then divided into 20 equal intervals and regressions for b were performed using interval 1 only, then interval 1

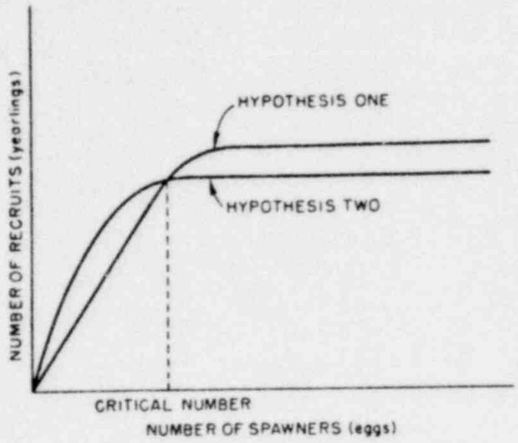
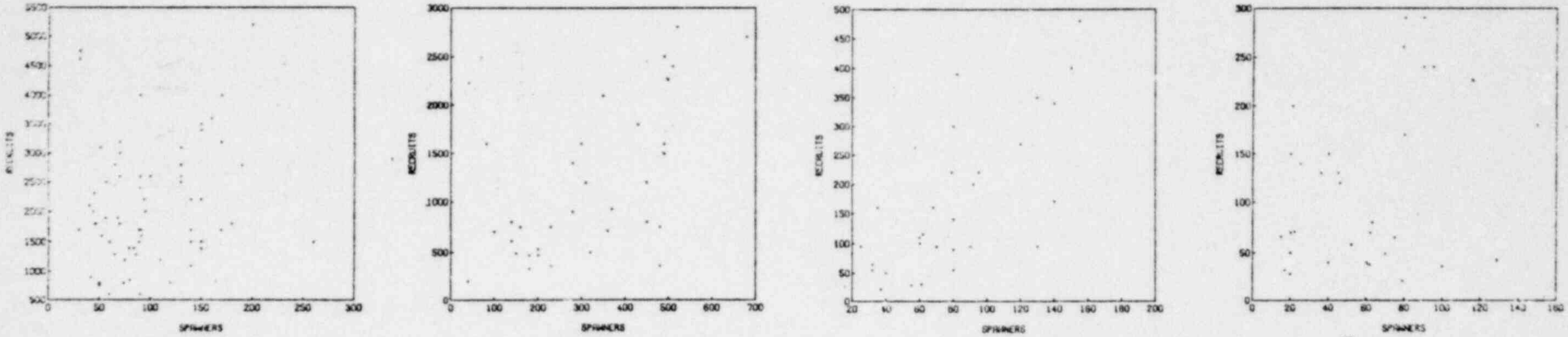
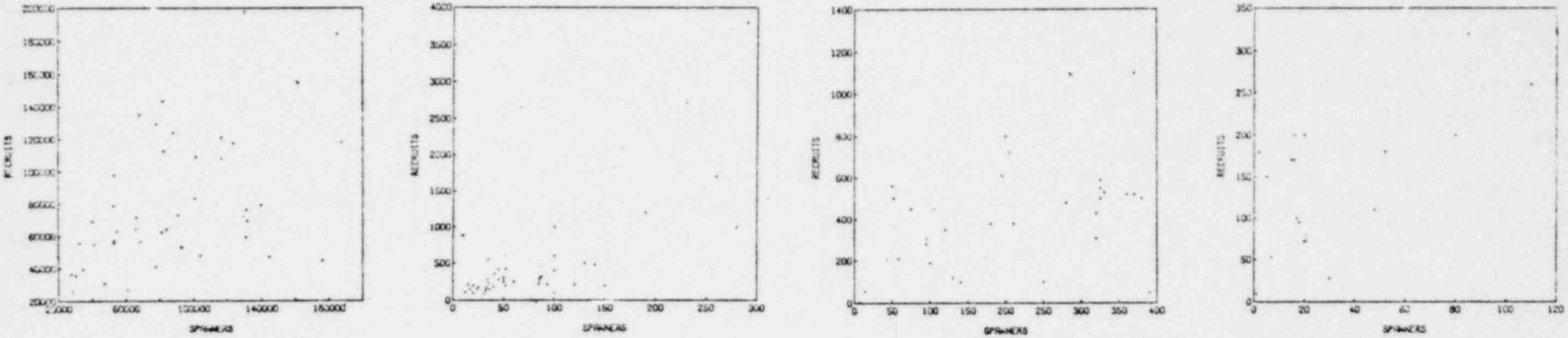


Fig. 3.4. Comparison of typical spawner-recruit curves resulting from density-dependent mortality based on Hypothesis 1 (ORNL) and Hypothesis 2 (LMS).



Karluk Columbia Ugashik Fraser



Naknek Skeena Nushagak Egekik

Fig. 3.5. Spawner recruit relationships for eight salmon stocks.

and 2, and so on. For example, the tenth regression would use all data points with P values less than the midpoint of the P range. This technique allows us to examine trends in b as the P range increases from smaller to larger P values. Figure 3.6 shows least-square -value estimates for each of the eight sockeye stocks.

We used the following criteria to decide which of the hypotheses was supported by Fig. 3.6: If $b \geq 1$ for low spawner levels then survival is not compensatory and hypothesis 1 is favored; if $b < 1$ then survival is compensatory and hypothesis 2 is favored. The S-R data from sockeye stocks in the rivers (Columbia, Ugashik, Fraser, Naknek, Nushagak, Skeena) appear to support hypothesis 1. The S-R data from the Karluk River stock appear to support hypothesis 2. The S-R data from the Egegik River stock do not appear to support either of these hypotheses since survival is apparently compensatory at low densities and d-i for a large domain of densities. By and large, hypothesis 1 is favored by this analysis; however, the stochasticity in these S-R values is quite large, thus statistical rejection of hypothesis 1 or 2 seems unlikely. The biological arguments presented by ORNL (USNRC 1975:127-144) for hypothesis 1 rather than 2 also seem more plausible to us. This is not to say that the S-R curve corresponding to hypothesis 2 is questioned, but rather that the survival equations for hypothesis 2 seem less plausible.

Assuming hypothesis 1 is more reasonable for striped bass, a major question still remains unanswered. What are the critical population values? If the critical population values are larger than populations actually observed in the y-o-y striped bass then, operationally, the survival equations would be d-i. Indeed, this is precisely the case in the ORNL 1-D model and results in relatively large PR. In contrast critical population values (e.g., equilibrium values of LMS 1-D, 1967) in the middle range of observed values substantially reduce the PR.

Another criticism of the LMS d-d survival formulation is the use of d-d compensatory survival for the later (J-II and J-III) life stages. We think this criticism is legitimate considering recent results from a detailed study of striped bass in Sacramento-San Joaquin Estuary. Quoting from this study (Chadwick et al. 1977), "In summary, the abundance indices for young and adults indicate that most of the variation in the survival of striped bass in the Sacramento-San Joaquin Estuary occurs during the first 2 months or so of life." Our analysis reveals that PR in the LMS models is very sensitive to the assumption of d-d survival in the J-II and J-III stages (Section 3.5.2). This result is supported by the sensitivity analysis done by LMS (Lawler 1973). Since d-i survival does not change the PR after the entrainment period has ended, the LMS predicted PR at the beginning of the J-II stage can be used to infer PR if d-i survival were assumed for J-II and J-III. Table 3.5 compares the PR given by LMS for cases with d-d J-II and J-III survival versus d-i J-II and J-III survival. From Table 3.5, observe that there is an order of magnitude difference in PR between d-d versus d-i J-II and J-III survival runs. We should remark that the reduction in PR with d-d J-II and J-III stages is not unique for the LMS d-d survival equation, but rather is a property of all

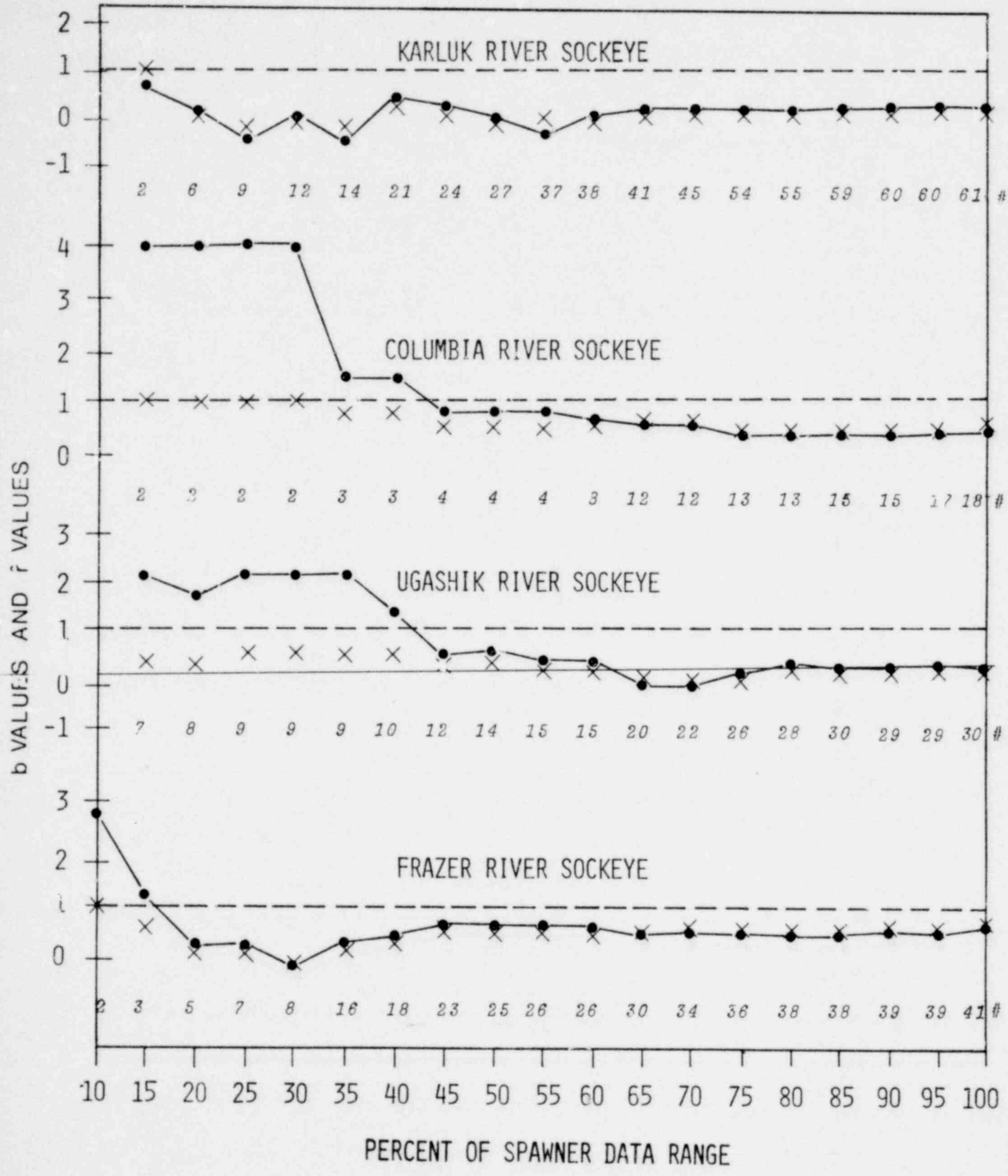


Fig. 3.6. Test to see whether salmon data support a d-d or d-i spawner recruit relationship.

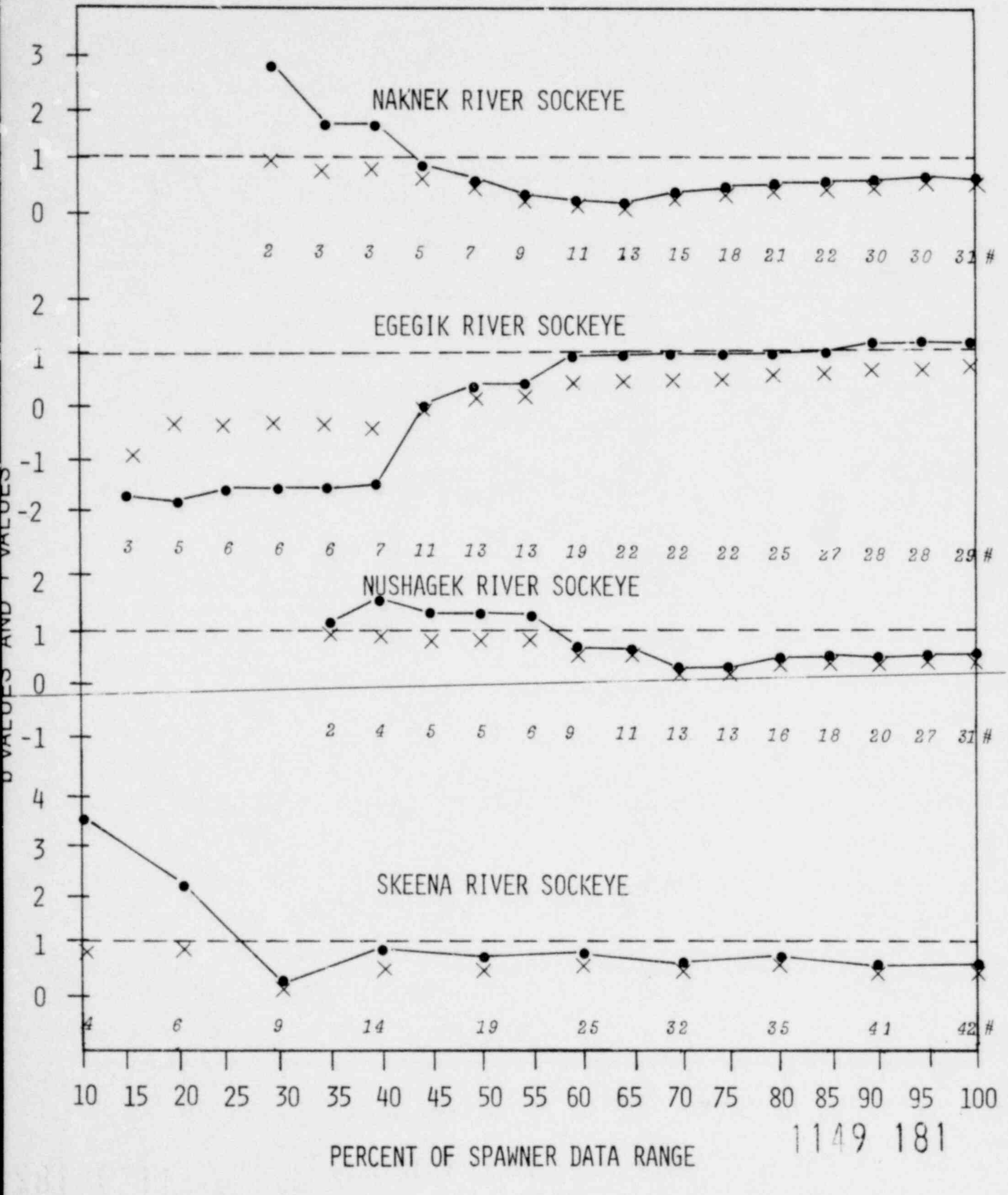


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Fig. 3.6. Test to see whether salmon data supports a d-d or d-i spawner recruit relationship. - Continued.

Table 3.5. Comparison of PR when d-d versus d-i survival of J-II and J-III is assumed. $k_o = 0.5\ k_e$ for larvae and J-I stages in all runs. No impingement is used.

1.	PR with d-i J-II and J-III	PR with d-d J-II and J-III	Remarks
1	13.16	1.32	LMS case 17 high *f* factors
2	3.80	.28	LMS case 18 low *f* factors
3	1.19	.08	LMS case 19 low *f* factors

Source - Lawler (1973), sensitivity analysis.

compensatory d-d survival equations. On the other hand, d-d depensatory survival will cause a higher PR than d-i survival.

For the presently used models, we prefer hypothesis 1 over 2 and suggest that PR predictions be presented for various critical population values. We also suggest that d-d survival be limited to the first 2 or 3 months of life for model striped bass.

3.3 Entrainment and Impingement

3.3.1 Plant Impact Factors

Once the hydrodynamic-biological y-o-y model has demonstrated its ability to predict the numbers and distribution of the y-o-y with some accurancy, the models can be adapted to include removal of y-o-y fish simulating the impact of the plant operation on the fish populations. The plant operation will remove fish through entrainment (passing through the plant cooling system in the cooling water) for eggs and larvae, and through impingement (trapping in the debris screens) for older fish. Entrainment losses are the most critical because of their magnitude and the consequences of this removal on future fish populations; therefore all the models include entrainment functions from which the entrainment losses are predicted. The LMS 1-D(67,73), LMS 2-D, and ORNL 1-D models also include impingement loss calculations.

3.3.2 Entrainment Predictions

All the models (Table 3.6) base their entrainment calculations on a modification of the "withdrawal from a fixed volume" method. This method states that the probability of entrainment for fish in the neighborhood of the plant is equal to the ratio of the volume of water taken in over a period of time to the volume of water in which the fish reside in the same period, or

$$P_f = V_i/V \qquad (3.12)$$

Because the models deal with concentrations (number/unit volume), the V is included implicitly in the concentration and need not be specified. The number entrained N is calculated from the entrainment function as

$$N = C_i V_i \qquad (3.13)$$

where C_i is the concentration of fish in the vicinity of the plant intake. The ratio of the intake concentration C_I to the concentration in the vicinity of the plant intake C_i is E. When the plant mortality is included to give the concentration killed by passage through the plant,

Table 3.6. Entrainment functions and types of modifications.

Models	Entrainment function[1]	Organism	Power plant cooling system	Physical intake differences considered	Plant mortality varies with life stage	Longitudinal distribution difference	Vertical distribution differences	Lateral distribution differences	Swimming ability
LMS 1-D completely mixed	fQ_I	Striped bass y-o-y	IP-II OT						
LMS 1-D	fQ_I	do	IP-III OT		*			*	
LMS 2-D	fQ_I	do	IP-III OT	*	*		*		
ORNL 1-D	fQ_I	do	IP-III OT	*	*			*	*
ORNL SUMMIT	$\frac{Cp_{p\hat{c}}}{Cc} Q_I$	do	Summit CT			*			
JHU	$10 \sum_{j=1}^{10} D^{j}(T)_{j}^{j}(T)Q_I$	do	Summit CT	*			*		*
DELMARVA modified	$\frac{L_{kj}}{\sum_j L_{kj}V_j} Q_I$	do	Summit CT					*	
WINTER FLOUNDER	Q_I	Winter flounder y-o-y	Millstone OT						

Table 3.6. Entrainment functions and types of modifications - (Continued)

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[a] Where C_p = average concentration in front of plant intake,

C_c = average concentration in the canal proper,

P_c = proportion in the canal,

L_{kj} = concentration at station j in cross section,

V_j = volume of water associated with station j, and

$D^j(T)$ = vertical distribution of age T fish.

$f^j(T) = G^j \left[1-\left(\frac{T-19}{72}\right)^n\right]$ (See section 2.8)

where G^j = fractional transport in layer j,

$\left(\frac{T-19}{72}\right)^n$ = fraction of swimming ability attained at age T.

Note: $F = E$.

the total entrainment factor, f gives the probability of entrainment and death. If all organisms are killed, as in closed-cycle cooling, then total entrainment factor including mortality $F = E$. The withdrawal from fixed volumes method assumes that the fish are uniformly distributed in the water body, that all organisms are equally entrainable, that the organisms are not mobile, and that all organisms are at some time susceptible to entrainment.

Values for E different from 1 would suggest that one or more of these assumptions is not valid. Commonly the modelers have changed the formulation to include E and f values different from 1 (mostly < 1) to reflect nonuniform distribution, mobility, and other factors both biological and physical that would cause this ratio to be different from 1 and likewise would change the predicted entrainment losses (Table 3.6).

The largest number of modifications by far has been introduced in the models for Indian Point II and II nuclear power plants. A list of the factors denoted by f_i and their definitions is given in Table 3.7. The original LMS completely mixed model did not present any individual factors and biological or physical justification for chosen values for f. In LMS 1-D(67) lateral differences in the fish distribution were suggested to justify the presentation of three f factors, f_1, f_2, and f_4, which reduced estimates of entrainment. The drawn-down factor f_4 is supposed to represent changes in entrainment estimates due to nonreplenishment of the entrained fish. It is difficult to envision how this factor could be estimated, so no value was assumed at this point. At this point too, the plant passage mortality f_3 was presented. The LMS 1-D(73) model also included diurnal differences in fish concentration and hours of day and night operation, f_7 and f_8, respectively. Here f_8 is based on the average number of hours of day and night during the period the models are run. Vertical differences in fish concentration and withdrawal of intake water were introduced in the LMS 2-D model. The ORNL 1-D model contained factors representing lateral differences in fish distribution (in this case $f_2 = f_1 f_2$ in LMS formulations) including a factor representing the swimming ability. The possibility of including factors representing changes in entrainment resulting from geometry of intake and discharge structures is also presented, but as no estimate can be made of this effect no values are given. The f_i factors for each model combine to form the total entrainment factor f (Table 3.8). The LMS model estimates most of the factors from sample data or the fish population with the exception of f_8, estimated from average number of day and night hours, and f_9, estimated from physical measurements of the extent of the intake zone. The ORNL based f_{10} on some laboratory measurements of swimming ability but for the most part the parameters for f_{10} and f_2 were chosen hypothetically. The f factors are estimated for each life stage and assumed constant within the life stage, and entrainment is calculated daily.

Each of the models developed for the Summit power plant used a different type of motivation for modification of the f factor (Table 3.6). The JHU included three components representing vertical distributional differences in fish concentration D^j, vertical differences in the withdrawal of intake water G^j, and acquisition of swimming ability. All

Table 3.7. Indian Point entrainment factors and definitions.

f_1 ≡ Plant vicinity density factor ≡ ratio of average river concentration to mean population density in front of the intake.

f_2 ≡ Intake density factor ≡ ratio of population density in front of intake to mean population density in the intake element.

f_3 ≡ Plant mortality factor ≡ fraction of organisms that die in passage through the plant.

f_4 ≡ Drawn down factor ≡ fraction of population in front of intake that is not immediately replenished.

$f_{5,6}$ ≡ Plant geometry factors ≡ factor relating plant intake and discharge geometry to plant passage survival.

f_7 ≡ Diurnal concentration factor ≡ ratio of daytime or nighttime cross-sectional river concentration to 24-hr average concentration.

f_8 ≡ Diurnal hours factor ≡ factor based on hours of daytime and nighttime plant operation.

f_9 ≡ 2-D intake factor ≡ fraction of intake water drawn from upper or lower layers.

f_{10} ≡ Intake avoidance factor ≡ factor based on ability to avoid entrainment due to increased mobility (See Sect. 2.8).

Table 3.8. Indian Point entrainment models.

LMS completely mixed

$$f = \text{constant}$$

LMS 1-D (67)

$$f = f_1 f_2 f_3 f_4$$

LMS 1-D (73)

$$f = (f_1 f_2 f_3 f_4 f_7 f_8)_{\text{day}} + (f_1 f_2 f_3 f_4 f_7 f_8)_{\text{night}}$$

LMS 2-D

$$f = [0.5([f_1 f_2 f_3 f_4 f_9]_{u} + [f_1 f_2 f_3 f_4 f_9]_{L}) f_8]_{\text{day}}$$

$$+ [0.5([f_1 f_2 f_3 f_4 f_9]_{u} + [f_1 f_2 f_3 f_4 f_9]_{L}) f_8]\text{night}$$

ORNL

$$f = f_2 f_3 f_5 f_6 f_{10}$$

Note $F = F/f_3$

Where subscript u = upper segment,
and L = lower segment.

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three formulations were chosen to represent the hypothetical relationships possible. Values of D^j and swimming ability are discussed in the migration section, and G^j, as mentioned in the convective transport section, is the fraction of transport attributed to each layer. Entrainment is calculated hourly; D^j represents the vertical distribution of the eggs and larvae. Three patterns used in the model are: 1) eggs slowly sinking, larvae rising; 2) eggs rapidly sinking, larvae rising; and 3) eggs rapidly sinking, larvae diving. In the Delmarva model the entrainment factor is based on the ratio of the concentration sampled at the plant intake to the numbers calculated in the model. The entrainment predictions were therefore very sensitive to model assumptions such as survival and rate of departure from the canal, and a modified form was developed that uses a daily ratio of the concentration at the station in front of the intake to the number in the cross section. After some time the samples become very small, and E is estimated from the average of the E's over the preceding days.

The ORNL Summit modified E by estimating the effects of the nonuniform longitudinal distribution of the fish in the canal. Two factors, P_c (the portion in the canal proper as opposed to that in the Elk River) and Cp/C_c, the ratio of the mean number at the intake versus the mean number in the canal, are calculated for either the length of the life stage (for eggs) or for some suitable subinterval of the life stage and assumed constant over that period.

The winter flounder formulation is probably also similar to the formulations in the other models except that there are no modifications to the basic formulation (see Table 3.6).

3.3.3 Estimation of Entrainment Factors

Most factors for which values must be determined are estimated from ratios of sample data on the fish populations and for most of these factors some kind of time averaging is assumed. Two methods for forming these averages exist. The first method, called mean of the ratios, sums the concentrations over the time period of interest and divides by the time period. The second, or ratio of the means, method divides the average of the numbers of individuals by the average of the volumes over which the samples are taken.

The method chosen for calculating the ratio can produce different results. From a statistical point of view, however, it is extremely difficult to say which is best. If the volumes sampled V_i are constant then both are the same, but if the volumes are different then one method will be better than the other. Which method that is depends both on the assumed distribution for the fish populations X_i and the parameters of that distribution, which may be difficult to determine. Likewise, if the flow rate into the power plant is assumed constant, the mean numbers entrained can be estimated from the mean concentration with no difficulty statistically.

When calculating the entrainment factors, which are ratios of concentration of fish, it is logical to use one method for calculating both mean concentrations since, although we may not be able to state exactly which method is better, it is better to choose one than to mix the two types.

One method of arriving at some realistic range for a sample estimate is to form a confidence interval. In doing this for *f* factors, difficulty arises because the variance of a ratio of numbers is usually very large and difficult to calculate. Indeed, estimates of the 95 percent confidence interval are so large as to be meaningless and thus discussions of confidence interval are totally inappropriate.

Finally, it must be recognized that all sample values include an error due to gear avoidance by the fish. Theoretically, for samples taken with the same gear, under identical conditions, ratios of the samples cancel out the effects of gear avoidance. Under normal conditions this is not the case. Gear avoidance changes with the type of gear, the swimming ability of the fish, illumination, and perhaps even the type of area sampled. Numbers upon which parameters are estimated and even the ratio contain biases covered by the effects of the sample method used. One method of estimating the effect is to calculate gear avoidance in the model as the discrepancy between model results and sampled data (S. Christensen, personal communication). This method, however, is sensitive to the model assumptions, which may have inherent errors resulting from use of sample data to estimate model parameters. It is, nevertheless, a first estimate. Field studies with gear types and observations of avoidance are also useful. Errors resulting from gear avoidance could be insignificant. The choice of gear for sampling, however, can give very different pictures of fish distribution, for example, just because of the effects of gear avoidance. Other problems in sampling can arise from clumped distributions, insignificant number of samples, and temporal variations in concentrations.

Parameters estimated for the models thus must be taken as broad estimates only, realizing the great number of errors that can arise from sampling and estimation techniques.

3.3.4 Comparison of Entrainment Values

It is probably meaningless to compare model by model each entrainment factor and its value, then attempt to justify which is better. In many cases the factors in the different models do not correspond to each other and the values are determined more by the method chosen for its computation than on whether that characteristic influences entrainment. Instead, comparison of the total entrainment factors *E* and *f* and their justification is more important. The entrainment factor has been incorrectly likened to a mortality rate. A mortality rate has dimensions 1/time and the entrainment factor is dimensionless. Nevertheless it has been found that PR is a nonlinear function of the entrainment factors (USNRC 1975). Thus, increases and decreases in the entrainment factor do not result in similar increases or decreases in PR. The shape of the curve and the region of most critical change depend on a variety of factors including egg production and compensation (see Section 3.5).

Since all investigators agree that the predicted entrainment is unlikely to be as high as that predicted by the withdrawal from a fixed volume method, one must now determine if the E value is less or greater than the critical value. Although the exact value of E or f can be endlessly debated as it indeed is, T.I. (1975) and Van Winkle (USNRC 1975) agree that for the Indian Point power plants E is probably > 0.5 although perhaps by not much. For all stages, especially the larval, the disagreement between the LMS and ORNL values is evident (Fig. 3.7 and Table 3.9). The Summit power plant models seem to agree that $E > 0.5$, although we did not have adequate information for computing E or f for most models. Individual f-factor values for Indian Point are given in USNRC (1975) and Lawler (1973) for the Summit plant in Christensen (1975) and Warsh (1975).

3.3.5 Recommendations

Focus should be drawn away from the discussion of the appropriateness of individual f factors and their values and instead directed toward a reasonable estimate of E, especially to determine if the value should lie above or below 1.0. Any value below 1.0 should be well justified and the effect on the PR of a range of values above and below the critical value should be presented. In the meantime attention of researchers should focus on the various characteristics suggested as important in determining the exact E values and the ways in which they could be included in such models. Ideally, the formulations should be general and based on experimentation as well as theory. Since the PR enters into the decision of whether the plant should be licensed, accurate prediction of E is necessary.

3.3.6 Impingement Predictions

The LMS and ORNL models include impingement losses to the older juvenile fish in PR estimates (J-II and J-III). The ONRL 1-D(73) approaches impingement as an extension of the entrainment method to the older age classes. As the juvenile fish grow and acquire swimming ability they are better able to resist entrainment in the intake flow; however, their swimming ability is dependent on the temperature. If the temperature is very low or very high then the fish cannot swim as well and are more susceptible to impingement (USNRC 1975). Likewise, if the salinity falls in a certain range the swimming ability is reduced and the fish are more susceptible to impingement (USNRC 1975). The temperature effect is based on physiological changes in the fish, but the salinity effects are included only to simulate the recorded rise in impingement when the salt wedge occurs in front of the plant intake. All juvenile fish that become impinged are assumed to die, so that f_3 is 1. The number of fish impinged can then be calculated as a linear function of the entrainment factor E

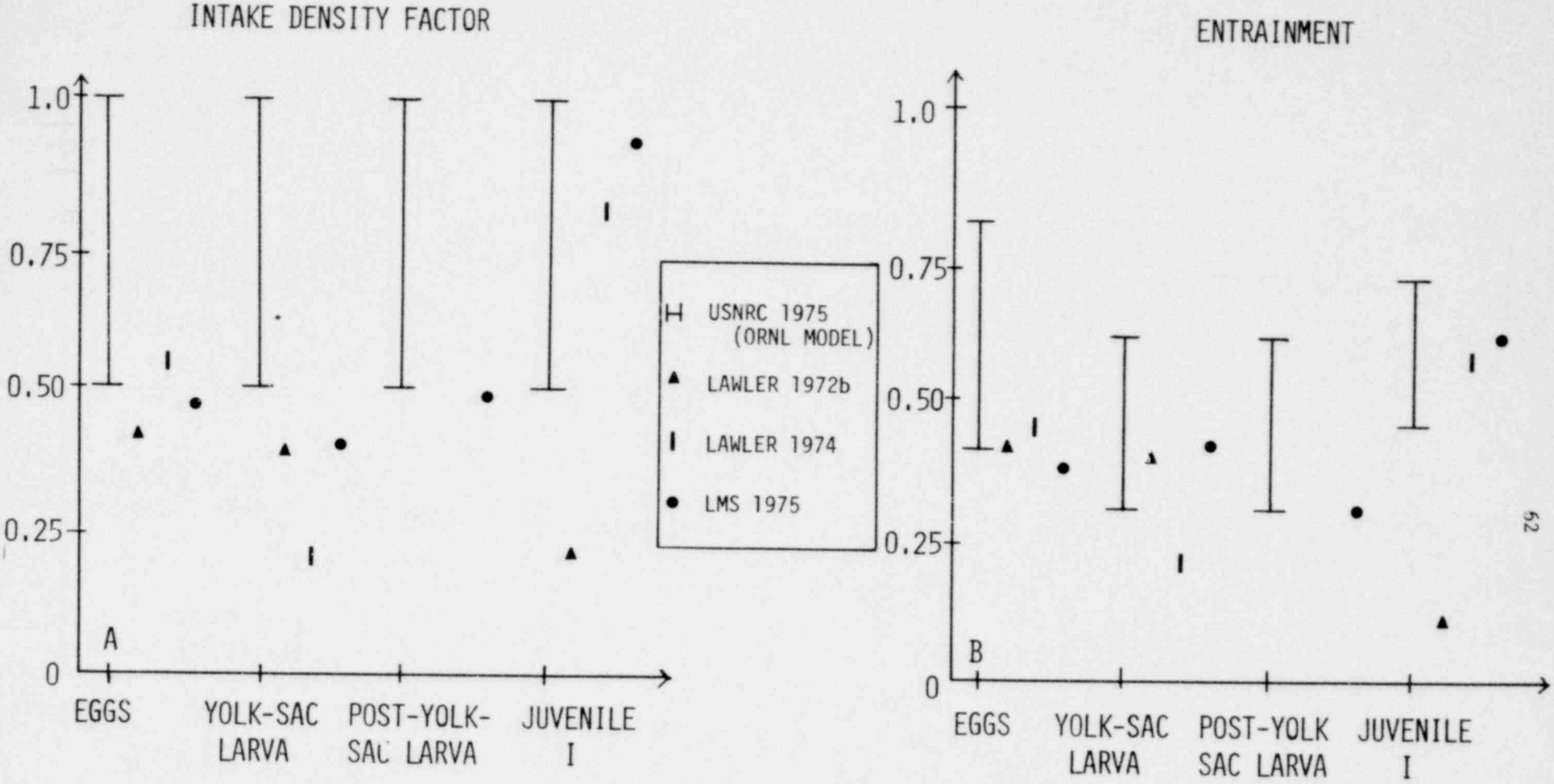

Fig. 3.7. Comparison of Indian Point intake density and entrainment factors.

Table 3.9. Entrainment factor values used in y-o-y models,
Indian Point

	Eggs			Yolk-sac larvae			Post-yolk-sac larvae			Juvenile-I		
Model	Min	Best est.	Max	Min	Best est.	Max	Min	Best est.	Max	Min	Best est.	Max
E intake density factor												
LMS completely mixed	0.5		1.	0.5		1.	0.5		1.	0.5		1.
LMS 1-D(67)	0.2	0.4	0.5	0.32	0.39	0.55	d		d	0.14	0.22	0.37
LMS 1-D(73)	0.55	0.55	0.55	0.20	0.21	0.21	d		d	0.76	0.81	0.87
LMS 2-D	0.45	0.45	0.47	0.31	0.40	0.50	0.43	0.54	0.54	0.76	0.78	1.17
ORNL 1-D	0.2	0.5	1.0	0.2	0.5	1.	0.2	0.5	1.	0.2	0.5	1.
f, total entrainment factor												
LMS completely mixed	0.5		1.	0.5		1.	0.5		1.	0.5		1.
LMS 1-D(67)	0.2	0.41	0.5	0.32	0.39	0.55	d		d	0.0	0.11	0.3
LMS 1-D(73)	0.44	0.44	0.44	0.12	0.13	0.13	d		d	0.53	0.57	0.61
LMS 2-D	0.36	0.36	0.38	0.24	0.24	0.30	0.30	0.32	0.32	0.55	0.55	0.82
ORNL 1-D	0.16	0.4	0.8	0.12	0.3	0.6	0.12	0.3	0.6	0.14	0.35	0.7

Table 3.9. Entrainment factor values used in y-o-y models. - Continued

E, *F*, intake density and total entrainment factor

			Post yolk sac
ORNL Summit	0.79	0.28 average[c]	d
Delmarva (modified)	b	b	b
JHU	0.98-0.87[a]	0.97-0.88	d

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[a] Estimated from Tables B-1 through B-15 in Warsh (1975).

[b] These values were not given.

[c] Values computed by two different methods.

[d] Post-yolk-sac larvae included with yolk-sac larvae in LMS 1-D models.

[e] ORNL summit values decrease with age of larvae.

and the plant flow rate, just as in entrainment. The LMS models remove a constant number of fish each day as the impingement loss to the juvenile fish. This number was calculated from measured impingement losses at Indian Point I (IP-I) and corrected for the larger flows expected at IP-II and IP-III. In the actual operation of the model, the removal is calculated from an *f* factor that has been calibrated with the number entering the J-II and J-III life stages. The *f* factors usually are less than 0.1 and have been reduced in the more recent LMS models.

3.4 Development of Y-O-Y Simulators

3.4.1 Rationale for Developing the Y-O-Y Simulator

A number of questions arose in our comparison of the y-o-y models which could not be answered from model documents alone: Is PR more sensitive in the cohort or dynamic pool survival formulation? Is PR insensitive to various model and sampling assumptions when d-i survival is assumed within the first year of life for fish? Is PR sensitive to the strength and timing of compensatory mortality? Is PR sensitive to changes in the size of the segments chosen in the physical stratification of the water body being modeled? Is PR sensitive to entrainment factors?

To answer the above questions, a y-o-y simulator was developed. Our main concern was PR sensitivity to changes in the survival and recruitment equations; thus, several simplifications were made. We feel these simplifications restrict our ability to "mimic" the results given in the models compared; however, it seems that we can reliably investigate the sensitivity of PR in such a simplified framework.

3.4.2 Structure of the Y-O-Y Simulator

A simplified 1-D physical transport mechanism was used in the y-o-y simulator. This transport mechanism is analogous to the migration equations used in the LMS 1-D(67) model for the juvenile age class (see Section 2.4). Basically, the transport operates 1) by input normalized* spatial distribution for each age class desired to be met by specified target dates based on sampling data (note: the input distributions can be changed between simulations with versus without plants operation); 2) during each time step of the simulation, transport of the proportion of individuals, within an age class and segment, which must move to an adjacent segment in order to meet the input distributions by target date. Operationally, the transport mechanism moves individuals in a manner consistent with the distributions found in a sampling program. We think this approach to transport provides an accurate alternative to the more

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*A distribution is normalized when each value of a data point is divided by the sum of all data points. The normalized distribution, then, has an area = 1 (e.g., a probability distribution).

complex and expensive hydrodynamic transport models (especially true for those hydrodynamic models that depend largely on correction factors, e.g., convective defect factors, Section 2.6, to reasonably replicate sampled distributions).

Thus far, the simulator has been used to compare the LMS 1-D and ORNL 1-D formulations for Hudson River striped bass. A 10-segment longitudinal stratification of the Hudson River (range 16-209 km) was used (Table 3.10). The QLM (now LMS) reduction of Texas Instruments (T.I. 1973a) data were used for input, target distributions, and egg production. The formulations were compared using only Indian Point I, II, and III plants operating with flow rates as given by Lawler (1974, Table 10). Daily time steps were used for all physical transport (including entrainment) and egg production input. Another approximation in our simulator was the reduction of the spawning season from 7 weeks (as indicated by T.I. data) to the approximate peak spawning season of 4 weeks (Table 3.11).

Survival equations used in the y-o-y simulator were either of the LMS cohort type (solved with daily time steps via a four-step Runge-Kutta method) or the ORNL dynamic pool type (solved with a 3-h time step, Euler technique). Age class durations and survival rates were identical to the values used by ORNL and LMS (Section 3.2) with the exception that the J-I stage duration is the LMS value.

The average cost, per simulated year run, for the y-o-y simulator has been quite low (less than $5). In comparison, some of the models compared (e.g., LMS 2-D) are expensive for yearly runs. The low cost has allowed us much flexibility in our analysis. A detailed documentation of the y-o-y simulator is in preparation.

3.5 Sensitivity Analysis and Simulation Study of Y-O-Y Models

The y-o-y simulator was employed in a simulation study of the LMS and ORNL survival and recruitment equations. Our major objective was to investigate the sensitivity of PR when parameters, equation forms, or total egg production were changed. The LMS and ORNL equations essentially cover the alternatives in modeling survival within the fish's first year of life: the important exception to the alternatives they have considered is the use of a spawner-recruit stock density-dependent relationship in conjunction with a density-independent y-o-y model (e.g., in the winter flounder model); LMS (1977) have also used such a spawner-recruit technique.

Sensitivity analysis in Sections 3.5.1, 3.5.2.1, 3.5.2.3, and 3.5.4 was conducted with entrainment as the sole source of power-plant-induced mortality. Parameter values for entrainment were based on *f*-factor values used by LMS 2-D (their Table 32; except averaged over depth) and the average daily fraction of water in the y-o-y simulator segment no. 7 (km point range 65-80) which is circulated through Indian Point plants 1, 2, and 3 (c.f. LMS 1-D(73), their Table 10); these entrainment values are

Table 3.10. Hudson River volumes of 10 segments used in the y-o-y simulator (Adapted from Lawler 1974, Table 4).

Segment number	Range (km)	Volume (10^4TCM)	Plants within segment
1	161-209	24.0106	
2	145-161	15.7354	
3	129-145	17.6251	
4	113-129	19.3707	
5	97-113	21.3640	Danskammer, Roseton
6	80- 97	22.4262	Cornwall
7	64- 80	23.9786	Lovett, Indian Point
8	48- 64	30.0881	Bowline
9	32-48	29.1856	
10	16-32	20.8653	

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Table 3.11. Comparison of fractional distribution of egg production from TI Data (Lawler 1974, Table 5) and peak distribution used in our simulator.

Calendar time	TI egg production	Peak approximation of egg production
April 30 - May 6	0.0016	
May 7-13	0.1826	0.1842
May 14-20	0.5108	0.5108
May 21-27	0.0594	0.0594
May 28 - June 3	0.2148	0.2456
June 4-10	0.0191	
June 11-17	0.0117	
Total	1.000	1.000

given in Table 3.12 (best estimate values). In Section 3.5.2.2, entrainment parameter values are based on *f*-factor values used by LMS 1-D (1973; their Tables 17, 18, 19) and are also given in Table 3.12.

Temporal and spatial distribution of egg production in all y-o-y simulator runs in based on Texas Instruments 1973 data given in LMS 1-D (1973; their Tables 5 and 6). Spatial and temporal distribution of y-o-y life stages in y-o-y simulator runs (in Sections 3.5.1, 3.5.2.1, 3.5.2.3, and 3.5.4) is based on T.I. (1973*a*) data. Spatial and temporal distribution of y-o-y life stages in Section 3.5.2.2 are similar to distributions from T.I. (1973*a*) data except for minor changes which arose from a miscalculation we made in the early stages of our simulation comparison. Section 3.5.2.2 results should not be compared to other sections' results, but the results are included because they illustrate some interesting phenomena about the compensation function.

For each sensitivity analysis, the parameters, equation form, or total egg production were changed (one at a time) from a "base case." The base case for the cohort and dynamic pool density-independent survival and recruitment equations use LMS 1-D (73) natural survival rates and life stage durations (Section 3.2) except for the following changes: the dynamic pool model separates the larvae stage into yolk-sac larvae and post yolk-sac larvae with durations used by ORNL 1-D and the duration of the egg stage is 2 days.

The base case for the density-dependent mortality functions in the cohort approach utilize LMS 1-D(73) equilibrium population levels, equilibrium mortality rates, and life stage durations except that the egg stage duration in most LMS runs is 1.5 days and mortality is high for eggs, a slightly lower surviving number of y-o-y is expected in our runs. We shall also see that the PR is higher in compensatory d-d survival equations when fewer individuals enter the larvae stage (such as by lengthening the egg stage duration to 2 days).

Table 3.13 compares the base case PR and surviving y-o-y from our y-o-y simulator with results given for the LMS 1-D(73) model. These results are not in complete agreement. We felt the y-o-y simulator was close enough for the sensitivity analyses, since: 1) the duration of the egg stage is changed; and 2) the LMS 1-D(73) runs do not agree completely with T.I. (1973<u>a</u>) sampled distributions, whereas the y-o-y simulator was constructed so as to agree closely with T.I. sampled distributions.

3.5.1 Sensitivity Analysis of the Cohort Approach versus the Dynamic Pool Approach Under the Assumptions of D-I Survival

In order to compare the cohort approach against the dynamic pool approach, the parameters of these two approaches should be functionally related. Unfortunately, the ORNL 1-D model bases survival for an individual in a life stage on its expected survival through the remaining time in a life stage, rather than survival per day as used in the cohort approach. This difference in survival interpretation motivated us to

Table 3.12. Entrainment values for Indian Point I, II, and III used in the y-o-y simulator.

	Life stage		
	Eggs	Larvae	J-I
f factor (average LMS 2-D values)	0.55	0.47	0.6
Daily fraction of fish in segment 7 entrained	0.026	0.022	0.028
f factor (LMS 1-D 1973 values)	0.44	0.13	0.57
Daily fraction of fish in segment 7 entrained	0.02	0.006	0.026

Table 3.13. Comparison of day 365 base number of y-o-y and PR for LMS 1-D(73) and our simulator.

	Egg production	No compensation $k_o = k_e$		Low compensation $k_o = 0.8k_e$		High compensation $k_o = 0.5k_e$	
		y-o-y number	PR	y-o-y number	PR	y-o-y number	PR
LMS 1-D(73)[1]	2.81275 x 10	-- not given --		667,202	2.95	670,324	1.643
y-o-y simulator	2.81275 x 10	617,338	16	594,199	7.71	628,570	3.85

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[1] Source - LMS (1975), Tables 30, 31, 32.

consider an alternative (but equally valid) representation for the dynamic pool approach. The survival and recruitment equation for this alternative representation is given by:

$$\Delta n_i = \underbrace{\hat{g}_{i-1}\hat{s}_{i-1}n_{i-1}}_{\substack{\text{i - 1st life-stage}\\ \text{survivors enter}\\ \text{ith life stage}}} - \underbrace{\hat{g}_i\hat{s}_i n_i}_{\substack{\text{ith life-stage}\\ \text{survivors leave}\\ \text{ith life stage}}} - \underbrace{(1 - s_i)n_i}_{\substack{\text{mortality for}\\ \text{ith life stage}}} \tag{3.14}$$

where $\hat{g}_i$ = proportion of individuals which transfer from life stage i to stage $i + 1$ per simulator time step; and $\hat{s}_i$ = survival proportion for individuals in life stage i (per simulator time step).

The ORNL 1-D assumption that organisms within each life stage are uniformly distributed by age is also employed in the simulator. Thus $\hat{g}_i$ is the inverse duration of the ith life stage (duration is in the number of simulator time steps). The survival term $\hat{s}_i$ is related to m_i, the mortality rate (per simulator time step Δt) in the cohort approach, by $\hat{s}_i = \exp(-m_i\Delta t)$.

Table 3.14 gives the y-o-y simulator results from a comparison of the cohort versus dynamic pool approach for different d-i mortality rates. The cohort approach is virtually insensitive to changes in mortality rates. The dynamic pool approach, however, gave higher and more variable PR than the cohort approach. Both approaches are virtually insensitive to the value of total egg production input to the models.

The sensitivity of the dynamic pool approach is not surprising. A change in the survival proportion generally induces a skew in the age distribution of organisms within any life stage. Thus the ORNL 1-D assumption of uniform age distribution is violated and individuals age to the next life stage faster (or slower) than they are supposed to. Since the entrainment probability is different for each life stage, changing the time an individual spends in a life stage generally changes the PR. It seems clear that the PR from the dynamic pool approach is sensitive to survival estimates.

To further investigate the dynamic pool approach, another simulation study was conducted. Here we look at the sensitivity of PR when the river segment size is changed. The purpose of these simulations was primarily to illustrate the change in age distribution by life stage and segment when the segment size is altered; however, we are not totally satisfied with the technique we have used to change river segment sizes.

The technique used to reduce our 10-segment simulator to a 5-segment simulator is as follows: pairwise group the adjacent segments in the 10-segment simulator, thus getting five segments; compute the number of

Table 3.14. Cohort versus dynamic pool approach with density-independent survival.

Approach	Multiples of "base" egg production	Survival parameter	PR range
Cohort	0.1, 1., 10.	"base"	16.0
Cohort	0.5, 1., 2., 5., 10.	1.5 * "base mortality rate"	16.0-16.10
Cohort	1.	0.75 * "base mortality rate"	15.9
Dynamic pool	0.5, 0.8,1., 2., 3., 10	"base"	19.5
Dynamic pool	1.	(a)	21.8

[a] Survival parameters for life stages egg,..., J III are, respectively, 0.9328, 0.9913, 0.9986, 0.9998, 0.9999, 0.9999.

individuals that will age out of a life stage in each of the five segments; and remove half of these aged individuals from each of the paired segments in the 10-segment model. This technique unfortunately caused errors in the predicted physical distributions and in entrainment probabilities, and this analysis is a first-approximation. In the future we should like to modify our technique to the computation of growth rates per individual for a better comparison of sensitivity of PR to segment size.

Table 3.15 presents these simulation results. Here we see that the PR has reduced substantially from the 10-segment model and that PR is also sensitive to survival estimates. The cohort approach is insensitive to number of segments for the d-i survival case.

Since the dynamic pool approach for d-i survival has much higher PR sensitivity to survival estimates than the cohort approach, the cohort approach is preferred for modeling survival and recruitment.

3.5.2 Sensitivity Analysis of D-D Mortality Functions, LMS Function versus ORNL Function, in the Cohort Approach

The simulation study in Section 3.5.1 shows that PR predictions based on the cohort approach differ from PR predictions based on the dynamic-pool approach and the dynamic-pool approach is more sensitive to survival estimates. The cohort approach was chosen as a framework for a further simulation study of the different compensatory mortality functions (used by models reviewed); and the difficulty in comparing cohort approach results to dynamic-pool approach results is avoided.

A main objective of this sensitivity study was the comparison of PR predictions from the LMS cubic survival function (Section 3.2.1.2) and the ORNL linear survival function (Section 3.2.1.3). The ORNL linear survival function requires estimates of the density of fish above which compensation takes place. To simplify our simulations, we chose values of zero for the ORNL minimum density estimates (this survival equation is due to Beverton and Holt 1957, B-H). This allowed us to construct a B-H linear survival function which has parameter controls similar to the LMS cubic survival function; that is, the linear survival function uses the mortality term

$$m_i = k_{e,i} + (k_{e,i} - k_{e,i}) \left(\frac{n_i - n_{e,i}}{n_{e,i}} \right) \tag{3.15}$$

Parameter values and a figure with the two mortality functions are given in Section 3.5.2.2.

Table 3.15. Dynamic pool approach with different size of river segments.

Number of river segments	Multiples of "base" egg production	Survival parameter	PR range
5	0.1, 1., 10.	"base"	13.1-13.2
5	0.1, 1., 10.	(a)	14.8
10	0.5, 1., 10.	"base"	19.5
10	1.	(a)	21.8

[a] Given in Table 3.14.

3.5.2.1 Effect on PR on Varying the Strength $(k_{o,i}/k_{e,i})$ of Density Independence in the Mortality Functions. The strength $(k_{o,i}/k_{e,i})$ of density independence was given values of 0.5, 0.8, and 1. Thus $k_o/k_e = 1$ implies d-i mortality, whereas $k_o/k_e = 0.5$ implies highly compensatory d-d. Table 3.16 gives the results of this simulation study.

There are a number of observations that can be made about this Table 3.16. These are:

1. PR decreases as egg production increases, for both the LMS and B-H compensatory survival functions.

2. PR is slightly lower with the B-H survival function (when $k_o = 0.5\ k_e$).

3. PR is slightly lower with the LMS survival function (when $k_o = 0.8\ k_e$).

4. PR is considerably less in all compensatory survival simulations than the PR from a d-i run (where PR = 16 and $k_o = k_e$) at base egg production.

5. PR increases as the ratio k_o/k_e increases ($k_o \leq k_e$).

The basic conclusion in this section is that PR apparently is very sensitive to changes in egg production values, as well as to the strength of d-d in these equations. It seems clear that the sensitivity of PR to egg production is common to any y-o-y model with a compensatory mortality function.

3.5.2.2 PR Effect of Changing the Minimum Density Value of Organisms for which D-D Survival is Assumed to Occur. In Section 3.2.3 we discussed the fact that if the ORNL minimum density value for the occurrence of compensation is larger than densities of fish in the y-o-y model, then the PR would equal the PR from a d-i survival model. Thus our simulation of the LMS cubic survival model with differing cutoff densities would have PR values from 3.8 to 16.0 (in the $k_o = 0.5\ k_e$ case) depending on the minimum density value.

It seemed clear to us that the PR decreases as the minimum density value decreases in compensatory survival y-o-y models, however the decrease in PR may not be significant for moderate changes in the minimum density value if average densities are quite high. To illustrate this a simulation study was performed.

Our main goals in the simulation study here are twofold: to illustrate the effect of clumping of organisms on PR and to illustrate that the sensitivity of PR to moderate changes in the minimum density values depends on the values of average fish densities in the model.

We have mentioned (Section 3.5) that entrainment probabilities and physical distribution were modified from "base" values for these runs.

Table 3.16. Comparison of PR sensitivity to the value of k_o/k_e (the term k_o and egg production value are the only terms varied from "base" conditions).

Multiples of "base" egg production value	PR with LMS cubic function ($k_o = 0.5k_e$)	PR with B-H linear function ($k_o = 0.5k_e$)	PR with LMS cubic function ($k_o = 0.8k_e$)	PR with B-H linear function ($k_o = 0.8k_e$)	PR with d-i function ($k_o = k_e$)
0.01	12.7				
0.05	9.4		13.8		
0.1	9.1		13.0		
0.5	7.8	4.1	13.0	10.13	
1.0	3.8	3.3	7.7	8.23	16.0
1.5		2.9			
5.0	2.6	2.0	4.2	5.24	

Actually, the modification of predicted distributions was accidental; however, this modification increased the "clumping" of fish into higher densities and into fewer physical segments (for juvenile life stages only).

This simulation study was conducted with the LMS cubic survival function. The minimum density was given values of $0, n_s$ (the equilibrium density), and a very large value (above the range of densities in the simulator). The results of this study are given in Table 3.17.

There are a number of observations that can be made about Table 3.17. These are:

1. At very low egg production values (multiples ≤ 0.10), survival is essentially d-i in all runs, thus changes in minimum density values have only a minor PR sensitivity.

2. At egg production values (multiples $\simeq 0.5$) where fish densities fluctuate around the minimum density values (near n_s), the PR is very sensitive to changes in the minimum density value. For example, PR goes from 3.0 to 0.68 (in the $k_o = 0.5\ k_e$, multiple = 0.5 case) when the minimum density goes from n_s to 0.

3. At larger egg production values (multiples ≥ 1) where most fish densities lie above minimum density values, PR is not very sensitive to moderate changes in minimum density values providing the minimum density is less than .

4. At the "base" egg production value, the reduction in PR due to compensatory mortality seems to be enhanced when fish densities are highly clumped. For example, here the PR is reduced an order of magnitude in the $k_o = 0.5\ k_e$ case (as compared with $k_o = k_e$ case--the no compensation case in Table 3.17), whereas the reduction in PR using "base" values is much less ($k_o = 0.5\ k_e$) compared with the $k_o = k_e$ (<u>see</u> Table 3.16). Notice that clumping has the general effect of reducing PR in this simulator.

The basic conclusion in this section is that PR is sensitive to the amount of clumping in physical distributions of fish and to the minimum density value (for values near average fish densities).

3.5.2.3 <u>PR Effect of Changing the Size of River Segments over which D-D is computed</u>. Survival in the LMS and ORNL y-o-y models is segment specific; that is, d-d in survival of fish in a river segment depends on the density of fishes in this river segment alone. Compensatory survival, however, implies that mortality is highest for river segments with the highest densities. It seemed to us that by enlarging the river segments, the highest densities, occurring more predominantly in the case with plant operation, would be lowered, thus reducing compensation and increasing PR. To examine this hypothesis, a simulation study was conducted.

The technique used in this simulation study of PR sensitivity to river segment size is as follows: Group the 10 physical segments (in our

Table 3.17. Comparison of PR values in our simulation of the LMS cubic survival y-o-y model with different strengths of compensation and with different minimum density values for the occurrence of compensation.

Multiples of "base" egg production value	PR with minimum density value = 0		PR with minimum density values = n_s		PR with minimum density values = do (no compensation)
	$k_o = 0.5k_e$	$k_o = 0.8k_e$	$k_o = 0.5k_e$	$k_o = 0.8k_e$	
0.1	4.6	5.9	6.9	6.9	6.9
0.5	0.68	2.58	3.0	4.5	6.9
1.0	0.60	0.78	0.77	0.85	6.9
5.0	0.45	0.71		0.89	6.9

simulation) in pairs, compute the average density in the paired segments, and use this average density value (only) for the computation of mortality rate for fishes in each of the paired segments. Thus the d-d mortality is computed as though the model segment sizes were doubled yet entrainment probabilities and predicted physical distributions are not altered. Table 3.18 gives the results of this study.

A number of observations can be made from a comparison of Table 3.18 with Table 3.16. They are:

1. The PR is increased as the size of the river segments is increased.

2. The PR is lower for the B-H survival equation (versus the LMS survival function) when $k_o = 0.8k_e$, at base egg production in the five-segment model. This is a reversal of the PR sensitivity from the 10-segment model.

3. The PR is lower for the LMS survival equation (versus the B-H equation when $k_o = 0.5\ k_e$, at base egg production in the five-segment model. This is a reversal of the PR sensitivity from the 10-segment model.

The conclusions from this study are that the PR is reduced if the river is stratified into more segments (for compensatory survival y-o-y models) and the LMS survival function has higher (or lower) PR values than the B-H survival function--depending on whether $k_{o,i}/k_{e,i}$ is large (or small) and on the number of segments into which the river is stratified.

3.5.2.4 PR Effect of Changing the Life Stage(s) for which D-D Mortality operates. In Section 3.2.3, we discussed evidence from empirical studies on striped bass (Chadwick et al. 1977); this study (as well as other studies) suggests that compensatory survival within the y-o-y is restricted to the first 2 or 3 months of life. We also mentioned that the LMS model showed high PR sensitivity to changes in the number of life stages over which compensation operates.

To examine the PR sensitivity to changes in the timing of compensation, a simulation study was conducted; we chose the ($k_o = 0.5\ k_e$) LMS cubic survival model to demonstrate this. Table 3.19 gives the results of this study.

We can make the following observations about Table 3.19:

1. The PR is very sensitive to main changes in the life stages for which compensation occurs. For example, at base egg production the PR goes from 4.4 to 9.1 for d-d in J-I, J-II and J-III stages versus d-d in larvae and J-I stages only.

2. The PR is much higher for the case having compensation only in the first 2 months of life for a fish than the PR value for compensation during the entire first year of life.

Table 3.18 . PR values in (compensatory survival) y-o-y simulations for density-dependence computed from average densities of adjacent segments (taken in pairs). This is a five-segment model for survival calculations.

Multiples of "base" egg production	PR with LMS cubic function		PR with B-H linear survival function	
	$k_o = 0.5k_e$	$k_o = 0.8k_e$	$k_o = 0.5k_e$	$k_o = 0.8k_e$
0.8	10.0			
1.0	7.9	13.1	9.0	9.47
1.2	6.11			
1.4	5.06			
1.6	4.52			
2.0	4.0			

Table 3.19. PR values for density-dependent survival operating in different life stages; LMS cubic y-o-y model is used ($k_o = 0.5k_e$).

Multiples of "base" egg production	PR with density-dependence in larvae and J-I stages only	PR with density-dependence in J-I, J-II, J-III stages only	PR with density-dependence in all y-o-y stages (except egg stages)
0.5	12.7	10.2	7.9
0.8	10.2	6.1	
1.0	9.1	4.4	3.9
1.5	8.3	3.0	3.3
3.0	7.5	2.0	2.7

3. The difference in PR is very small in the comparison of the case having d-d for J-I, J-II, J-III with the case having d-d for larvae, J-I, J-II, J-III. Thus, the elimination of d-d in the larvae stage made little difference in the PR value.

Another variation in the timing of compensation can occur by differences in life-stage durations. In Section 3.2.3 we discussed the fact that the ORNL y-o-y model had a J-I duration 10 days longer than the LMS y-o-y model.

We decided to perform a single-run sensitivity study to see the difference in PR values for the dynamic pool survival model when the LMS J-I duration was increased by 10 days: The PR increased from 21.8 to 23.5 by increasing the J-I duration (survival parameters are given in the footnote of Table 3.14).

The conclusion from this section is that PR is very sensitive to major changes in the life stage(s) for which compensation occurs.

3.5.3 Sensitivity Analysis of Entrainment Factors

Entrainment and impingement losses are considered critical to fish populations. In these simulation studies the relationships between the magnitude of the entrainment factors, the amount of egg production, and the level of compensation are examined in terms of the PR in the y-o-y population. Entrainment and impingement factors are incremented in steps of 0.2 (0.02) over the range of 0 to 1 (0 to 0.1), respectively, and are considered equal for all age classes. Egg numbers are represented as some proportion of the original or normal egg production (eggs = 1). Finally, compensation is represented by no compensation ($k_e/k_c = 1$), low compensation ($k_e/k_o = 0.8$) and high compensation (k_e/k_o 0.5). For clarity the results are presented as graphs. Entrainment occurs only for the first three age classes (egg, larvae, J-I) and impingement occurs in the last two age classes (J-II and J-III).

3.5.3.1 Equal Entrainment for All Age Classes. One series of simulations looked at the response to different levels of entrainment of all entrainable life stages (eggs, larvae, and J-I) for a wide variety of egg productions and for the three levels of compensation mentioned above.

For the wide range of conditions examined in the simulations, the curves of entrainment fraction versus PR and compensation are similar in form for all values of egg production. Most notable are the differences in the amount of reduction in PR caused by compensation. The most dramatic decrease in PR is for the highest level of entrainment (1) and the highest level of egg production (eggs = 2). The greatest reduction occurs when compensatory effects are included. The PR decreases as the entrainment fraction decreases and the effect of compensation is reduced at low entrainment levels. As the egg numbers decrease below the normal egg production level the reduction in PR with increased compensation is less than at higher egg productions. Compensation is an important factor in reducing the expected PR at all levels of egg production. Low compensation is most effective at reducing the PR at high egg numbers (eggs = 2), while high compensation is necessary to achieve the same low PR values at low egg numbers (eggs = 0.5).

The relationship between compensation and egg number at various entrainment levels is clearly illustrated in Fig. 3.8A-B. At low compensation the curves look very similar to those above. As egg numbers increase the PR decreases for all levels of the entrainment fraction; the PR values still remain fairly high. For high compensation, however, a dramatic reduction in PR is predicted as egg numbers approach normal or above-normal levels. Even for high compensation, the simulation predicts very high PR for lower-than-normal egg production (eggs = 0.5).

In all cases the reduction in PR as the entrainment fraction decreases is nearly linear. For some cases where the PR values are high the curve shows a slight bowed shape with a steeper increase over the lower entrainment fractions, dropping off as the entrainment fraction increases.

3.5.3.2 Entrainment of Single Age Classes. It is possible, because of the siting of the power plants or the distribution and behavior of the fish, that only certain age classes are entrained. The PR in the fish measured at the end of the year depends on the life stage at which entrainment losses occur, the length of that life stage, the level of compensation, and the level of entrainment (the factor). All these simulations are for normal egg production. The graphs for the three life stages have similar forms as those described previously, although the values of PR are much smaller. The very low levels of PR (Fig. 3.9) even for the highest levels of entrainment probably can be accounted for by the short length of the egg stage (3 days) and the long period of time after entrainment, during which compensation occurs. The further dramatic reduction in PR resulting from addition of compensation demonstrates the ability of compensation in reducing PR especially when that compensation acts over long time periods.

The PR predicted for entrainment of the larval stage is larger than that for the egg stage, probably in part because of the longer length (28 days). Once again compensation causes a dramatic reduction of PR almost to zero. The J-I stage, which is the longest of the three entrainable life stages, has the largest predicted PR once again in part because of the length of the life stage (128 days). Compensation has much less effect on reducing the PR for the J-I stage than for the previous stage. In fact the entrainment curve (Fig. 3.9C) for the J-I stage looks very similar to that predicted for entrainment of all three life stages together. This suggests that the J-I stage is the most critical in terms of the reduction in y-o-y caused by entrainment.

3.5.3.3 Impingement. The simulation studies for impingement were done in the same way as those for the entrainment given above. The impingement fractions are considered to be very small and thus are given as 0.1 of the corresponding entrainment fractions. Impingement

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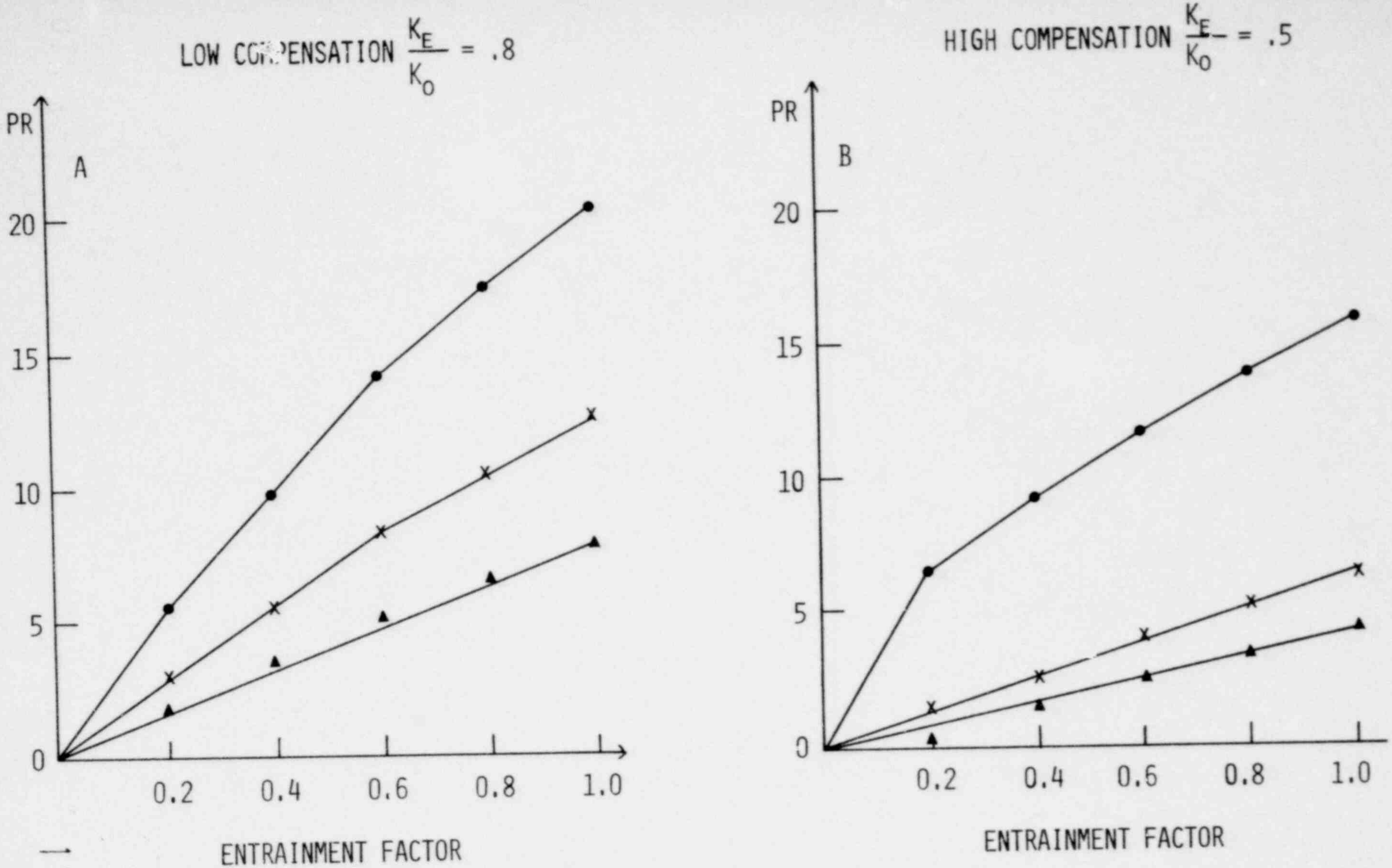

Fig. 3.8. Effect of entrainment factors on PR for low compensation (K_e/K_o = 0.8) and high compensation (K_e/K_o = 0.5) relative to equilibrium egg production.

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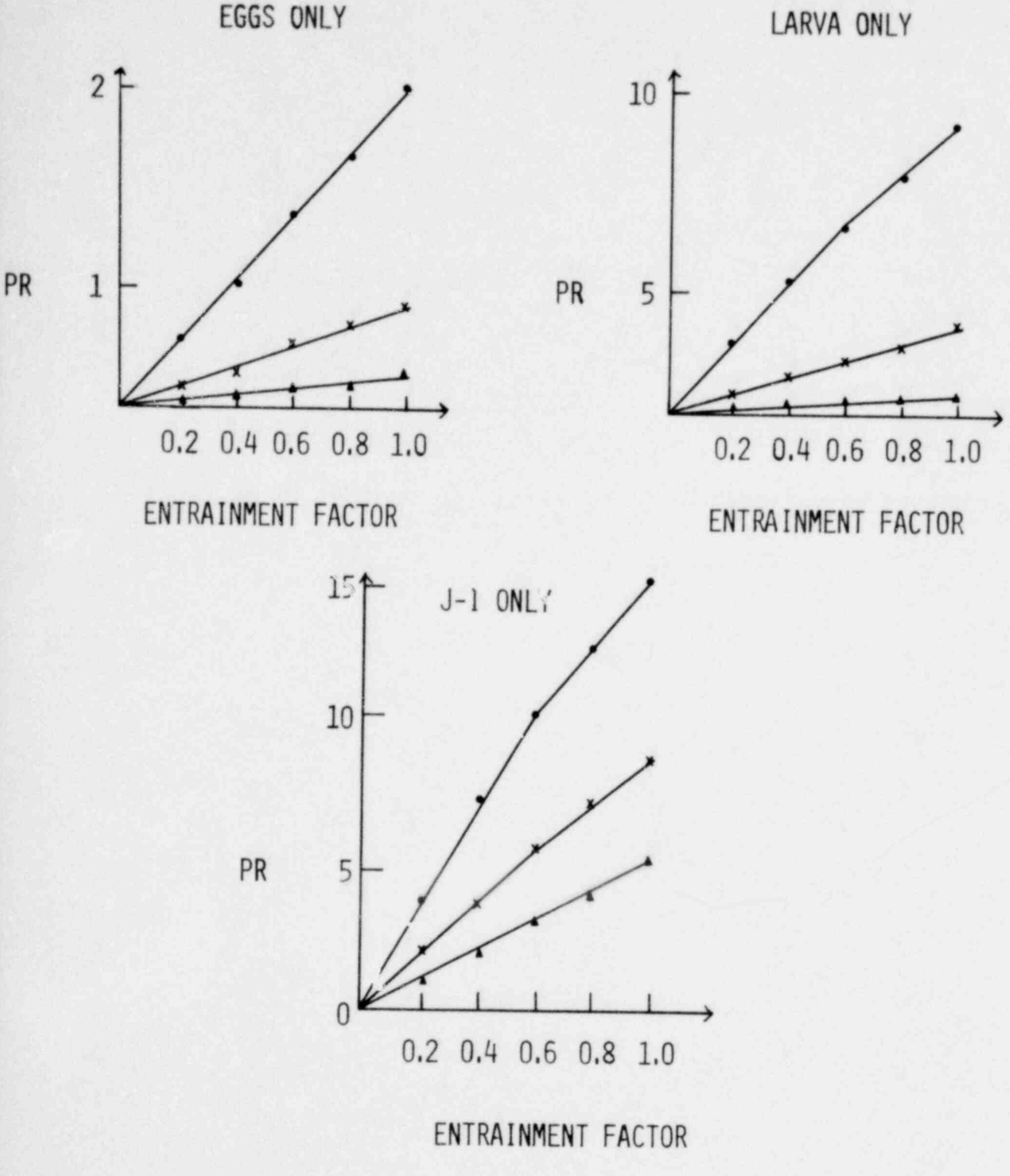

Fig. 3.9. Effect on PR of having entrainment in only a single life stage; eggs = 1.0; no CM - •; low CM - χ, high CM - ▲.

simulations were run for various levels of compensation and for various egg numbers. Once again the curves have the same shapes as those for entrainment (Fig. 3.10A-C). Compensation even at high levels, however, has a much smaller effect than for entrainment, although the maximum PR for impingement is less than the maximum value for comparable entrainment cases. Interaction of eggs and compensation is the same as that shown for entrainment. Juvenile 2 impingement causes the greatest PR of the y-o-y. With no compensation most of the PR comes from impingement of the J-II, but as compensation increases more PR comes from impingement of the J-III life stage. Interestingly, compensation has a slight reverse effect on the predicted PR for J-III. The PR actually increases as compensation increases. Compensation has very little effect on reducing the PR for impingement of J-II or J-III (Fig. 3.11A-B).

3.5.3.4 Entrainment and Impingement of All Age Classes. In many cases all age classes of y-o-y fish are subjected to some level of entrainment or impingement. The entrainment and impingement values used are the same as those given above. Remember that the ranges of impingement values considered are 0.1 of the entrainment fractions. Simulations were done for various entrainment fractions, various levels of compensation, and various values for egg production. The curves produced from the simulations (Fig. 3.12) are similar to those for entrainment as are the relationships between egg number, compensation, and entrainment.

The results of the simulation studies on entrainment and impingement indicate a few basic behaviors of the model: (1) compensation is most effective in reducing the PR if egg numbers are higher than normal. (2) The longer compensation has to act after entrainment has occurred the greater the reduction in PR. (3) Juvenile-1 and -2 are the critical life stages for determining the losses due to entrainment and impingement.

3.5.4 Sensitivity Analysis of Migration with D-I Mortality Functions, Passive versus Nonpassive Movement

In section 3.4, we discussed the fact that, in the y-o-y simulator, physical movement of fish is based on "predicted" sampled distributions of fish. Migratory behavior is implicitly contained in this approach to modeling physical movement. In addition, the ability of fish to swim to the "predicted" distributions can be modeled with this approach.

Migratory ability of fish is quantified by the following technique: Run the simulator for the case of power plants not operating for each segment, life stage, and time step in the model; and store the fraction of fish that migrate to another segment (define this as the "stored physical movement"). There are similar physical movements for the case of power plants operating (i.e., potential physical movements) and they are used for modeling fish that have a well-developed ability to migrate. Define the relationship

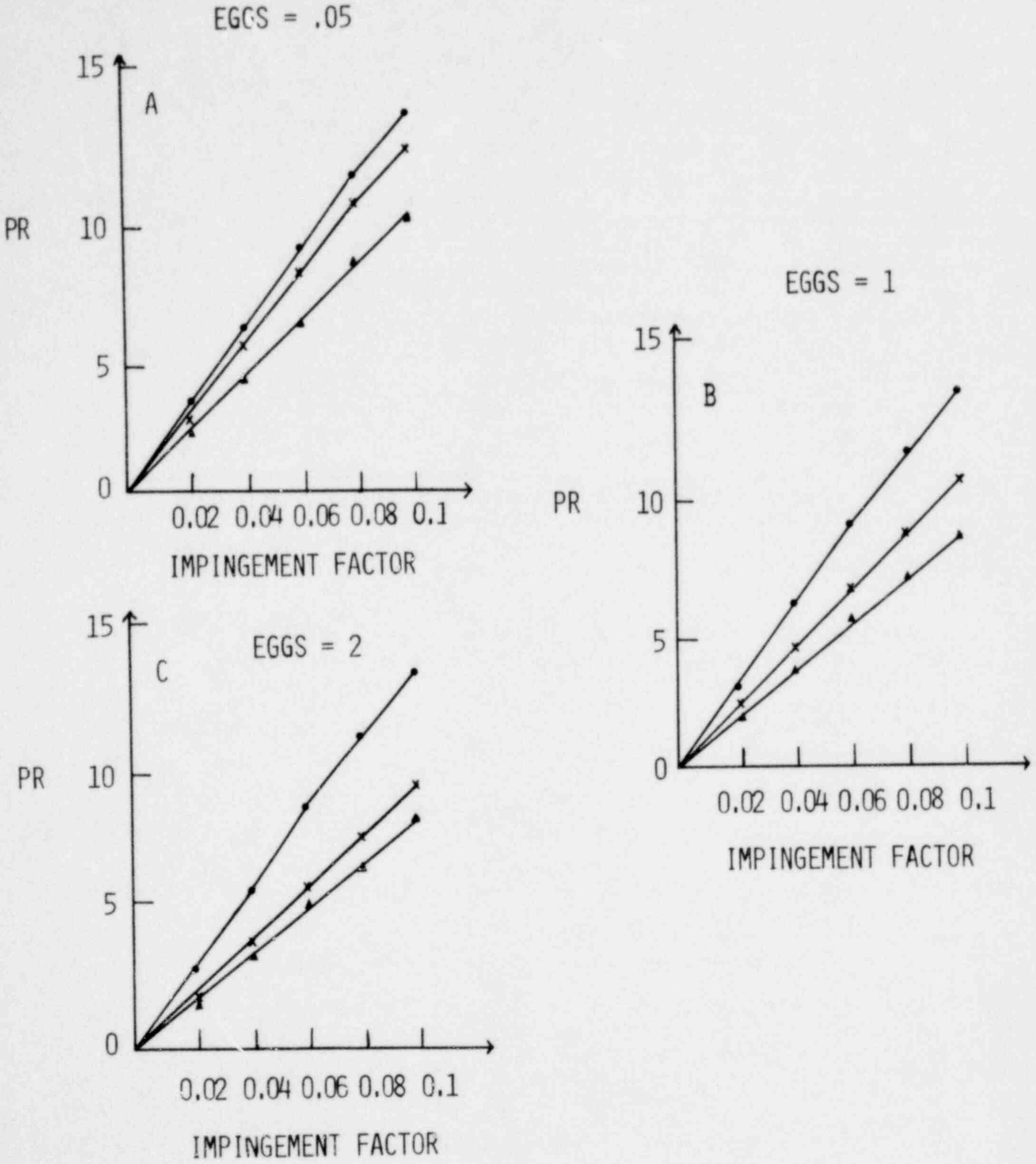

Fig. 3.10. Effect on PR of impingement of juveniles; no CM - •; low CM - χ; high CM - ▲.

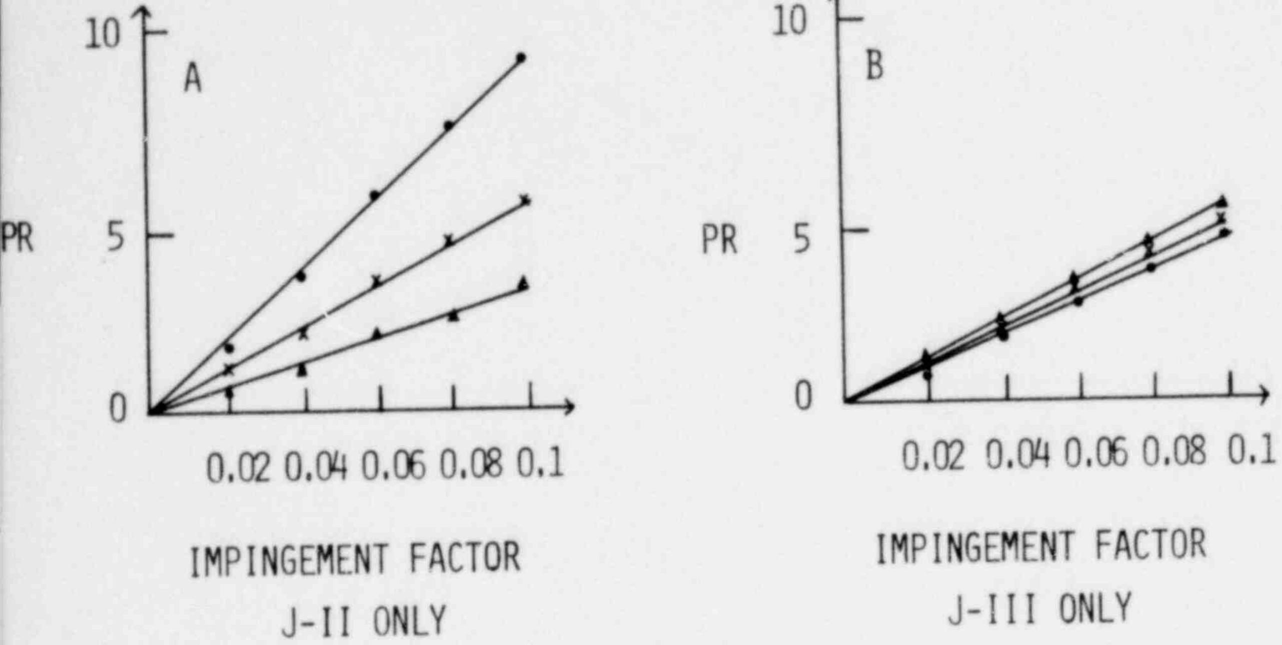

Fig. 3.11. Effect on PR of impingement of only a single life stage; eggs = 1.8; no CM - •; low CM - x; high CM - ▲.

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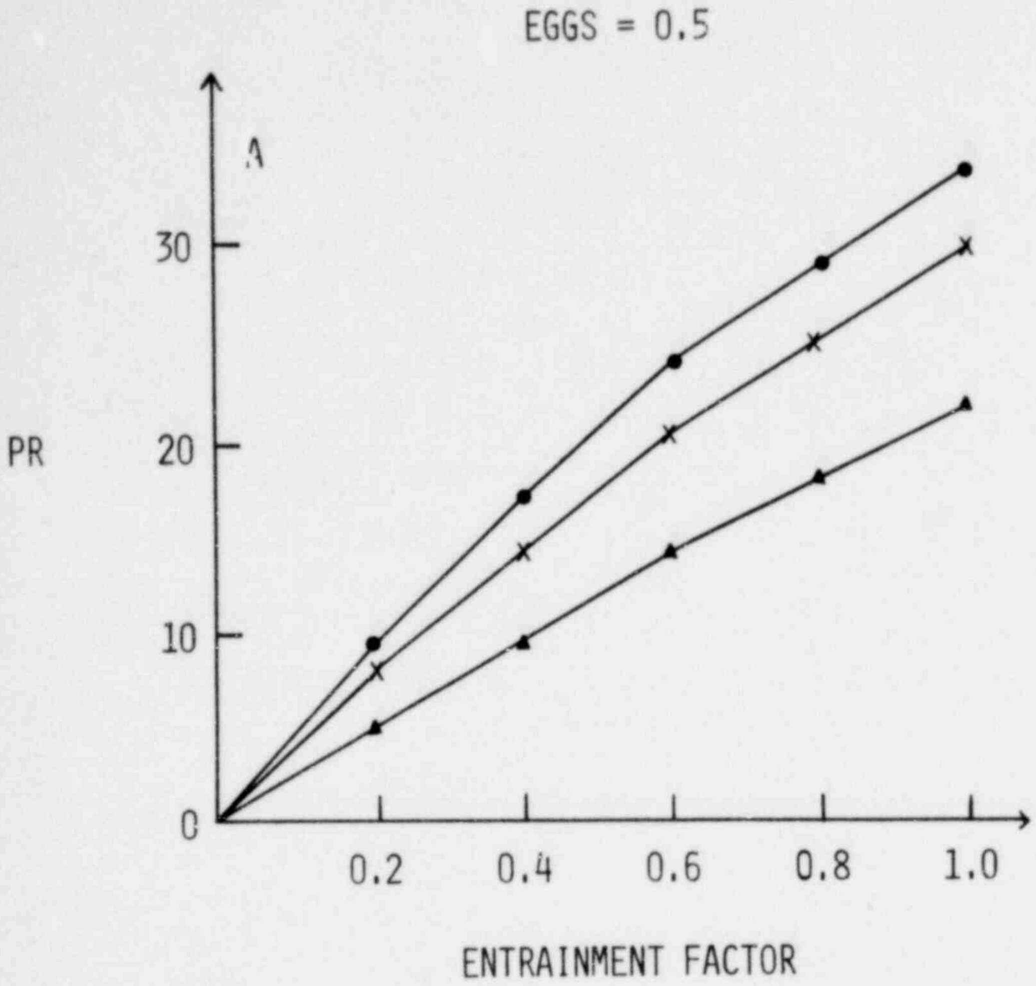

Fig. 3.12. Effect of both entrainment and impingement (impingement factor = 0.1 x entrainment factor) and compensation on PR for A) eggs = 0.5 B) eggs = 1.0 and C) eggs = 2.0 times equilibrium egg production; •- no compensation, X - moderate compensation, ▲ - high compensation.

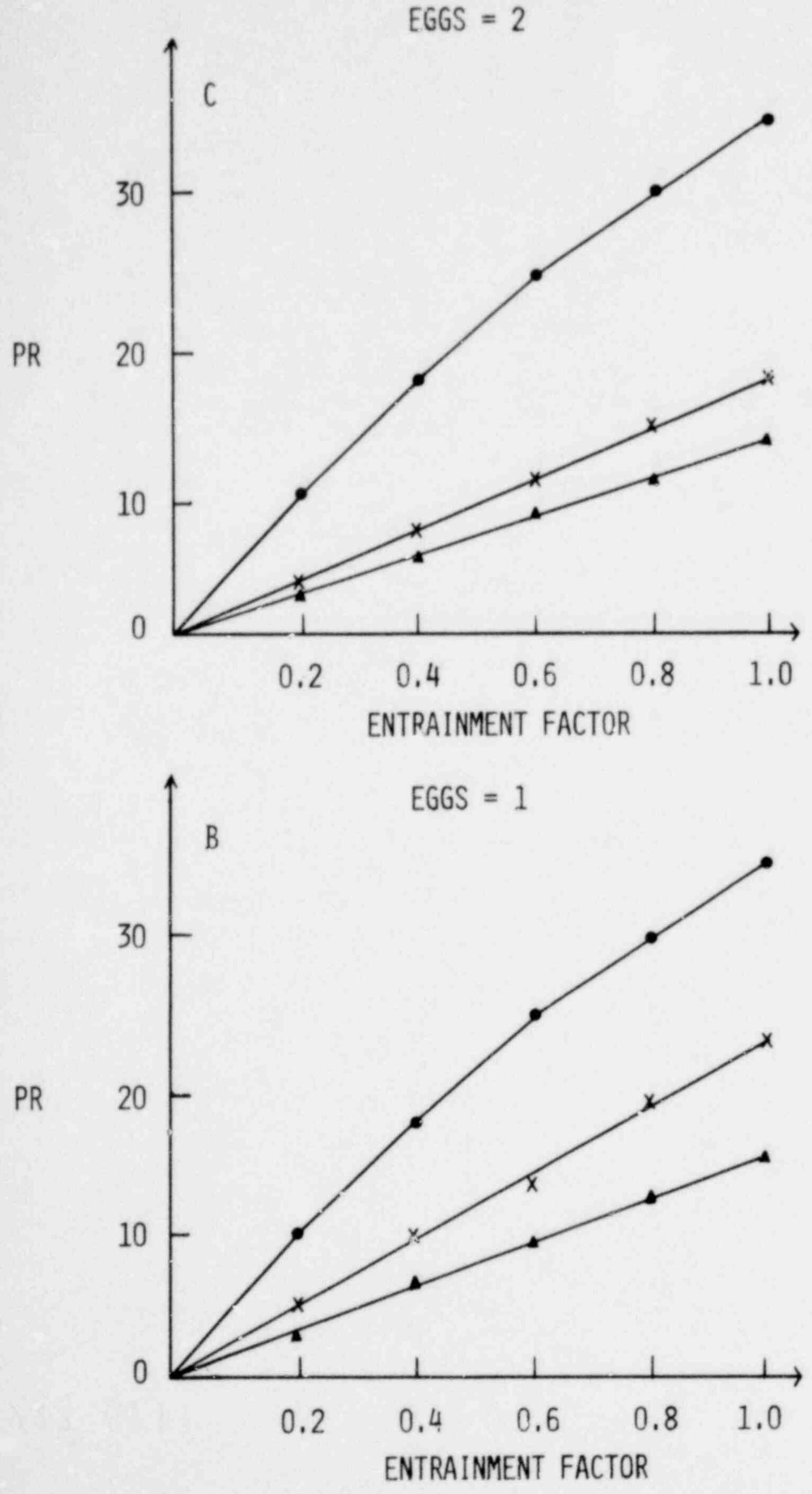

Fig. 3.12. Effect of both entrainment and impingement (impingement factor = 0.1 x entrainment factor) and compensation on PR for A) eggs = 0.5; B) eggs = 1.0 and C) eggs = 2.0 times equilibrium egg production; • - no CM; x - low CM; Δ - high CM. - Continued.

$$\text{actual movement} = \alpha\,(\text{stored physical movement}) + (1 - \alpha)\,(\text{potential physical movement}) \qquad (3.16)$$

For runs with the power plant operating, input an α value and use the "actual movement" to compute the fraction of fish that migrate to another segment.

The rationale for the technique is as follows: If fish are passive movers (i.e., they have little ability to control their location), then the "predicted" distributions are interpreted as distributions caused by hydrodynamic forces and α = 1 (these fish do not correct or change their movement when the power plant is operating. If fish are highly mobile, then the "predicted" distributions are interpreted as distributions caused by the fishes' preference for that distribution and α = 0 (these fish move toward their "predicted" distributions even with the power plant operating). For fish partly passive, partly mobile, α takes on a value between 0 and 1. The α values used in y-o-y simulator runs for Section 3.5.1 are = 1 for eggs and larvae, α = 0.5 for J-I and α = 0 for J-II and J-III.

We are only beginning to investigate the effect of migratory ability on the PR value. We found that the PR value (PR = 16) from the "base" case d-i cohort model was increased to a PR value of 17.7 by changing all values to 0; that is, high migratory ability increased the PR. The increase in PR can be explained by an increased migration of fish to the location of the power plant. Because of local depletion of fish in this area by the power plant, fish increase their migration into the area in an attempt to reach the "predicted" distribution value for this segment.

A basic conclusion can be inferred from this section: If fish are mobile, a portion of these fish prefer to be located near the power plant. If these fish are entrainable (or impingeable), then the PR is higher than the PR from passively moving fish (if susceptibility to entrainment and impingement remain the same in both cases).

4.0 MODELS TRANSLATING ENTRAINMENT LOSS INTO AN IMPACT FISH POPULATION

4.1 Introduction

All the models reviewed translated a predicted loss in y-o-y fish due to plant operation (PR) into a loss in adult populations, in recruitment to adults, or in fishery yield. These computations varied in complexity. All eight models reviewed used one or more of the following three methods:

1. Translate local entrainment loss into fishery loss by estimating fraction of fish contributed by the impacted stock available to various fisheries concerned.

2. Use the results from a y-o-y impact model as a direct prediction of loss in recruits to adult populations.

3. Use a life-cycle model of the Leslie matrix type (Leslie 1945) to translate estimated y-o-y entrainment loss into yield loss to the fishery, long-term reduction in adult populations, or both.

The ORNL 1-D model (Van Winkle et al. 1974) used method 3), and the LMS models reviewed (Lawler 1972a and 1972b, LMS 1975) all used methods 2) and 3), running their y-o-y model together with a life-cycle model to give long-term impact predictions. The URI model (Sissenwine et al. 1974, Saila 1976) used approach 3), modifying a Leslie type model with a Ricker spawner-recruit model (Ricker 1954). The ORNL Summit model (Christensen et al. 1975) used 1) and 3), together with the ONRL life-cycle model to translate entrainment loss into yield reduction, then modified the loss by factors for the relative contribution of entrained stock to various Atlantic Coast fisheries. The JHU model (Portner 1975) used approach 1), converting an entrainment loss to a fishery yield loss for various fisheries. The Delmarva model (Delmarva 1974) used method 2).

Our review of these impact calculations involved the following procedures: 1) Compare the models in general. 2) Compare the model equations and the biological assumptions upon which they are based. 3) Compare the parameter values and data sources used to estimate them. 4) Compare the measures of impact used. 5) Compare the model predictions. 6) Develop a simulator to: a) make models more comparable; b) investigate the effect of changing parameter values, environmental conditions, and initial conditions (sensitivity analysis); c) look at the importance of differences in equation forms to model predictions. 7) Make recommendations on the most reasonable approach and point out limitations, difficulties, or errors with various parts of the models.

4.2 General Model Comparison

Our general model comparison categorizes models into three major topic areas: underlying model assumptions, biological assumptions, and measures of impact. Table 4.1 shows how the models compare according to categories within these three topic areas.

4.2.1 Underlying Assumptions

Dynamic refers to the use of time-varying estimates of long-term impact. All the dynamic models involved computer simulations. A deterministic model is one that uses fixed estimates for all the parameter values without ascribing any probability to them. Semideterministic models use deterministic parameters but look at maximum and minimum parameter estimates in addition to the best estimate, thereby including data uncertainty and variability in the parameters but not in a strictly probabilistic fashion.

Dynamic models are usually a series of equations setting rules for the change or flow of material through time. All the models reviewed use a difference equation approach, where time is viewed at discrete intervals and equations determine the amount of material transferred between compartments over a time interval. This is in contrast to a differential equation approach, where time is viewed as continuous and equations fix the rates of flow between compartments or to even-oriented models in which transfers occur only at specific times associated with particular events.

The term spatially heterogeneous refers to a model that explicitly considers the spatial relationship of various segments. In the reviewed models it refers implicitly to the treatment of the effect of entrainment loss on various Atlantic Coast fisheries (e.g., the Summit and JHU models). The other models are spatially homogeneous. Actually, all the life-cycle models reviewed are strictly spatially homogeneous, since none explicitly considers the spatial configuration of segments.

The underlying model assumptions are basic to the structure of a model, but they are sometimes not mentioned in model descriptions. We think that the underlying assumptions set the tone for the degree of detail or resolution of the biological part of the model, and as such cannot be passed over. For example, impact models that are static rather than dynamic implicitly assume that predictions about impact on adult fish can be made without concern for year-to-year variation and that things will continue in the same way next year as they were this year--i.e., there is no feedback from one year to the next. Although we know that feedback of this sort definitely does exist in biological (fish) populations, proponents of a static view might assert that such patterns cannot be separated from the randomness of the year-to-year fluctuations. They might argue that this fluctuation makes average, static predictions as accurate as dynamic predictions based on equations postulating biological feedback mechanisms. Whatever the outcome of this argument it illustrates the type of differences in the inclusion of biological mechanisms in a static or a dynamic model.

4.2.2 Biological Assumptions

The biological assumptions in the adult impact models reviewed centered on the questions of whether age classes are included explicitly in the model and whether compensation mechanisms operate on the fish, and

Table 4.1. Comparison of models for prediction of impact on adult fish populations.

	Hudson River			C&D--Summit		
	ORNL	LMS	URI	ORNL	JHU	Delmarva
<u>Underlying assumptions</u>						
Dynamic	X	X	X	X		
Deterministic	Semi	X	X	Semi	X	Semi
Computer simulation	X	X	X	X		
Difference equation	X	X	X	X		X
Spatial heterogeneity (of fishery)				X	X	
<u>Biological assumptions</u>						
Use Leslie matrix	X	X	X	X		
y-o-y compensatory survival		X	X			
Adult compensatory survival	X			X		
<u>Measure of impact</u>						
Yield	X			X	X	
Adult populations	X	X	X	X		
New recruits	X	X				X

if so in what life stage and from what cause. All the dynamic adult impact models divided the fish populations into year classes and used a survival-fecundity matrix based on the Leslie matrix (Leslie 1945) to predict long-term impact of entrainment loss. We term these life-cycle models, in that they trace fish populations through time according to age class, and as such generate life cycles for each cohort.

Leslie matrices model survival and recruitment (survival of individuals from one age class to become the next age class over a yearly time interval) and fecundity (egg production by females in the mature age classes to become age class 0 individuals [eggs] over a year). Since the time step in all the fish models reviewed is a year, while fecundity occurs over a small time period in striped bass and winter flounder, some assumption about timing of egg production must be made. Usually egg production is assumed to occur as an event at the beginning or end of a time step. Leslie's original formulation dealt only with females but all the models except the ORNL model use total fish populations. The use of total fish populations can lead to problems if sex ratios are age specific, but otherwise the two approaches are equivalent.

4.3 Equation Comparison

A Leslie matrix model represents the change in numbers of individuals in each age class in a population, over time. These variables at any time t are represented by a vector $\overline{N}(t)$ with the number of elements in $\overline{N}(t)$ equal to the number of age classes (n) in the model. The fraction of the population (or the probability of an individual) surviving from age class i to age class $i + 1$ in a year is denoted by S_i. It is generally assumed to be independent of time and to depend only on the age class, thus it is an age-specific parameter. The numbers of female eggs produced by mature females in age class i, e_i, are the other parameters used in the model. The Leslie matrix model for $\overline{N}(t)$ is given by

$$\overline{N}(t) = AN(t - 1) \qquad (4.1)$$

where $\overline{A}$ is the survival-fecundity matrix:

$$\overline{A} = \begin{pmatrix} S_0e & S_1e_2 & & 0 & S_ne_n \\ S_0 & 0 & & \cdot & 0 \\ 0 & S_1 & \cdot & \cdot & 0 \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & \cdot & 0 & \cdot \\ 0 & 0 & & S_{n-1} & S_n \end{pmatrix}$$

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When the population vector at any time $t - 1$ is multiplied by matrix $\overline{A}$, the population vector at time t is generated.

Many of the models reviewed use a modification of the Leslie equation (4.1). The major variants involve making survival a function of the population size, usually through the introduction of a compensatory mechanism in y-o-y survival S_0 or in the S_i values for the legally fishable adult age classes, thus making fish mortality density-dependent (d-d).

The Leslie formulation assumes egg production occurs at the end of the year, since egg generation is based on adult populations for the preceding year. A variant on Leslie matrix models that we encountered in our review uses the total adult population instead of the female population.

Matrix Equation (4.1) for the Leslie model is given in nonmatrix form by Equations (4.2) and (4.3):

$$N_i(t) = N_{i-1}\,(t - 1)S_{i-1} \qquad \text{for } i = 1, \ldots, a \qquad (4.2)$$

where $N_i(t)$ is the number of female fish in year class i at time t.

$$N_0(t) = \sum_{i=1}^{a} N_i(t - 1)S_i e_{i+1} F_{i,\text{mat}} \qquad (4.3)$$

where $F_{i,\text{mat}}$ is the fraction of females of age class i that are sexually mature and $N_0(t)$ is the number of female eggs produced at time .

If total populations are used instead of females, the $N_i(t)$ denotes the total fish population in year class i and Equation (4.3) becomes

$$N_0(t) = \sum_{i=1}^{a} N_i(t - 1)S_i e_{i+1} F_{i,\text{mat}} F_{i,\text{fem}}/F_{0,\text{fem}} \qquad (4.3a)$$

where $F_{i,\text{fem}}$ is the female fraction of the fish in year class i. The equation is divided by $F_{0,\text{fem}}$ (egg female fraction) to convert e_i, which is female eggs per female, into total eggs per female.

The ORNL model divides survival into two components, survival from natural causes $S_{i,nat}$ and survival from fishing $S_{i,fish}$. These represent the fraction of the fish in age class i that were fortunate enough to escape mortality due to natural causes and fishing predation, respectively. The two mortality sources are assumed to act independently and thus the two survival fractions are multiplied together to give S_i.

Natural mortality in the ORNL model is assumed to be an age-specific constant, while fishing mortality is assumed to be a density-dependent function of the total adult female fish biomass available to the fishery B. The legally fishable female population is identified in the ORNL model by a catchability parameter, which is 1.0 for all age classes older than the pivotal age class (the first legally fishable age class) and 0 for all younger age classes. The parameter for the pivotal age class is some fraction between 0 and 1, depending upon the average length of the fish in that age class compared with the legal minimum catchable size. For all legally fishable age classes $S_{i,\mathrm{fish}}$ is related to fishing mortality rate by:

$$S_{i,\mathrm{fish}} = \mu p\ (-M_{\mathrm{fish}}) \qquad (4.4)$$

Female populations are used in the ORNL fishing model, presumably for compatibility with the Leslie model.

Mortality rate M_{fish} is given by the nonlinear function of legally fishable biomass B shown in Fig. 4.1. There are a number of parameters in this relationship, both biological and fisheries-controlled. Parameter B_{min} is the biomass below which fishing occurs at a constant minimum rate F_{min} and below which fish have the maximum chance P_{max} of surviving fishing. Here P_{max} is represented in terms of probability, since there is too much uncertainty both for the fish and the fisher to ascribe determinism to it. The maximum fishing harvest rate F_{max} is approached at high population densities (high B), and is associated with P_{min}, the minimum probability of surviving fishing mortality. Here M_B relates the increase in fishing mortality to increase in B when B is greater than B_{min}. It controls the slope of the curve in Fig. 4.1. The difficult problem of estimating the parameters in the fishing model is discussed when we treat parameter values and estimation techniques (Section 4.4.2.1).

The existence of a d-d and a d-i part of fishing mortality (ORNL model) is based on the assumption that a difference exists between the effect of commercial and sports fisheries on fish populations. Commercial fishing operations, which rely on a number of fish species in addition to striped bass, are not expected to alter fishing effort or methods based on bass densities (USNRC 1975), and are not expected to suffer reduced effectiveness at low densities (i.e., fish behavior or migration patterns under low fish densities are assumed not to affect fish vulnerability to commercial fishing). Bass sports fishermen are more likely to be discouraged by low bass densities and to achieve smaller catches than indicated by the proportional reduction in amount of bass available. This is especially true with the Atlantic sports fishery, which is largely a one-species (striped bass) fishery (USNRC 1975).

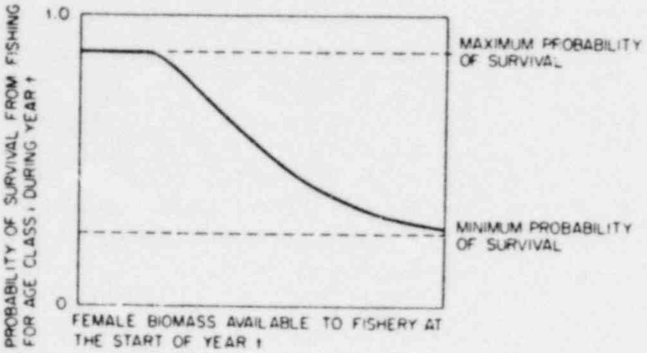

Fig. 4.1. Density-dependent fishing mortality rate M_F, and probability of surviving fishing, S_F. From USNRC (1975) FES, Figures B-41 and B-42.

One restriction implicit in the assumptions underlying the fishing mortality model is that the relative importance of commercial and sports fishing is fairly constant. There is no straightforward way to change parameters to apply the model to a different region where one or the other type of fishery is more or less dominant.

Fishing mortality is assumed to be age independent (for all legally fishable fish), an assumption that may not hold. For example, studies on the Roanoke River in North Carolina indicate increased vulnerability of first-year river-run bass (Trent and Hassler 1968) when compared with vulnerability to catch of older fish.

Because biomass instead of numbers of fish is used in the fishing mortality model, a conversion to biomass is made by multiplying numbers in each age class by average weight of individuals in each age class. Total fishable biomass is the sum of the age-specific biomasses for all the fishable year classes. The biomass for the pivotal year class is multiplied by the fraction of that year class estimated to be legally fishable.

4.4 Parameter Data Sources and Values

We have organized this section into groups of related parameters including those relating to: 1) fecundity; 2) survival and mortality; and 3) equilibrium or initial conditions.

4.4.1 Fecundity Parameters

Fecundity parameters include the age-specific probability that a female is sexually mature in each age class, the female fraction for each age class (sex ratio), the probability an egg will develop into a female, and the average number of eggs for a mature female for each age class. Each of these parameters is given in Table 4.2, along with its values in each of the relevant models used, the data reference, and, where pertinent, the method of data refinement used.

In the ORNL model, fecundity was given as a range of values from which a minimum value, a best estimate, and a maximum value were estimated. The ORNL model was run separately with each of the three values so that model behavior over all possible values of parameters could be observed. Series of parameters (e.g., maturity fraction) were treated as a group, and when maximum, minimum, or best estimate runs were made they were made with all parameters in the specific group set in the same way (e.g., all the maximum values for a given group were used in a run).

The ORNL and URI models estimated eggs from a regression relationship on fish weights, while the LMS models used fecundity data directly. In fact, both LMS and ORNL used the same data set (T.I. 1973a), but the data were refined differently. The ORNL model used T.I. egg production and female fish weight data from a 1972 sample, and did a linear regression

Table 4.2. Fecundity parameters used in life cycle models.

Paramater	Definition	Model^1	Age	Values used in model: Minimum	Values used in model: Best estimate	Values used in model: Maximum	Source
F_{fem}	Probability that a fertile egg will develop into a female	(1,2, 3,4)			0.5		T.I. 1973 data reported in Lawler (1974, Table II)
		(5)			0.7		Saila (1961)
$F_{i,\text{ mat}}$	Probability that a female striped bass in the Hudson is sexually mature entering age class i	(1,4)	1	0	0	0	Sexual maturity estimated by ratio of ovary weight to total body weight (T.I. 1973; USNRC 1975, Table B-42)
			2	0	0	0	
			3	0	0	0	
			4	0	0	0	
			5	0	0	0.5	
			6	0	0.67	1.0	
			7	0.5	1.0	1.0	
			8	1.0	1.0	1.0	
		(6)	1		0		Based on Merriman (1941), Vladyhow & Wallace (1952), and Lawler (1972a, Table 5)
			2		0		
			3		0		
			4		0.25		
			5		0.75		
			6		0.95		
			7		1.0		
		(2)	1		0		Based on ORNL 1-D model parameters with observation that Chesapeake females mature earlier than Hudson females (Jackson & Tiller 1952) USNRC (1975); also tag-recapture studies by Raney (1952)
			2		0		
			3		0.25		
			4		0.75		
			5		1.0		
			6		1.0		
		(5)	1		0		No reference given; presumably from Saila (1961).
			2		0		
			3		1		
			4		1		
			.		.		
			.		.		
			12		1		

Table 4.2. Fecundity parameters - (Continued)

Parameter	Definition	Model[1]	Age	Values used in model			Source
				Minimum	Best estimate	Maximum	
e_i	Number of eggs per mature female in age class i	(6)	4		345,000	3.45×10^5	Based on Lawler (1972a, table 5; data from Lewis & Bonner 1966)
			5		438,000		
			6		615,000		
			7		752,000		
			8		820,000		
			9		909,000		
			10		910,000		
			11		964,000		
			12		1,136,000	1.136×10^6	
			13		908,000		
		(4)	5		451,000		Based on LMS (1975, table II; data from T.I. 1973a)
			6		780,000		
			7		1,543,000		
			8		1,563,000		
			9		1,841,000		
			10		2,095,000		
			11		2,350,000		
			12		2,268,000		
			13		2,189,000		
		(1)	6	98,900	141,000	198,000	Calculated from regression equations in USNRC (1975, table B-45)
			7	187,000	286,000	424,000	
			8	229,000	374,000	582,000	
			9				
			10				
			.				
			.				
			15				

Table 4.2. Fecundity parameters - (Continued)

Parameter	Definition	Model[1]		Values used in model Minimum	 Best estimate	 Maximum	Source
b_1 (eggs)	Regression parameters relating av ratio of eggs produced by mature female to av wt of adult females	(1,2)	b_1 =		1.38×10^6		T.I. (1973a, figure V-14) egg sampling data regression, N = 39, r^2 = 0.76
$b2$ (eggs/kg)			b_2 =		1.61		
		(5)	b_1 =		2,6712		Saila (1961) regression of $\log_{10}$ e_i vs $\log_{10}$ (WT_i) ($\log_{10}$ (WT_i) = weight)
			b_2 =		1.1383		
WTMEAN (kg)	Av wt of mature adult female striped bass	(1)			8		USNRC (1975, table B-42) from T.I. (1973a) mature female sample
b_3	Parameters in regression relating av female wt to length	(1)	b_3 =		-5.34		USNRC (1975, tables B-37 & B-42) from T.I. (1973a) adult fish wt sampling regression data
b_4		(4)	b_4 =		3.130		
($\log_{10}$g/ $\log_{10}$ mm)		(5)	b_3 = b_4 =		-5.239 3.138		Sissenwine et al. (1974, table 2.2), data from Lux (1969)
b	b = coefficient of first-order term in quadratic regression of length on age; = coefficient of second-order term in regression	(1)	b =	106	115.1	124.1	T.I. (1973a) April-Sept. 1972 data used
		(4)	c =	-3.88	-3.09	-2.29	USNRC (1975, figure B-45, table B-42) for total adult sample, which gave results close to female values: B = 117, C = -3.191, r^2 = 0.998, N = 74

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[1] Numbers in parentheses refer to models as follows: (1) ORNL 1-D, (2) ORNL Summit, (3) LMS 1-D (1973), (4) LMS 2-D (5) winter flounder, (6) LMS 1-D (1967).

obtaining coefficients b_1 and b_2 in Table 4.2. The URI model used a similar regression, employing the logarithms of egg production and body weight. The units of b_1 and b_2 were $\log_{10}$(eggs) and $\log_{10}$(eggs)/$\log_{10}$(kg) this instance. Both the URI and ORNL models predicted fish weights by linearly regressing the logarithm of weight on the logarithm of fish length (parameters b_3 and b_4). The numbers for the regression coefficients for the two species agree very closely. The ORNL model further regresses length on age, using a quadratic regression equation (parameters b and c), while URI uses fish length data directly. The ORNL model regressions allow fecundity to be computed directly for each age class from the age alone.

We see no benefit in using regression in the life-cycle model, especially as the correlation coefficient for the weight--egg production regression was not particularly high. Presumably regression allows for alteration of fecundity predictions as new data become available, but it is certainly less accurate for any 1 year than the primary data themselves.

Sex ratios for the ORNL and URI models remain constant with age, while in the LMS models they increase with age. We are not convinced that the data cited by LMS to indicate variable sex ratios actually do indicate such variation. Our skepticism is based on the small size of sample for the older age classes in the Hudson River sample (T.I. 1973a) and the dissimilarity between the fisheries on the Atlantic Coast and in the Roanoke River, North Carolina, where studies (Trent and Hassler 1968) indicated that changing sex ratio was due to high fishery harvest of young males who make spawning runs earlier in life than females.

It seems to us that, in light of inconclusive evidence concerning changing of striped bass sex ratios with age, the simpler assumption of constant sex ratios is preferable. As the LMS models did have variable sex ratios, however, we investigated the effect of that assumption on model predictions (see Section 4.8.1). The study showed little effect from changing sex ratios on model predictions, and supported our preference for a constant sex ratio.

4.4.2 Survival-Mortality Parameters

The survival-mortality parameters are related to natural mortality and fishing mortality. Fishing mortality parameters are used in the ORNL d-d fishing function shown in Fig. 4.1. Natural mortality parameters are chosen, in all the life-cycle models reviewed, such that under conditions without plant operation the population is in steady state or equilibrium. The parameter values are shown in Table 4.3.

4.4.2.1 Fishing Mortality Parameters. We introduced several parameters in our discussion of the ORNL fishing mortality model in Fig. 4.1. At present it is impossible to estimate these parameters directly. For example, how can we explicitly estimate the maximum probability that a fish will survive fishing mortality when fish

Parameter	Definition	Model	age	Values used in model: Min.	Best estimate	Max.	Source
S_i	Probability of survival from natural mortality of age i to age i+1	O NL Indian Point & Summit	1	0.2	0.4	0.6	Based on Sommani: (1972) tagging recapture study over ten years on San Joaquin River. (table B-39 Indian Point 3 PES. model values are given in table B-42).
			2	0.4	0.6	0.8	
			3	0.6	0.8	0.9	
			⋮	⋮	⋮	⋮	
			15	0.6	0.8	0.9	
		LMS Mixed[1]	1	0.668	0.518	0.99	Calculated to give equilibrium. Table 6, 7, 8 in Lawler 1972a).
			2	0.668	0.518	0.99	
			3	0.3	0.518	0.801	
			4	0.3	0.518	0.8	
			⋮	⋮	⋮	⋮	
			13	0.3	0.518	0.8	
		LMS 1-D[1]	1		0.16		$S_4 \rightarrow S_{13}$ calculated to give equilibrium $S_3 \rightarrow S$ values assumed. Table 4 in Lawler, 1972b)
			2		0.16		
			3		0.16		
			4		0.614		
			⋮		⋮		
			13		0.614		
		LMS	1			0.3	T. Englert (Pers. comm.)
			2			0.3	
		LMS 1-D('73)	3			0.3	Derived from information on Table LMS 1975. and assuming $S_1 \rightarrow S_3$ values equal and $S_4 \rightarrow S_{14}$ values equal. Corroborated by T. Englert (Pers. Comm.).
			4			0.456	
			5			0.456	
			6			⋮	
			14			0.456	

Table 4.3. Natural and fishing mortality parameters - (Continued).

Parameters	Definition	Model	Age	Values used in model Min.	Best estimate	Max.	Date source and comments
		Winter Flounder (Cont)	2		0.33		Poole 1969. $S_{1\ nat}$ was calculated to fit data of Saila (1961)
			3		0.33		
			'		'		
			'		'		
			'		'		
			12		0.33		
Fishing model parameters							
B_1	Min. biomass available to fishery (females in kg.)	ORNL Indian Point & Summit		0.5x10^5	5x 100.5x10^7		Commercial landing min. = 305,268 kg. (1963-1972). Assumed approximately equal number of sport and commercial landings for Hudson spawned striped bass
		LMS		0.5x10^6			
B_{nat}	Ratio of max. to min. biomass available to fishery	ORNL Indian Point & Summit		2	3	5	Average of ratio for Hudson River, New York. Mid-Atlantic & Chesapeake fisheries of maximum to minimum catch, for 8 overlapping 10-yr periods (1933-1972) spaced at 5-yr intervals. Koo (1970). Maximum to minimum catch. Table B-41, B-42 Indian Point 3 FES.
		LMS 2-D			2.37		Based on range of commercial landings for New York 1964-1973 to get average ratio of maximum and minimum catch.
P_{max}	Max. probability of survival from fishing	ORNL Indian Point		0.75	0.85	0.95	No tagging studies done on the Hudson River.
		LMS 2-D			0.85		
		ORNL		0.65	0.75	0.85	Reflects greater fishing mortality of striped bass in Chesapeake than that along Atlantic Coast.

Table 4.3. Natural and fishing mortality parameters - (Continued).

Parameters	Definition	Model	Values used in model: Min.	Best estimate	Max.	Data source comments
$P_{\text{min.}}$	Min. probability of survival from fishing	ORNL Indian Point & Summit	0.5	0.6	0.7	Chesapeake Bay tag recapture studies to get range of fishing loss. (Raney 1952, Mansueti 1961) R. J. Mansueti (pers. comm.) believes fish loss to be between 30% and 60%. Studies done outside Chesapeake include T.I. (1972) Schaefer (1968). Table B-42. Indian Pt. 3 FES).
			0.4	0.5	0.6	
		LMS 2-D		0.6		
R_d	The ratio of survival when min. fish biomass is available to fishery, to that when max fish biomass is available	ORNL Indian Point & Summit	0.4	0.6	0.8	Chosen so that under expected range of population conditions the probability of survival would never reach P_{max} or $P_{\text{min.}}$
		LMS 2-D		0.6		
B_{leg} (mm)	Min. legal length of fish available to fishery	ORNL Indian Point	338	438	538	Legal size limits in North Atlantic waters.
		ORNL Summit			305	Legal size limit in Chesapeake Bay.
$S_{0,\text{nat}}$	Probability that eggs survive 0 to become y-o-y in absence of entrainment	ORNL Indian Point	5.4×10^{-6}	2.126×10^{-5}	2.5×10^{-4}	Computed from estimates of natural and fishing survival fractions for other age classes
		LMS mixed	8×10^{-7}	1.84×10^{-5}	4.8×10^{-5}	Taken from runs of LMS y-o-y model without plant operation
		Winter flounder		5.5×10^{-5}		Calculated for equilibrium population.
		LMS 1-D	2.847×10^{-4}	2.847×10^{-4}	9.49×10^{-5}	(Table 4 in Lawler 1972b).
		LMS 2-D		2.18×10^{-4}		

populations are not known, fish mobility makes tracking difficult if not impossible, and other variables that might affect the parameter (e.g., fishing pressure) are constantly changing? The ORNL model developers were well aware of the problem and so contrived to estimate the parameters indirectly to reflect historical fisheries success, and to use information from tag-recapture studies.

The method for obtaining P_{max} and P_{min} (and thereby F_{max} and F_{min}) was to examine a number of tag-recapture studies on Chesapeake Bay and elsewhere to estimate survival probability. Tag-recapture studies, however, reflect survival probability under normal conditions and as such may not apply to estimates of maximum and minimum fishing harvest rates. Expert opinions also were sought on the probable range of fishing mortality.

To obtain estimates of B_{min} and M_B, three other parameters were introduced. They are B_1 the average minimum fish biomass available to the fishery over a 10-year period; B_{rat} the ratio of average maximum to minimum fish biomass available to the fishery over a 10-year period; and R_d the ratio of probability of survival from fishing at average maximum available fish biomass to that at the average minimum available biomass. It was further assumed that the two probabilities whose ratio is R_d are spaced equidistant about $(P_{max} + P_{min})2$; B_{rat} and B_1 are estimated from historical records of commercial catches. Here R_d is chosen so that under normal population fluctuations P_{max} and P_{min} are not reached.

The LMS 2-D model document (LMS 1975) discussed use of the ORNL d-d fishing model, and used the same parameter values except for B_{rat}. Long-term records reported in the Indian Point 3 FES (USNRC 1975) tend to support a higher value for B_{rat} that the 2.37 LMS value, which was based on only 10 years of data. Lawler, Matusky, and Skelly (T. Englert, personal communication), however did not use this model in any official reports or hearings.

The wide value range (e.g., 10^5-10^7 for B_1) for many of the fishing mortality parameters in Table 4.3 aroused our interest in the sensitivity of model predictions to changes in parameters. They are given by an ORNL sensitivity analysis and are discussed in the sensitivity analysis section.

4.4.2.2 Natural Mortality Parameters. Natural mortality parameters $S_{i,nat}$ were estimated to satisfy an equilibrium condition. Mathematically, this means that:

$$\overline{N}(t) = \overline{N}(t - 1) = \overline{A}\ \overline{N}(t - 1) \qquad (4.5)$$

(see Equation 4.1). Matrix theory allows us to specify the equilibrium state (the stable age distribution of the population) uniquely from matrix A; however only the fecundities e_i and the fishing survival probabilities of $S_{i,fish}$ (where a d-d fishing model is used) are known. Without the

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natural mortality survival fraction, neither the S_i nor the N_i can be computed.

Some assumption, estimate, or both are needed to make estimation of S_1 feasible. Several approaches were adopted. The ORNL approach estimates the adult survival properties S_i from tag-recapture studies. They then assume an equilibrium adult population, the average fish population available to the fishery over a 10-year period (half the sum of the average minimum and the average maximum fish populations available to the fishery B_1 and $B_{\text{rat}}B_1$, respectively); and estimate a class 0 natural survival $S_{0,\text{nat}}$ to satisfy Equation (4.5). The LMS models used an estimate of total egg production, obtained a value of $S_{0,\text{nat}}$ from running their y-o-y model for that number of eggs, and assumed $S_1 = S_2 = S_3$ and all other adult survival probabilities are equal. A Newton-Raphson technique was then used to converge upon the unique adult population N(t) and $S_1 \rightarrow S_1$ and $S_4 \rightarrow S_{13}$ values. The URI model estimated $S_1 \rightarrow S_{12}$ from data and calculated $S_{0,\text{nat}}$ to give an equilibrium population.

The $S_{1,\text{nat}} \rightarrow S_{3,\text{nat}}$ values for the LMS 1-D model are lower than the ORNL best estimates, especially $S_{3,\text{nat}}$ (<u>see</u> Table 4.3). In light of the tag-recapture results of Sommani (1972) on 3-year and older fish, the LMS estimate for $S_{3,\text{nat}}$ seems particularly low.

We decided to investigate the effect of this difference on model predictions, as it was so striking. Results of this investigation are discussed in the life-cycle simulator section.

4.4.3 Equilibrium Conditions

The equilibrium conditions were used as initial conditions in all the life-cycle models reviewed. They are given in Table 4.4. It is striking that the ORNL and LMS 1-D equilibrium adult populations differ by two orders of magnitude despite the fact that they are both modeling the same population--there is even an order of magnitude difference in egg production estimates. We think that present population estimation techniques (e.g., tag-recapture, direct sampling, and so on) are precise enough to reduce the disparity between the estimates.

4.5 Measures of Plant Impact

From Table 4.1 we see that three criteria have been used to measure long-term impact resulting from entrainment loss of larvae and juveniles. They are the change in yield of the relevant fisheries, the change in total adult population, and the change in the annual number of new recruits entering the adult population. Often they are expressed in terms of relative yield, relative adult population, or relative recruitment. Here relative is defined by:

$$\text{relative } X = \frac{X \text{ without plant operation} - X \text{ with plant operation}}{X \text{ without plant operation}} \quad (4.6)$$

Table 4.4. Initial conditions for models compared. (Female populations).

Model	Age Class	Populations
ORNL 1-D	0	5.2E10
	1	1.1E6
	2	4.4E5
	3	2.6E5
	4	2.1E5
	5	1.3E5
	6	7.7E4
	7	4.3E4
	8	2.5E4
	9	1.4E4
	10	8E3
	11	4.5E3
	12	2.6E3
	13	1.5E3
	14	8.3E2
	15+	1.1E3
LMS 1-D	0	1.07E9
	1	3.07E5
	2	5.72E4
	3	1.06E4
	4	1.97E3
	5	1.26E3
	6	7.97E2
	7	5.06E2
	8	3.21E2
	9	2.03E2
	10	1.29E2
	11	8.1E1
	12	5.0E1
	13	3.1E1
LMS 2-D	0	1.4E9
	1	1.86E5
	2	5.60E4
	3	1.68E4
	4	5.04E3
	5	2.3E3
	6	1.05E3
	7	4.8E2
	8	2.2E2
	9	1.0E2
	10	4.5E1
	11	2.1E1
	12	9.0
	13	4.0
	14	2.0
	15	1.0

Table 4.1 shows which measures were used in which models. The ORNL 1-D model is the only one that uses all three measures of impact. There are some differences between the models in computation of the various measures. Adult population size is used in the LMS and URI models. The ORNL and Summit models use B, the total biomass of legally fishable females at the start of the year.

Yield of fish is computed in the ORNL 1-D model as the average biomass of legally fishable adults in that age class over the year times the fraction that die from all causes times the ratio of fishing mortality rate over total mortality rate. (Fishing mortality rate $M_{i,\text{fish}}$ is given by Equation [4.41], natural mortality rate is equal to -ln [S_i]). The ORNL document cites Ricker (1958), who suggested that the ratio of fishing to total mortality rates can be used as an estimate of fishing yield if the fishery and natural mortalities are proportionately distributed over the year. The reasons that such a complex estimate is used are presumably because: 1) fishing mortality is not uniformly distributed throughout the year; 2) the weights of fish change markedly through the year, thus average weight (weight at halfway between age i and $i + 1$) is used rather than initial weight; and 3) fish are subject to natural as well as fishing mortality (fish dying of natural causes during the year are not available for harvest). A crude approximation to the yield estimate used is to multiply B, the legally available fish at the start of the year, by the fraction (1 - SF [SF = scaling factor]) that die from fishing. We think that some measure of yield to relevant fisheries is an essential part of the index of impact, and we recommend its inclusion in those models that do not use it. We have investigated the LMS model predictions of long-term relative yield using a life-cycle model simulator (Section 4.7) to see how their model affects yield even though yield was not explicitly considered by LMS.

While the yield and fishing mortality calculations in the ORNL model are based on reasoning concerning commercial and sports fisheries, there is no separation of yield into commercial and sports fisheries yield. That separation was made in the JHU and Summit models, where great pains were taken to ascertain yield loss in both fisheries in different regions due to plant entrainment. Tagging studies and other evidence and opinions (Raney et al. 1954, Raney and Sylva 1953, Mansueti 1961, Nicholson and Lewis 1973, Nichols and Miller 1967, Schaefer 1972) indicate the importance of fish spawned in the Chesapeake-Delaware system to fisheries along the Atlantic Coast from North Carolina to mid-Massachusetts.

The JHU and Summit models divide the Atlantic Coast striped bass fisheries into two large regions, the North Atlantic (New England and New York) and the Middle Atlantic (New Jersey to Cape Hatteras, North Carolina). The Middle Atlantic fishery includes the Chesapeake Bay fishery. Average annual catch estimates for commercial and sports fisheries were made based on saltwater anglers' surveys, commercial catch statistics, and estimates of data biases (especially overestimates of reported sports catches). Tagging and sampling studies were used to ascertain the relative contribution to the North and Middle Atlantic fisheries of fish spawned in regions subject to entrainment. Estimates are reported in Lawler (1974) and in USNRC (1975) for the North Atlantic fishery, divided into an inner zone (Hudson River, western half of Long Island Sound, and the New York Bight) and an outer zone (Maine to Cape May, New Jersey), of the fractional contribution of bass spawned in the Hudson River to the total bass catch. As the other major spawning area is the Chesapeake Bay drainage, these estimates were used by the Summit modelers to compute the Chesapeake contribution to the North Atlantic fishery (Christensen et al. 1975).

Egg and larva sampling studies on major known spawning areas in the Chesapeake-Delaware drainage (e.g., U.S. Army Corps and Engineers 1974, Dovel and Edmunds 1971) as well as juvenile samples near major spawning areas (Maryland Fisheries Commission data reported in Christensen et al. 1975) were used in the Summit model to given an estimate of the relative contribution of the C&D Canal stock to the total Chesapeake Bay stock. The variability in these data led the Summit modelers to use three values, a maximum, minimum, and best estimate, for each parameter in their estimate of canal contributions to the various fisheries. Table 4.5 gives the relevant estimates for the Summit and JHU models with data sources.

The closeness of the numbers for the JHU and Summit models is reassuring, since the data sets reviewed and used in the models were almost the same. The summit values for the contribution of the Chesapeake stock to the North Atlantic fishery are based on ORNL (USNRC 1975, chap. v) estimates of fractional contribution of Hudson River stock to an inner and outer zone of influence.

The difference in contribution of the Chesapeake to commercial and to sports fisheries is due to the difference between the Atlantic Coast and Chesapeake Bay in the relative importance of sports and commercial fisheries. Sports and commercial fisheries in Chesapeake Bay are estimated to be about equal in importance, while on the Atlantic Coast sports fisheries catches are estimated to be from 7.5 to 16.5 times as large as commercial catches (USNRC 1975, p. 176). Thus Chesapeake Bay contributes a higher fraction to the total Atlantic Coast commercial catch of striped bass than to the sports catch.

When multiplied by plant reduction percentage (PR), the scaling factor (SF) gives the fractional loss in yield due to plant operation, which, when multiplied by the estimated total catch for the fishery, gives an estimate of loss in yield. This estimate was used in the Summit and JHU models.

In both the JHU and Summit models the estimated fractional loss in yield of the entrained population is multiplied by conversion factors shown in Table 4.5 to convert C&D Canal population yield loss to Chesapeake Bay stock loss and Atlantic fishery yield loss--assuming fish larvae not spawned in the C&D Canal are not subject to entrainment.

Table 4.5. Fishery catch and fish migration estimation.

	Model	Values			Total Catch estimate	Source
		Min.	Best estimate	Max.		
Fraction of total Atlantic coast sports fishery catch attributed to Chesapeake Bay juveniles	ORNL	0.4	0.55	0.7[a]	17,697[a]	Christensen et al. (1975: table 7.3). Catch estimates are based on salt water angling surveys. An exaggeration factor is applied to reported catches (0.5 for ORNL, 0.4 for JHU model). JHU values in Portner (1975: table 9).
	Summit	0.4	0.6	0.8	9904[b] (6000)[c]	
	JHU		0.6		22,061 (5869)[c]	
Fraction of east coast commercial catch contributed by Chesapeake Bay juveniles	ORNL Summit	0.85	0.9	0.95	8610	Christensen et al. (1975:table 7.1)
	JHU		0.6		7936 (5869)[c]	Portner (1975:table 9)
Fraction of Chesapeake Delaware fishery contributed in C&D Canal spawn	ORNL Summit	0.06	0.19	0.38		Christensen et al. (1975:table 8.1, appendix A-4) computed value
C&D Canal contribution to Delaware fishery	ORNL Summit	0.25	0.5	0.75		Christensen et al. (1975:table 6.1)
Canal contribution to Chesapeake Bay fishery	ORNL Summit	0.03	0.1225	0.30		Christensen et al. (1975:table 6.2)
	JHU		0.15	0.30		Portner (1975:table 10 and p. 60, based on data from Hollis, 1967 Dovel and Edmunds 1971, U.S. Army Corps Engr. 1974)
Fraction of canal spawn reaching the Chesapeake as juvenile	ORNL Summit	0.4	0.551	0.667		Christensen et al. (1975:tables 8.1-8.3)
	JHU		0.4			From model by Warsh (1975)

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Table 4.5. Fishery catch and fish migration estimation - (Continued).

		Values				
	Model	Min.	Best estimate	Max.	Total Catch estimate	Source
Fraction of canal spawn reaching Delaware River as juveniles	ORNL Summit	0.333	0.449	0.6		Same as Christensen et al. (1975: table 6.1)
	JHU		0.6			
PR into long-term adult population loss	ORNL Summit	0.75	1.375	2.0		From ORNL life cycle model (Van Winkle et al. 1974)
Scaling factor to convert PR into long-term fractional loss in fish yield	ORNL	1.0	1.5	2.0		From ORNL life cycle model (Van Winkle et al. 1974)

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[a] Numbers are from north Atlantic fishery only.

[b] Numbers are for middle Atlantic fishery, including Chesapeake Bay. Chesapeake Bay catch estimates are in parenthese.

[c] Assume commercial catch = sports catch in Chesapeak Bay.

4.6 Comparison of Model Impact Predictions

Comparison of predictions of impact according to the various criteria used is given in Table 4.6. The life-cycle models report results after a number of years of plant operation with various PR values (either generated by the y-o-y model as with LMS, or arbitrarily chosen based on "reasonable" estimates obtained from the y-o-y model as in the ORNL and URI models). The Summit and JHU results are average annual yield predictions and are not at any explicit time, although the Summit values are based on a scaling factor obtained from the ORNL life-cycle model.

As was pointed out by Portner (1975), there are two basic approaches to impact assessment. One approach makes impact calculations by assessing a certain egg production and then using a model to compute subsequent mortality due to natural and entrainment sources. A fishing model based on the resultant adult fish biomass may be overlaid on this structure (as in the ORNL model) to compute yield to the fishery. The other approach is based on estimating the fish catch directly from fish catch statistics and back-calculating the fish biomass recruited from the spawning area in question, making assumptions about fractional contributions of various fish stocks to the fisheries. The first approach was used in the Delmarva, ORNL, URI, and LMS models, while the second was used in the Summit and JHU models. The Summit model actually used a combined approach, converting entrainment PR loss into loss in yield using the ORNL life-cycle model. The first approach has a potential error of an order of magnitude in egg production estimates (see Table 4.2) and in survival fractions (see Table 4.3). The fishery estimation approach has error in estimation of the size of the fishery (see Table 4.5), approximately a factor of 2 uncertainty, and of the contribution of the spawned stock to the various fisheries (see Table 4.5). Portner (1975) thought the errors in the second approach were significantly smaller. For an example of potential disparity between the two approaches, the JHU predictions of fish catch recruited from upper Chesapeake Bay differed from predictions from the Delmarva model (Portner 1975:66-67) by a factor of 3.5 to 7.

Our observations of the various models tend to support Portner's view that, in light of year-to-year variability in egg production and mortality rates, a static (or steady-state) model would best approach impact assessment from the standpoint of fishery yield and fish migration rather than steady-state egg production and survival.

A dynamic predictor should be able to predict changes in egg production and survival from year to year in response to changes in fish population dynamics. Such a predictor might be approached more profitably from an egg production--survival model. This kind of model can include biological feedback mechanisms that are likely to be operative in the real system and that cause changes in fish populations that vary with time. The latter approach, however, depends for its success upon better, more precise data on egg production and especially on surviving adults than is presently available--otherwise a dynamic model may not be justifiable.

Table 4.6. Comparison of life cycle model impact predictions.

Model	PR[a]	y-o-y compensation	PR in total adults			PR in 1-year-old fish			Source
			Number of years			Number of years			
			5	10		5	10		
LMS 1-D(67)	2.07	High	2.52	3.93		2.71	4.01		Table 1, Lawler (1973)
	3.42	Low	4.93	9.74		5.68	7.48		
	3.13	None	4.82	11.39		5.55	12.00		
			Number of years			Number of years			
			7	10	40	7	10	40	
LMS 2-D	1.21	High	1.29	1.64	2.18	1.33	1.68	2.18	Tables 36 and 37. LMS (1975)
	1.26	High	1.34	1.70	2.26	1.38	1.75	2.26	
	2.44	Low	2.64	3.70	6.82	2.81	3.91	6.99	
	3.14	Low	3.46	4.86	8.95	3.61	5.03	8.99	
	4.47	Low	4.93	6.88	12.42	5.13	7.11	12.46	

Model	PR	y-o-y compensation	Relative yield				PR in 1-year-old fish				Source
			Number of years				Number of years				
			5	10	20	40	5	10	20	40	
ORNL	10	None	0.96	0.90	0.85	0.83	10	14	17	18	Figs. B-47 and B-48 USNRC (1975)
	25	None	0.88	0.75	0.64	0.60	25	33	38	42	
	50	None	0.78	0.52	0.35	0.26	50	62	70	75	

Table 4.6. Comparison of life cycle model impact predictions - (Continued).

Model	PR	y-o-y compensation	PR in annual yield	Source
ORNL	0.5	None	0.03	Tables 8.1, 8.2, and 8.3.
Summit	2.75	None	0.77	Christensen et al. (1975)
	5.0	None	3.7	
JHU	2.5	None	0.45	Portner (1975)
	5.0	None	1.7	
Model	PR	y-o-y compensation	PR in total adults	Source
			35 years	
Winter Flounder	1.0	Best estimate	6.0	Sissenwine et al. (1974)
	1.0	None	9.0	

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[a] PR = percentage reduction.

The Summit model used the ORNL life-cycle model to convert from loss of y-o-y juveniles via entrainment to loss in average long-term fish yield. The life cycle model was run with three different PR values (representing high, moderate, and low entrainment loss) and nine different combinations of $P_{\max}$, $P_{\min}$ and R_d values (Section 4.4.2.1). Scaling factors for each case were obtained from the model runs (Table 5.3 in Christensen et al. 1975) and were found to be relatively insensitive to PR, but quite sensitive to the fishing mortality parameters. The SF obtained from the relative yield and adult populations for each set of runs of the life-cycle model with and without plant operation (relative yield is defined in Equation [4.6]) was:

$$SF = \frac{1 - \text{relative yield}}{PR} \qquad (4.7)$$

The Summit model predictions chose maximum and minimum values for a large number of parameters (<u>see</u> Table 4.5). All the maximum (minimum) values are used together in computing the maximum (minimum) loss. The JHU model had a range of values for only one parameter (C&D Canal contribution to upper Chesapeake Bay), so its maximum value is smaller than the Summit prediction.

Predictions from the ORNL and LMS models are not directly comparable from model documents for three major reasons. First, there is no overlap in y-o-y PR in the cases given. The ORNL models are in the 10-25 percent range and LMS models are in the 1-4.5 percent range. Second, the ORNL model has d-i y-o-y survival, while LMS uses d-d y-o-y survival. This means that a PR listed for the LMS model applies only for the first year because PR depends on egg production (<u>see</u> Table 3.16), which changes from year to year as adult stock is reduced because of reduced recruitment. Third, the ORNL runs are for a simulated scenario of 20 years of plant operation followed by 20 years recovery, while the LMS results are for 40 years of plant operation.

The LMS life cycle and y-o-y models are run as a single model. The life cycle part supplies egg production to the y-o-y part, and the y-o-y part computes the annual number of surviving 1-year-olds for use in the life cycle part. Although it is not stated in their document, the LMS 1-D (2-D) life cycle model runs the 1-D (2-D) y-o-y model for a couple of years and then uses the completely mixed y-o-y model (Lawler 1972<u>a</u>) to save time and expense, since a 40-year run of the LMS 1-D (2-D) y-o-y model is rather expensive. Because the number of surviving y-o-y predicted by the y-o-y model with a given set of entrainment factors depends only on the egg production (the entrainment factors never change in a single simulation), we suggest using an equation for number of surviving y-o-y as a function of egg production (obtained by running the y-o-y model over a range of egg production and using "best estimate" entrainment values) instead of running the y-o-y model each time. It is a less expensive and no less acurate alternative. We adopted this approach in our life cycle model simulator to include the effect of y-o-y compensatory mortality.

The LMS 1-D and 2-D results given in Table 4.6 have y-o-y compensatory mortality, while the ORNL model has compensation only in the fishing mortality function. It is not possible to see from Table 4.6 whether the difference in 1-year-old recruitment after 40 years between the two models is due to: 1) differences in PR; 2) parameter differences; 3) differences in compensation; or 4) scenario differences. Our desire to answer questions about sources of differences in model predictions was instrumental in providing incentive to develop a life-cycle model simulator.

The document for the LMS 2-D model (LMS 1975) leads the reader to believe that they used the ORNL d-d fishing model. T. Englert, modeling team leader for LMS (personal communication), however, assures us that the ORNL fishing mortality model was tried but is not contained in the version of the model presented in their document (LMS 1975). That is fortunate, as the equilibrium adult population used in the LMS 2-D model (see Table 4.4) is well below $B_{\min}$, the adult population below which compensation does not act. Thus adapting the ORNL fishing model to the LMS model would require parameter values significantly different from those reported in LMS (1975).

Some measure of the effect of y-o-y compensation on survival can be obtained by looking at the results of the URI model, where runs were made with and without y-o-y compensation. After 35 years, compensation resulted in one-third less reduction in adult stock. The Ricker (1954) type curve used for compensation in the URI model is not equivalent, however, to the spawner-recruit curves resulting from running the LMS y-o-y model.

Some type of sensitivity analysis (looking at the effects on model behavior of changes in model parameters) was performed by model developers for the LMS, ORNL, and Summit models, though similar parameters were not changed in most cases. A comparison of changes in impact predictions resulting from variability in model parameters (as given in model documents) appears in Table 4.7.

The LMS models examined the effect of changes in their y-o-y model on long-term impact as measured by reduction in total adult and first-year adult populations. We report some of their sensitivity results in changing (1) the parameters in the y-o-y compensatory mortality function, (2) the entrainment fractions for fish in the vicinity of the plant (f factors), and (3) both factors (1) and (2). Unfortunately, the LMS sensitivity runs almost never changed a single parameter at a time, and thus a clear picture of sensitivity is not available from their reported results (Lawler 1974).

Table 4.7 shows clearly that there is an interaction between compensation and the f factors in the LMS model. For example, going from high (best estimate) compensatory mortality to no compensation increases

Table 4.7. Effect of changing parameters on long-term impact predictions.

Model	PR	Parameter changed and value	Effect of change	Relative yield	Reduction (%)		Source
					y-o-y	Adult	
				yr 40	yr 40		
ORNL 1-D	10	None		0.83	18.0		a
	10	$M_{6,fish} = 0$ $M_{7,fish} = 0.5$	Late maturation	0.86	14.0		
	10	$M_{5,fish} = 0.5$ $M_{6,fish} = 1.0$	Early maturation	0.80	20.0		
	10	$PS_{1,nat} = 0.2$ $PS_{2,nat} = 0.4$ $PS_{3,nat} = 0.6$	Reduced survival of young	0.78	19.0		
	10	$PS_{1,nat} = 0.6$ $PS_{2,nat} = 0.8$ $PS_{3,nat} = 0.9$	Increased survival of young	0.86	17.0		
	10	$b = 106.1$ $c = -3.890$	Increased growth & fecundity	0.85	16.0		
	10	$b = 124.1$ $c = -2.290$	Reduced growth & fecundity	0.78	21.0		
	10	$B_1 = 1 \times 10^5 \times$ (1×10^7)	Reduced (increased) minimum fish available to fishery	0.83	18.0		
	10	$P_{max} = 0.75$ $P_{min} = 0.7$ $R_d = 0.4$	Reduced range of fishing mortality	0.67	36.0		
	10	$P_{max} = 0.95$ $P_{min} = 0.5$ $R_d = 0.8$	Increased range of fishing mortality	0.86	15.0		
	10	$B_{rat} = 2.0$	Reduced ration of max. to min. fish available to fishery	0.86	14.0		
	10	$B_{rat} = 5.0$	Increased ratio of max. to min. fish available to	0.8	20.0		
	10	$B_{leg} = 338$	Reduced legal size limit for fishing	86.0	15.0		

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Table 4.7. Effect of changing parameters on long-term impact predictions. - (Continued)

Model	PR	Parameter changed and value	Effect of change	Relative yield	Reduction (%)						Source
					y-o-y			Adult			
					yr			yr			
					5	10		5	10		
LMS 1-D 1967 data	2.07	normal[b]			2.71	4.01		2.52	3.93		c
	3.13	$k_o/k_e = 1.0$	No compensation								
	3.28		Reduced larval survival		3.54	3.89		3.47	3.87		
	3.51		Increased egg production, reduced larval survival		3.47	4.07		3.42	4.04		
	12.39		Increased f factors; no compensation, with impingement		18.01	32.44		16.3	31.15		
	2.91		Increased f factors; high compensation, with impingement		4.42	7.47		4.19	7.31		
	2.26		Low f factors		3.16	5.01		2.88	4.90		
	3.54	$k_o/k_e = 0.8$	Low f factors, low compensation		5.68	7.48		4.93	9.74		
	5.92		Low f factors, no compensation		9.46	18.79		8.39	17.93		
					yr			yr			
					7	10	40	7	10	40	
LMS 2-D 1973 data	1.26	$k_o/k_e = 0.5$	High compensation		1.38	1.75	2.26	1.34	1.70	2.26	
	3.14	$k_o/k_e = 0.8$	L - compensation		3.61	5.03	8.99	3.46	4.86	8.95	
	1.7	hatch. per. - 3 days	Increased hatching period, high compensation		1.87	2.36	30.06	1.82	2.31	3.06	d
					yr = 25			yr = 25			
ORNL SUMMIT	10	Normal			0.85			0.86			e
	10	$P_{max} = 0.65$ $P_{min} = 0.6$ $R_d = 0.4$	Reduced fishing mortality range		0.72			0.74			
		$P_{max} = 0.85$ $P_{min} = 0.4$ $R_d = 0.8$	Increased fishing mortality range		0.925			0.94			

[a] USNRC (1975, tables B47, B48)

[b] High compensation (k_o/k_e - 0.5)

[c] Lawler (1974), table 1.

[d] LMS (1975).

[e] Christensen et al. (1975), table 5.3.

adult PR after 10 years from 3.93 percent to 17.93 percent with one set of entrainment factors and from 7.31 percent to 31.15 percent with another set of (higher) entrainment factors.

The ORNL sensitivity analysis (USNRC 1975) focuses largely on changing fecundity, growth rate, survival, and fishery mortality parameters over a range of annual PR values from 10 percent to 50 percent. As this range does not overlap with PR values in the LMS model and as LMS does no sensitivity runs with life cycle model parameters, we cannot compare the sensitivity results between the two models from the information presented.

Some conclusions can be drawn from the relatively complete sensitivity results presented for the ORNL model (USNRC 1975). Since the ORNL model reported has d-i y-o-y survival, a PR given for the first year holds for all subsequent years of the run, providing plant operating conditions do not change substantially over the time period of the simulation. Table 4.7 shows relative yield and reduction in first-year adults after 20 years of plant operation and 20 years of recovery to be quite sensitive to the young adult (age class 1-3) survival fraction, the maximum and minimum probabilities for surviving fishing mortality, and the ratio of maximum and minimum catch available to the fishery. The results are almost completely independent of B_1. That is reasonable, as initial conditions are based only on B_1 and B_{rat}. Thus raising B_1 changes the initial condition, both with and without plant operation. Since the only d-d factor, the fishery mortality, is based on B_1 directly, no substantial changes in fishery mortality loss (as a fraction of the total population) result from changing B_1.

The Summit model sensitivity analysis varied the fishing mortality parameters that were found to influence model behavior most strongly--namely, maximum and minimum survival probabilities and R_d, a measure of the difference in survival probability at maximum and minimum fish biomass available to the fishery. The Summit model differs from the ORNL model only in the best estimate of the aforementioned parameters and in having a lower legal fishing limit and earlier adult [illegible]urity.

Although the ORNL and Summit sensitivity runs both [illegible] PR = 10 percent case, they were not directly comparable since t[illegible]er gives results after 10, 20, and 40 yr and the latter after 25 [illegible] simulated plant operation. Relative yield predictions are 0.85 for both models (ORNL after 20 yr and Summit after 25 yr), indicating the relative unimportance of maturity and legal limit parameters to model predictions.

4.7 Development of a Life Cycle Model Simulator

We decided to develop our own life cycle model simulator because we have insufficient information from many of the available documents. That is understandable, since none of the models really compared behavior with other models. We also used the simulator to answer questions that could not be answered with information from the model documents. They include:

1. Which has a stronger effect on reducing long-term impact predictions, a d-d fishing model (as ORNL used) or a d-d y-o-y model (as URI and LMS used)?

2. How important to model predictions is having an age-specific sex ratio, as the LMS models have?

3. How would the ORNL and LMS models compare if they had equivalent survival probabilities, especially for the younger age classes?

4. How do model predictions compare when comparable y-o-y PR values are used?

5. What predictions for relative yield do the LMS models give?

6. How would the models behave with different kinds of compensation functions (e.g., compare Ricker 1954 with Beverton and Holt 1957 spawner-recruit functions)?

7. How many years do the models predict it will take to recover after plant operation is discontinued?

8. How would a model behave with both d-d fishing and y-o-y survival?

With these questions in mind we decided to develop a Leslie matrix life cycle model that could accept d-d assumptions for both y-o-y and fishing survival, allow parameters to be varied easily from run to run, and allow plant operation to go on or off at any time to simulate various scenarios for plant operation.

The existing ORNL life cycle model had some of the flexibility we wanted and, since it was relative well documented and the code was available (Van Winkle et al. 1974), we decided to adapt it to our purposes. Parameter changes and various plant scenarios are easily accomplished with the interactive version of the ORNL model. We needed to change the model to be able to read in fecundities directly as a possible alternative to calculating them from a regression relationship, to allow for d-i y-o-y survival, and to allow for d-i fishing mortality.

Figure 4.2 is a flow chart for operation of our interactive life cycle model simulator. As shown there, the model initially sets up all the parameter values needed. In some instances some parameter values read in are not used; e.g., fishing mortality models are not used if the d-i fishing mortality option is chosen but are requested to be read in nonetheless, a feature left over from the ORNL model that was not changed for the sake of expediency. If the d-d fishing model option is taken, the model recalculates fishing survival probability for each time step, using the adult fish biomass available to the fishery at the beginning of the year. Similarly with d-d y-o-y survival, the survival probability (and PR if the plant is operating) is computed annually based on egg production at the end of the previous year.

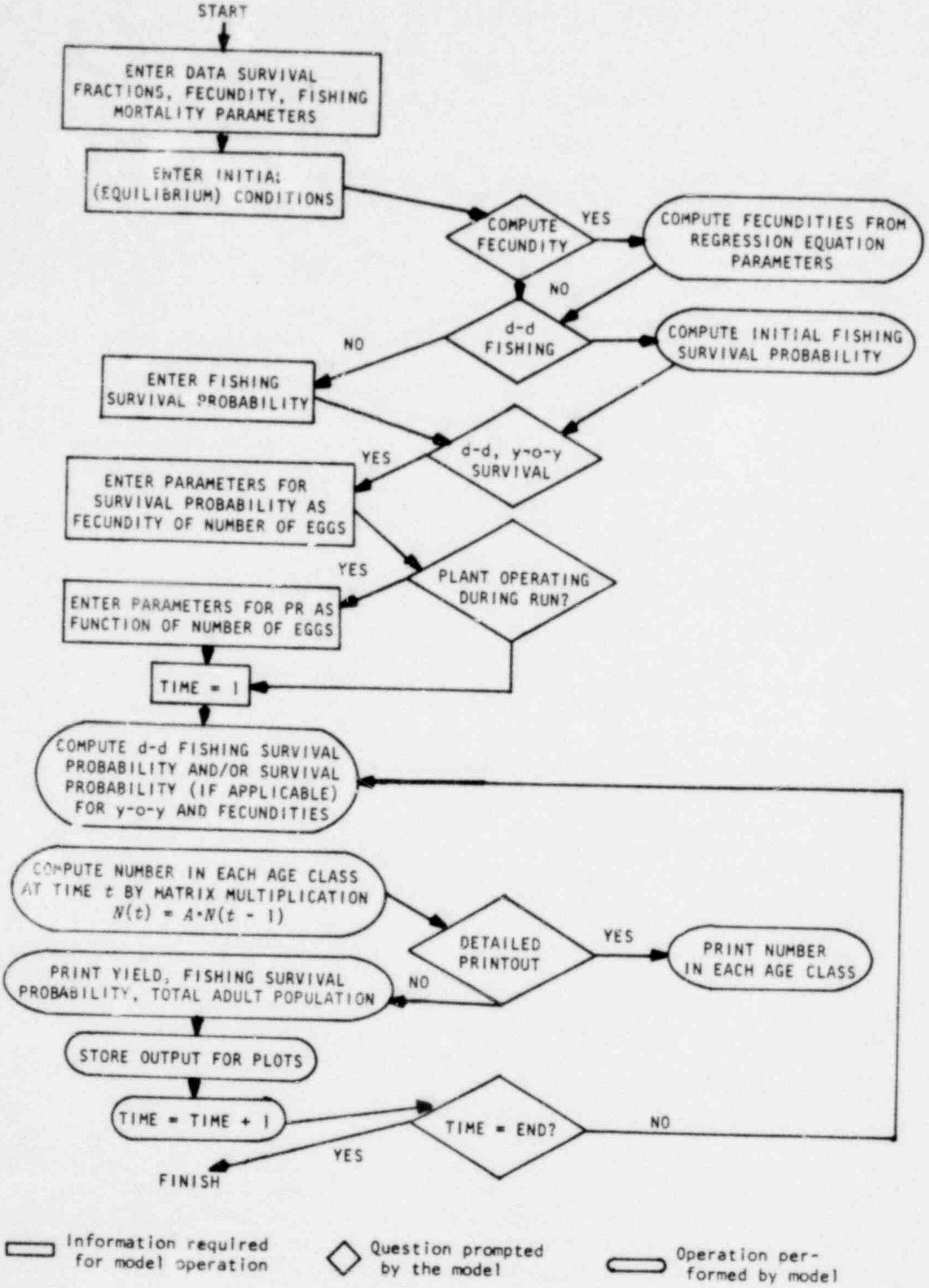

Fig. 4.2. Flow chart for life cycle model simulator.

Some explanation is in order on how the y-o-y d-d model was implemented. Plant operation was simulated in the URI life cycle model by applying the Ricker spawner-recruit curve and then reducing surviving recruits by PR. This seems like an improper application of the Ricker curve, since most mortality takes place on the younger age classes, which are subject to entrainment. The URI y-o-y model computes a reduction in larva survival due to plant operation, so the "spawners" in the URI Ricker curve should be larvae, not eggs. Unfortunately, methodology for a larvae-recruit curve is not worked out, nor are data available to do one. The URI method gives an overestimate of impact on fish populations if the Ricker spawner-recruit curve is taken to be accurate.

The LMS model used its y-o-y simulation as part of the life cycle model to compute surviving numbers of y-o-y. We thought this method too expensive and recognized that the surviving number of y-o-y fish depends only on egg production and on whether or not the plant is operating (assuming a given set of entrainment fractions in the y-o-y model). To obtain comparable runs of the LMS and the ORNL models and to investigate the effect of compensation in analogous situations we chose entrainment factors such that the LMS and ORNL models give equivalent PR predictions at equilibrium. We ran our LMS 1-D model simulator, adjusting the entrainment factors on our LMS y-o-y model simulator to give 10, 5, 2, and 1 percent PR under equilibrium egg production, and then ran the y-o-y model for each of these cases over a range of egg productions ranging from 0.01 to 10 times average production. From those runs we obtained curves of surviving y-o-y versus egg production both with and without plant operation (Fig. 4.3). Beverton-Holt (1957) and Ricker (1954) curves were fitted to these y-o-y/egg production curves in the region of average egg production (<u>see</u> Section 4.8.2). These curves are implemented in the life cycle simulator by specifying either the Beverton-Holt or Ricker curves and allowing parameters to be changed in any year, thus permitting various scenarios of plant operation.

4.8 Analysis Using a Life Cycle Model Simulator

4.8.1 Sex Ratio Study

The LMS model has sex ratio increasing from [illegible] percent to 70 percent females from age class 1 to age class 10, respectively. We wished to investigate the effect of this assumption on impact predictions for the LMS models. We worked with a model using the survival and fecundity parameters from the LMS 1-D model, assuming d-i y-o-y survival (no compensation) and d-i fishing mortality. Runs were made with PR equal to 5, 10, and 25 percent for a sex ratio of 0.5 and again for a sex ratio of 0.7. Because the two runs represent outer limits on the assumed sex ratios for the LMS models, we used the results from these two sets of runs as a measure of the maximum difference in predictions due to changing sex ratio. Parameter adjustment was necessary to obtain "comparable" conditions for the two sets of runs. We had the option of keeping either the egg production or the total adult population the same in the two runs--since sex ratios were different, identical total populations would

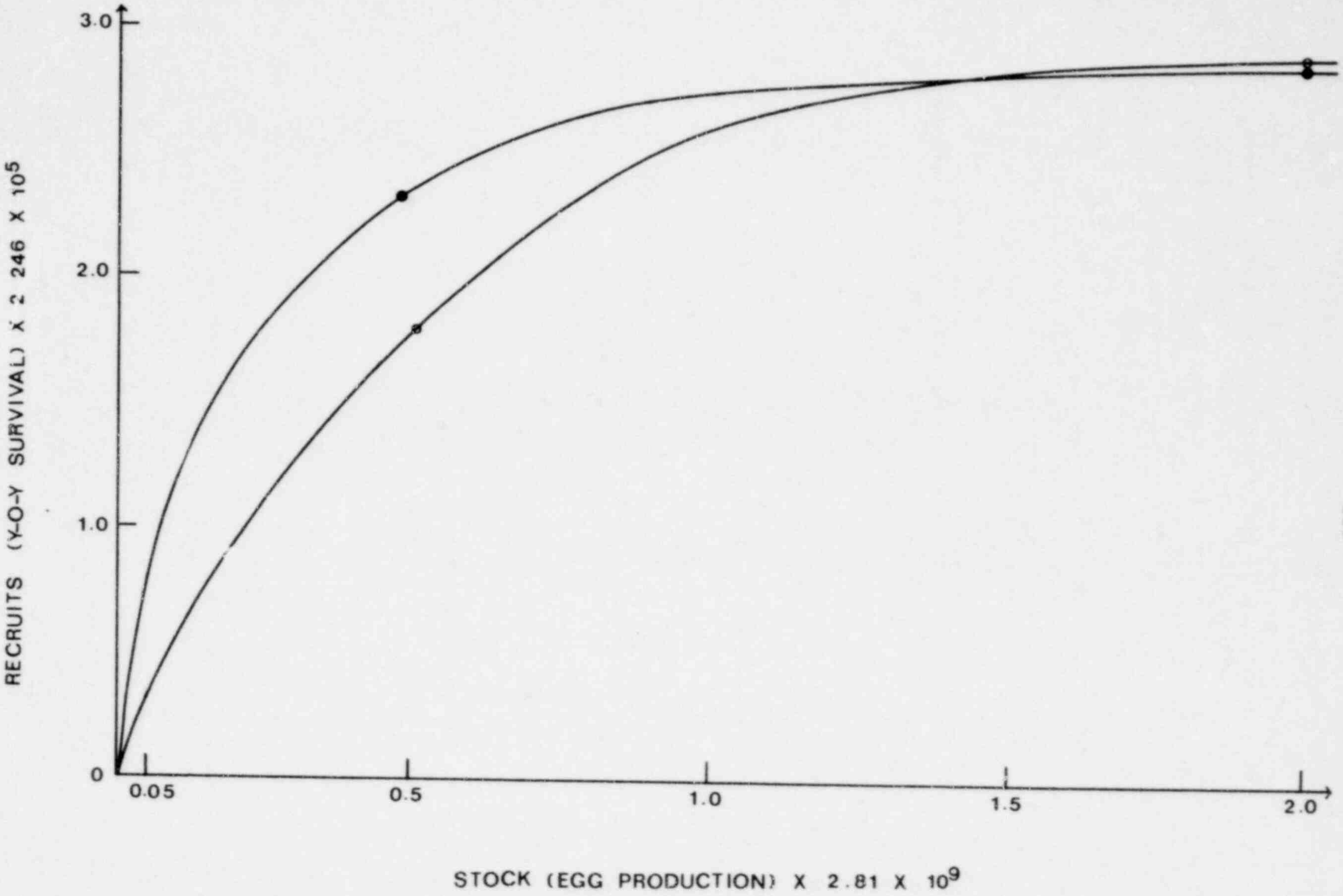

Fig. 4.3. Stock progeny curve from LMS y-o-y model.

• - without plant; ° - with plant.

result in different egg productions in the two cases. We chose constancy of egg production and therefore adjusted $S_4 \rightarrow S_{12}$. The values we chose for survival fraction resulting in equilibrium were 0.6613 for the 0.5 sex ratio run and 0.5875 for the 0.7 sex ratio case (as opposed to 0.614 for the ordinary case). A scenario of 20 yr of plant operation followed by 20 yr without plant operation was used. Relative yield after 10, 20, and 40 yr for each of the three cases is shown in Table 4.8.

4.8.2 Implementation of Y-O-Y Compensatory Mortality Life Cycle Models

In reviewing the methods used for combining a y-o-y compensatory effect with a life cycle model, we decided that each of the approaches was unacceptable for use in our simulator for differing reasons.

The URI model used a Ricker (1954) stock-progeny curve to compute surviving y-o-y as a function of egg production. Plant operation was included by reducing these surviving y-o-y by a constant, the ratio of numbers of surviving larvae with plant operation to those surviving without plant operation, obtained from a hydrodynamic y-o-y simulator. We think this is an improper application of the Ricker function since Ricker's curve assumes compensation acting to produce a relationship between stock (eggs) and progeny. This compensation, presumably in the form of a d-d mortality, was not included in the hydrodynamic simulator. If compensation of the Ricker type is to occur, it probably occurs in the younger life stages of fish larvae (Chadwick et al. 1977) while they are being entrained. Use of the Ricker curve as in the URI model should overestimate the effect of plant operation on the mature fish population since is is reducing y-o-y survivors by a larger fraction than would be reflected if compensation were occurring while entrainment was acting on the population.

The ORNL life cycle model did not include compensation. Instead they ran the model at differing PR levels, which did not change as a function of egg production. The LMS life cycle model ran the y-o-y model each year to obtain a surviving number of y-o-y for that year. Since the only change from year to year is the egg production, the LMS method seems overly expensive. We instead adopted the following procedure in simulating the LMS compensatory mortality (CM) effect and in simulating the effect including this CM in the ORNL model would have.

After computing an equilibrium age structure without plant operation and adjusting the fishing mortality constants to give the same equilibrium, the LMS y-o-y simulator was run with egg productions of 0.1, 0.5, 0.8, 0.9, 1, and 2 times equilibrium egg production to obtain a stock-progeny curve for surviving y-o-y (progeny) as a function of egg production (stock). Stock-progeny curves were obtained without the plants operating for high CM, low CM, and no CM (d-i mortality), and also with the plant operating at each of these compensation levels. The stock-progeny curve for high CM is compared with that for low CM in Fig. 4.4 for the case without the plants operating. Similar stock-progeny curves were obtained at differing f (entrainment) factors, which were used

Table 4.8. Sex ratio effect on relative yield predictions LMS 1-D model.

Model	PR	Number of years		
		10	20	40
LMS 1-D	5	0.98	0.89	0.87
Sex ratio = 0.5	10	0.92	0.78	0.75
LMS 1-D	5	0.95	0.88	0.86
Changing sex ratio	10	0.90	0.78	0.74
	25	0.76	0.51	0.45
LMS 1-D	5	0.95	0.88	0.86
Sex ratio = 0.7	10	0.90	0.76	0.73
	25	0.74	0.48	0.43

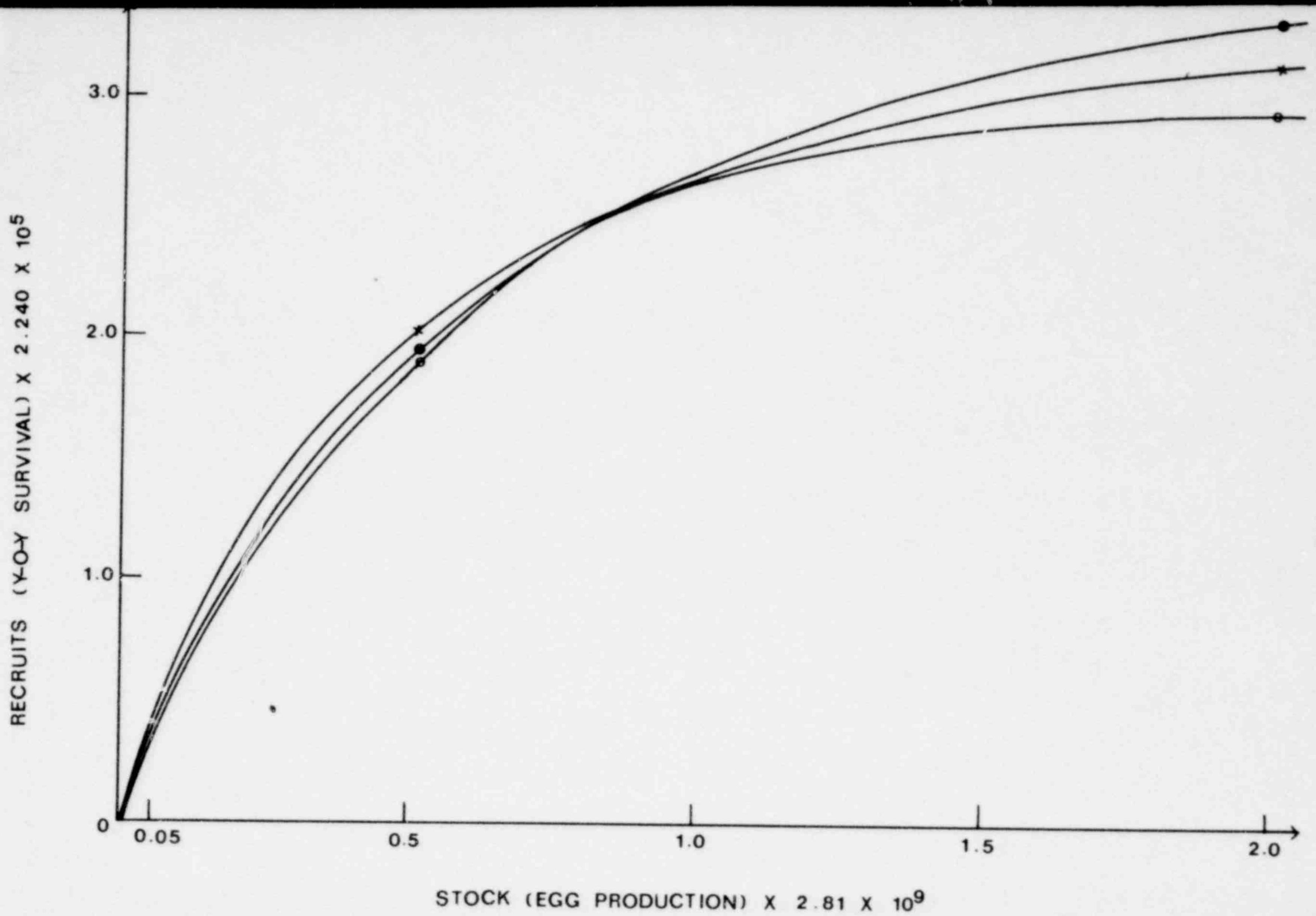

Fig. 4.4. Beverton-Holt curves best fitting LMS y-o-y model stock production curve for low compensatory mortality. ° - actual LMS curve, x - best overall fit, • - best fit near equilibrium egg production.

to examine the effect of changing f factors on fish populations and also to obtain stock-progeny curves for different PR levels than those obtained for the best-estimate f factors used in the LMS model. The y-o-y model was also run to obtain a stock-progeny curve using a linear CM effect instead of a third-order effect, and with the left arm of the linear effect (below the equilibrium population levels) disabled (i.e., constant mortality rate below the equilibrium population level), as was done in the ORNL model.

Although the stock-progeny curves obtained from the y-o-y model could be used directly in the life cycle model as a table lookup function, we preferred to obtain an equation that would closely fit the stock-progeny curves obtained from the y-o-y simulator. Figure 4.4 shows the stock-progeny curves to be monotonically increasing rather than dome-shaped, which suggests a Beverton-Holt (1957) type stock-progeny curve rather than a Ricker curve. Denoting stock and progeny by S and R, respectively, the Beverton-Holt curve may be expressed by

$$R = \frac{S}{\alpha + \beta S} \tag{4.8}$$

The Ricker curve is given by

$$R = \alpha' S e^{-\beta' S} \tag{4.9}$$

Best estimate parameters for α and β in the Beverton-Holt curve can be obtained by graphing $1/R$ versus $1/S$ which gives a straight line having intercept β and slope α. Ricker curve parameters can be obtained from the best straight-line fit to a graph of ln (R/S) versus S.

In our case, we found that the Beverton-Holt parameters best fitting the LMS y-o-y model stock-progeny curve did not fit well near the equilibrium egg production. Since this was the region of the stock-progeny curve most used in running the life cycle model, we instead fit the Beverton-Holt curves to exactly replicate results at 0.8 and 1.0 times equilibrium egg production. Figure 4.4 shows the best fitting Beverton-Holt curves over the entire range of egg production and close to equilibrium egg production compared with the stock-progeny curves obtained from the LMS y-o-y simulator without plants operating and using high CM $(k_o/k_e = 0.5)$.

Parameter values for Beverton-Holt curves fit to 0.8 and 1 times equilibrium egg production values obtained from the LMS y-o-y simulator are given in Table 4.9. Since equilibrium age distributions were obtained from model documents while surviving y-o-y was obtained from our y-o-y

Table 4.9. Parameter values for the Beverton-Holt stock progeny curve best fitting LMS y-o-y model output.

Compensation		With plant operation	Without plant operation
High	α	7.272×10^{2}	6.316×10^{2}
	β	2.8×10^{-6}	2.74×10^{-6}
Low	α	2.083×10^{3}	1.875×10^{3}
	β	2.2×10^{-6}	2.0×10^{-6}

simulator, there are small differences in the equilibrium y-o-y survival. We adjusted the survival fraction of 1-year-olds and the equilibrium y-o-y population to reflect this difference in order to maintain the same equilibrium adult population. Thus different equilibrium values are obtained for different CM levels (high, low, or none).

The life cycle models were run with 20 yr of simulated plant operation and 20 yr of "recovery" without plants operating. Plots were obtained of yield and total adult biomass versus time and tabulation was made of PR in yield and of total adult biomass, after 5, 10, and 20 yr of plant operation. These are displayed (Table 4.10) in connection with the discussion of results obtained to answer different questions about the relative predictions of the models and sensitivity of model predictions to obvious assumptions.

4.8.3 Comparison of Effect of ORNL and LMS Life Cycle Parameters on Long-Term Predictions

As mentioned earlier, direct comparison of the ORNL and LMS models under analogous conditions could not be obtained from model documentation since PR values were so different. To remedy this, we ran simulators of the LMS 2-D and ORNL 1-D life cycle models both with no y-o-y compensation at equivalent PR values and then with Beverton-Holt y-o-y compensation fitted to give a "best" fit to the stock-progeny curve based on the LMS 2-D y-o-y simulator. Compensation in the ORNL model was included by using the LMS stock-progeny curves adjusted to equilibrium egg production and equilibrium y-o-y survival for the ORNL model. We also assumed the same ratio of surviving y-o-y at 80 percent of equilibrium egg production to that at equilibrium egg production as in the LMS stock-progeny curve and the same PR values at these two levels of egg production, as in the LMS case. The results of this comparison are given in Table 4.10 in terms of reduction in yield and in the adult population.

The basic parameter differences between the ORNL and LMS models are:

1. Survival of immature adults (1-, 2-, and 3-year-old) is higher in the ORNL models.

2. Equilibrium egg production and equilibrium survival of y-o-y is higher in the ORNL model.

3. For d-d fishing, the ORNL model used a higher ratio of maximum to minimum fish biomass available to the fishery. This gives the ORNL fishing mortality model a stronger compensatory mortality due to fishing.

4. Maturity in the LMS 1-D model occurs earlier.

5. Fecundities are different.

Table 4.10. Comparison of long-term predictions in LMS and ORNL models.

	PR	PR in adult biomass			PR in fisheries yield		
Model	1st yr	yr 5	yr 10	yr 20	yr 5	yr 10	yr 20
Part A. Density-independent y-o-y and fishing survival							
LMS 1-D	2	0.51	1.32	3.19	0.6	1.54	3.5
	5	1.26	4.62	10.36	a	a	10.6
	10	2.55	9.36	21.7	3.5	9.1	21.7
	25	6.5	23.5	49	7.6	23.0	48.2
LMS 2-D	3.5	2.13	4.62	10.1	1.95	4.49	10.02
	5	2.68	5.92	12.98	2.49	5.76	12.9
	7.83	3.97	8.92	19.42	3.71	8.73	19.28
ORNL 1-D	4.18	1.36	4.34	9.84	1.23	4.28	9.77
	5	1.41	4.54	10.25	1.30	4.48	10.18
Part B. Density-dependent fishing survival only							
LMS 2-D	3.5	1.89	3.28	4.97	2.95	5.18	8.0
	5	2.37	4.10	6.31	3.79	6.63	10.24
	7.84	3.67	6.35	9.83	5.67	10.15	15.72
	15.9	7.73	13.38	20.32	12.15	21.2	31.85
ORNL	4.51	a	a	4.59	a	a	7.03
	5	1.31	3.08	4.75	1.89	4.66	7.22
	10	3.7	6.4	9.7	4.5	10.3	14.6
Part C. Density-dependent y-o-y survival only							
LMS 2-D - high CM	3.53	2.1	3.9	4.3	2.0	3.8	4.3
LMS 1-D - low CM	7.86	4.0	8.1	11.8	3.7	8.0	11.8
ORNL 1-D - high CM	3.80	1.2	3.3	4.3	1.0	3.3	4.2
ORNL 1-D - low CM	7.74	2.4	7.0	11.1	2.3	7.0	11.0
Part D. Density-dependent y-o-y and fishing survival							
LMS 2-D - high CM	3.53	1.9	2.8	2.9	3.0	4.5	4.7
LMS 2-D - low CM	7.86	3.6	5.8	7.0	5.7	9.3	11.2
ORNL 1-D - high CM	3.8	0.96	2.2	2.4	1.4	3.4	3.7

[a] Not calculated.

Since results are presented in relative terms (percentage reduction), they are independent of differences in equilibrium egg production and adult biomass.

Comparing all the cases with d-i conditions, the LMS 2-D life cycle model gives the highest PR predictions while the LMS 1-D and ORNL 1-D life cycle models seem very close. As expected, making the LMS models d-i results in much higher reductions due to plant operation than reported in the LMS documents.

When d-d fishing mortality is included, the LMS 2-D predictions for PR are clearly greater than the ORNL predictions. For example, with PR = 3.5 for the LMS model and PR = 4.5 for the ORNL model, the reductions in adult population after 20 yr are 4.97 and 4.59, respectively. Thus the LMS model predicts greater reductions in adult populations than the ORNL model even in a case where annual PR in 1-year-olds is greater in the ORNL model. While the same pattern also obtains with the analogous d-i model, it is less striking. These results clearly show the ORNL fishing mortality model to be a stronger compensatory mechanism than the LMS 1-D model.

Comparing the LMS 1-D model with the ORNL model having the same y-o-y compensatory mortality terms and almost identical annual PR in y-o-y due to plant operation, the ORNL model shows greater compensation that the LMS model. The fact that the relative difference between the two models is increased when d-d fishing mortality is added is due to the differences in the fishing models.

It is important to point out again in this comparison that the ORNL model was not developed with a y-o-y compensation function nor did the LMS model use d-d fishing mortality (though they presented such a model--LMS 1975) and thus these differences are not indicated in model documents.

Results of this comparison of differences in model predictions due to model parameter values alone indicate that the LMS 2-D model gives higher predictions for reduction in adult population and yield than the ORNL model. Examining cases with annual y-o-y PR equal to 5 percent shows that after 20 yr the LMS adult population PR prediction is 27 percent greater than the ORNL prediction in the d-i case while it is 33 percent greater in the d-d fishing case. Yield PR predictions are even more disparate, with [illegible]7 percent and 42 percent differences between the two models for the above two cases. This indicates that, while most difference in model predictions in these analogous cases is due to parameter values in the survival-fecundity matrix, the differences of parameter values in the fishing mortality models also affect predictions, especially fishery yield.

4.8.4 D-D Y-O-Y Mortality versus D-D Fishing Mortality

We can see that y-o-y compensation is a much stronger compensatory mechanism than fishing mortality. Comparing analogous PR cases of the LMS 2-D model having d-d fishing mortality with cases having low y-o-y CM, we see that low CM acting alone predicts a PR in adult populations after 20 yr 42 percent below and in yield 63 percent below the case with d-d fishing mortality acting alone. This difference is striking and when high y-o-y CM is considered, the difference increases to 79 percent and 86 percent for adult population and yield, respectively. Note that the annual PR values for high, low, and no y-o-y compensatory mortality are different. This difference arises from running the LMS y-o-y simulator with different strengths of d-d mortality (k_o/k_e = 0.5 for high CM, k_o/k_e = 0.8 for low CM, and k_o/k_e = 1 for no CM or d-i mortality).

Running the life cycle model with both d-d y-o-y and fishing mortality reduces PR predictions but the d-d fishing is not as effective at reducing the predicted reduction due to plant operation as it is when d-d fishing is added to a d-i model. For example, when d-d fishing is added to a d-i model having annual y-o-y PR = 3.5 percent, adult PR and yield PR after 20 yr are reduced by 51 percent and 20 percent, respectively, while when d-d fishing is added to a model having high y-o-y CM adult population PR is reduced by only 33 percent and yield PR is increased by 9 percent. This illustrates the striking quality of d-d fishing mortality of initially reducing fishery yield to compensate for the reduced adult stocks. In all other cases shown, this reduction in fishery yield allows the adult stock to fare better than in cases without d-d fishing, and by 20 yr the trend has reversed and yields in the d-d fishing case are higher. This is not so here, although simulating plant operation in the model for a longer time would certainly cause long-term yield to eventually be higher in the d-d fishing case than the d-i fishing case.

4.8.5 Effect of Changing Entrainment Factors

Both the ORNL and LMS y-o-y models use an f or entrainment factor that determines the fraction of fish in the neighborhood of a power plant that are entrained. The effect of changing this f factor (best estimates of which differ markedly between the above two groups of models) on predictions of surviving y-o-y and PR is discussed earlier in this report in studies made with the y-o-y simulator (Section 3.). By running the simulator at different egg production levels and at both high and low CM for entrainment factors varying from 0.2 (low entrainment) to 1.0 (all fish in the neighborhood of the plant entrainment), a stock-progeny curve was obtained for each f factor at each CM level. These were then fit to Beverton-Holt curves for use in the life cycle model to see the effect of changing f factors on long-term PR values.

Results are given in Table 4.' for long-term PR in total adult biomass and fishery yield due to plant operation for each f factor and both high and low CM. These results are based on our runs of the y-o-y simulator. Initially striking is the constant relationship between change in long-term PR and changes in f factors. Entraining five times the fish in the neighborhood of the plant (changing f from 0.2 to 1) increases plant reduction predictions after 20 yr by a factor of 4.5-5.0 and this relationship bears out for all the other cases. This seems to indicate

Table 4.11. Effect of entrainment factors on long-term population survival, LMS 2-D model.

f	PR	PR in total adults			PR in yield			PR in 1-yr-olds		
factor	1st yr	yr 5	yr 10	yr 20	yr 5	yr 10	yr 20	yr 5	yr 10	yr 20
Part A - low CM										
0.2	3.09	1.54	3.04	4.18	1.39	2.96	4.10			
0.4	5.74	2.88	5.84	8.33	2.68	5.76	8.26			
0.6	8.34	4.22	8.60	12.63	3.95	8.50	12.58			
0.8	10.63	5.4	11.0	16.7	5.1	10.9	16.1	5.0	9.6	12.7
1.0	12.85	6.6	13.5	20.6	6.2	13.3	20.5	7.3	13.1	17.4
Part B - high CM										
0.2	1.10	0.87	1.46	1.58	0.79	1.39	1.53			
0.4	2.38	1.54	2.72	3.00	1.41	2.67	2.96			
0.6	3.68	2.21	4.03	4.54	2.05	3.95	4.46			
0.8	4.86	2.80	5.21	5.88	2.62	5.14	5.82			
1.0	5.96	3.39	6.31	7.18	3.16	6.24	7.14			

that there is no confounding or interaction effect in these CM models between f factors and level of compensation. If that is true, then we can say that doubling the entrainment of a plant will double the model prediction of long-term reduction in both adult fish populations and fishery yield.

This result is at first startling because it is not the case for short-term predictions that, for example, doubling the f factor doubles PR--it more than doubles it in the high CM case and less than doubles it in the low CM case. Oddly enough, the situation is reversed after 20 yr. Doubling f results in a greater increase in PR for both adult population and yield in the low CM case than for high CM. We can think of no obvious reason for this effect. Figure 4.5 shows both fishery yield and total adult biomass plotted against time for each of the five f factors and low CM, with the best estimate f factor values shown with dots for 20 yr of simulated plant operation followed by 20 yr of recovery. The recovery curve for $f = 0.8$ is incorrect because of an improper parameter value in that run.

4.8.6 Effect of Changing Type of Compensation

To answer the question of how changing the compensatory curve affects PR predictions, we explored two approaches: 1) fitting the best estimate case to a Ricker function instead of a Beverton-Holt; and 2) using a linear d-d y-o-y mortality curve instead of a third-order curve as used by LMS.

The linear curve was chosen to go through the same equilibrium point as the LMS curve and the same k_o point. The results presented here are for $k_o/k_e = 0.5$ and with the lines below the equilibrium level disabled. Previous work (Swartzman et al. 1977) has suggested that compensation operates mainly at high densities, and keeping mortality rate constant below the equilibrium seems a good way to ensure this. Also, this piecewise linear curve used in the LMS model is analogous to the d-d mortality function used in the ORNL 1-D y-o-y model.

The parameter for the Ricker curves fit to the stock-progeny curve based on the y-o-y model with low CM and best estimate f factors are: 4.42×10^{-4} and so on

	without plant operating	with plant operating
α'	4.42×10^{-4}	3.6×10^{-4}
β'	5.244×10^{-10}	4.306×10^{-10}

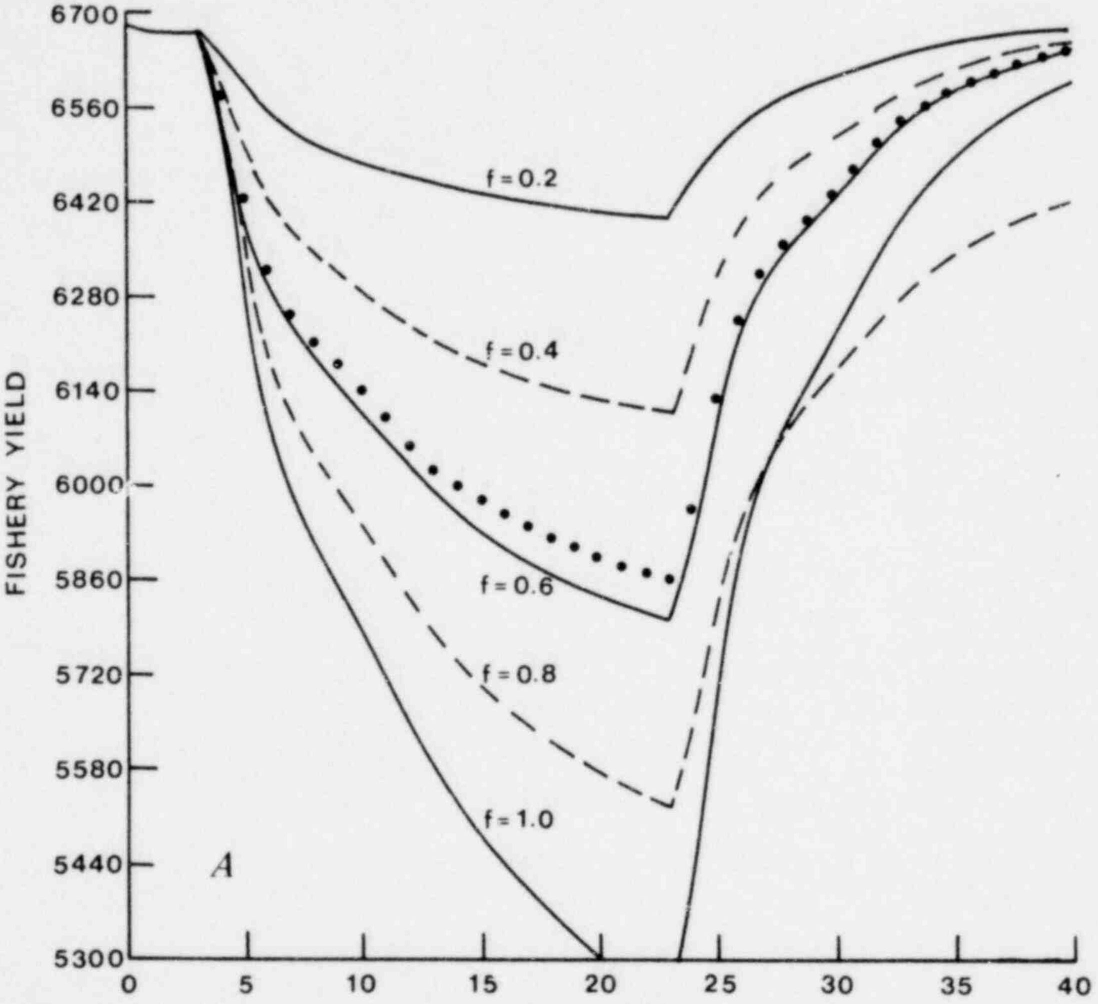

Fig. 4.5*a*. Effect of entrainment factors and compensatory mortality on fishery yield. (Beverton - Holt low compensation) ••• - best estimate entrainment factors.

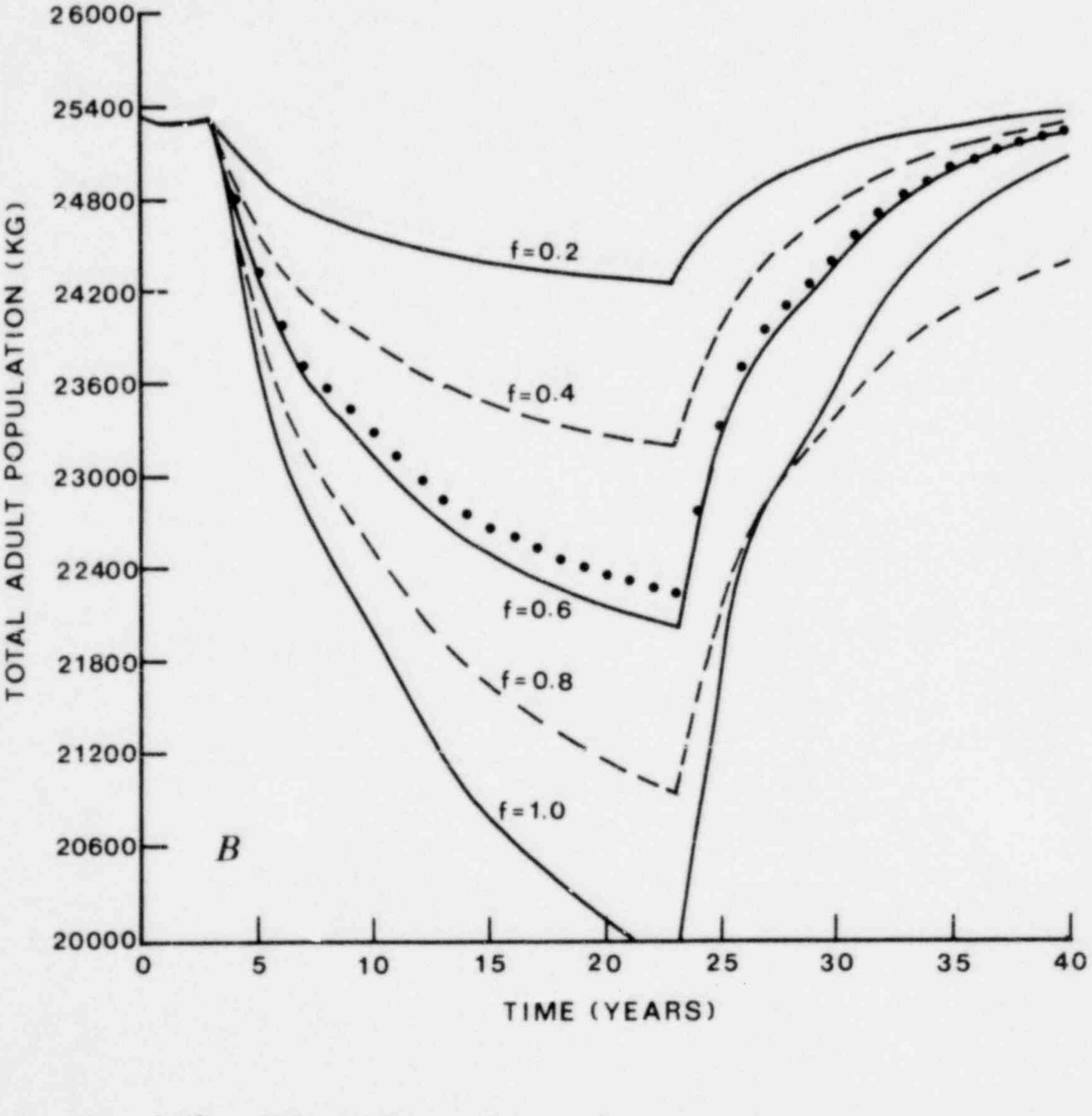

Fig. 4.5*b*. Effect of entrainment factors and compensatory mortality on adult populations. (Beverton - Holt low compensation). ••• - best estimate entrainment factors.

The fit of a Ricker CM curve to the data is shown in Fig. 4.6. The fit is actually better over the 0.6 to 1 times equilibrium egg production range, although not in the high egg production range, than the Beverton-Holt curve.

Using the Ricker CM functions with parameters as above (low CM), in the life cycle model with d-d fishing mortality give PR values in adult biomass and yield after 20 yr of 10.58 percent and 10.54 percent, respectively. The analogous Beverton-Holt runs gave 11.8 percent reductions on both quantities. This difference is due somewhat to a slight difference in PR the first year for y-o-y fish (7.86 for the Beverton-Holt and 7.71 for the Ricker model), but some effect may be due to differences in the two curves. There is little difference in the long-term predictions (with PR in the 0-20 percent range) between Beverton-Holt and Ricker stock-progeny curve fit to output of the LMS y-o-y model.

Using a linear mortality function (with constant mortality below the equilibrium population) instead of a third-order function in the LMS y-o-y simulator results in a stock-progeny curve that is more closely fitted over its entire range to Beverton-Holt or Ricker stock-progeny curves than the stock-progeny curve generated by the simulator using the LMS third-order curve. Parameters for these fit Beverton-Holt curves to the high linear CM case are:

	without plant operating	with plant operating
α	2.218×10^{3}	2.782×10^{3}
β	3.184×10^{-6}	3.354×10^{-6}

Running the life cycle model with those values gives 15.6 percent and 15.5 percent reductions in adult population and fishery yield. The equivalent third-order CM case gave 4.3 percent reductions. We note a fourfold increase in prediction of long-term loss in adults and yield by disabling the left limb of the y-o-y CM function and using a linear right limb. We know the major effect is due to disabling the part of the CM function that reduces mortality rate at low densities because analogous runs of the y-o-y simulator with a linear CM function replacing the third-order function over the entire range gave PR predictions very close to those with the third-order function (Section 3.).

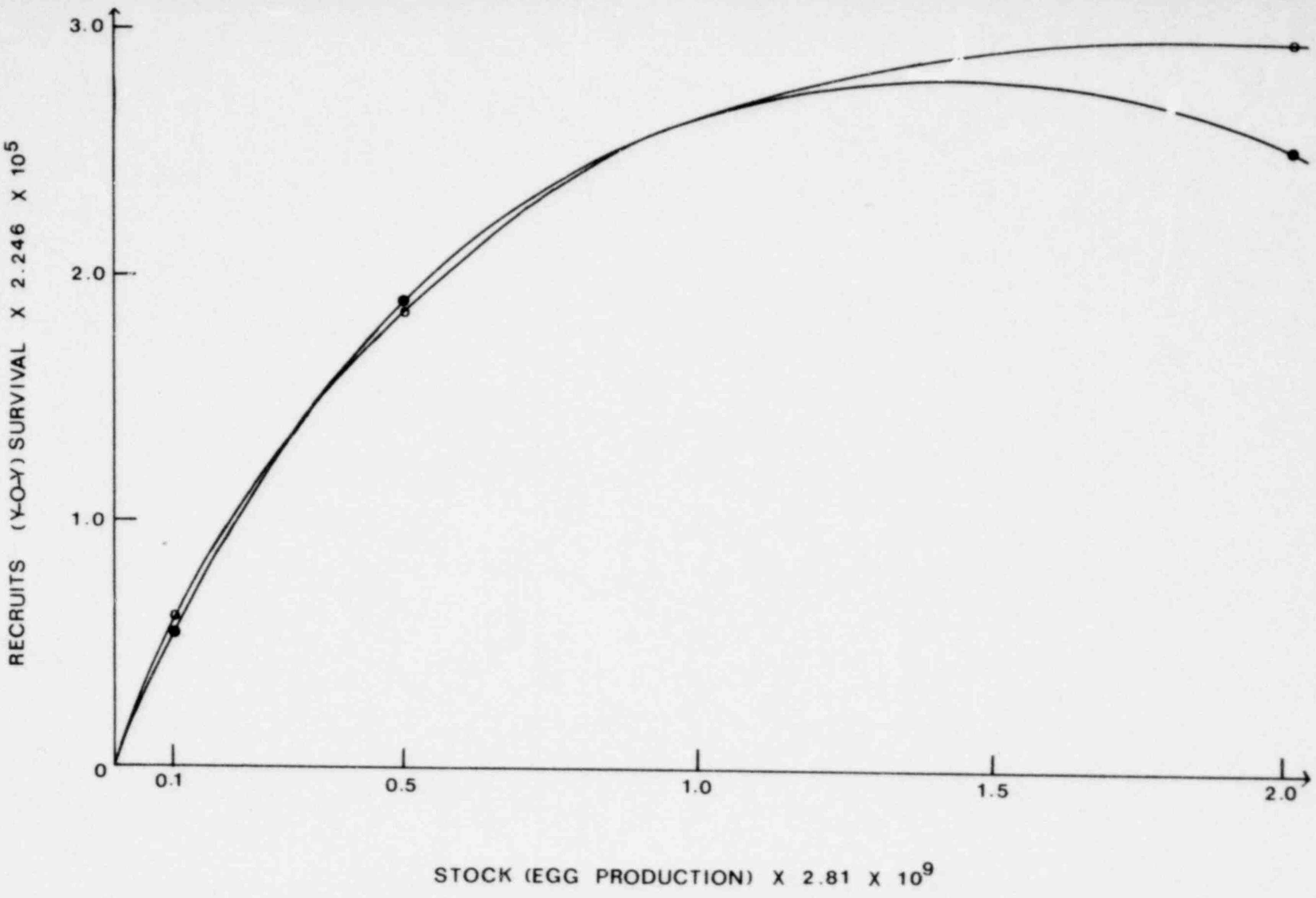

Fig. 4.6. Ricker curve compared with low-compensation LMS stock progeny curve.
• - Ricker curve.

5.0 CONCLUSIONS

This report compares models developed to predict the impact of power plant operation on fish recruitment, adult populations, and fisheries yield. This comparison evaluates predictive ability and the biological realism of model assumptions, investigates differences of prediction between analogous models and the nature of and cause for these differences and recommends preferred approaches as well as possible new approaches to impact modeling.

Table 5.1 summarizes the approaches to impact modeling in the models reviewed. The major differences in approach were in the use of equations for compensatory or density-dependent mortality and in basing the impact prediction either primarily on detailed egg and larval sampling data or on comprehensive fisheries catch and effort data.

The question of compensation is central to the wide differences in impact prediction given by the various models. The LMS models invariably assume an equation for density-dependent mortality that strongly compensates for losses induced by entrainment. There are no data presented in any of the LMS models substantiating the particular equation forms used for their d-d mortality function. What is presented are a number of intuitive arguments that compensation should be operative based primarily on cannibalism, bluefish predation, increased food resources at lower populations, and fishing.

While the existence of compensation in some fish species is probable, most evidence for d-d mortality presented (McFadden 1977) is for high fish densities. The density dependence presented by LMS is largely operative at low densities (below normal because of reduced populations due to entrainment). Furthermore, LMS has d-d mortality operating not only during early life stages but through the entire first year of life. This is counter to information by Chadwick (1977) that year class strength of striped bass can be 'predicted' from population densities at 3 months.

The second major question discussed by Portner (1975) is whether to base models primarily on intensive sampling of egg production data, larval and juvenile densities, and estimated survival rates or on catch statistics and migration studies. Present data availability favors the second approach since the high variability of fish egg and young fish densities from year to year and place to place is so high. However, fish catch data are also variable from place to place due to variability of reporting regulations and measures of effort used and migration data are expensive to obtain and difficult to interpret. Also the second approach offers no hope of year-to-year preditions and has a built-in lag period of the time to reach fishable age.

The high variablity in data used for both approaches and the simplicity of assumption and lack of information in such areas as density-dependent mortality make no existing model useful as a predictor of power plant impact. Much of the work done in this study involves substantiating what we have indicated above--i.e., that differences in model parameter values in the absence of data empirically supporting any chosen parameter values are the primary source of differences between model predictions. In the case of the Chesapeake, the models agree fairly closely in predictions which serves only to accentuate the

Table 5.1 Comparison of model approaches.

Criterion		LMS	ORNL	ORNL SUMMIT	JHU	URI
Compensation						
a) y-o-y	Highly d-d	✓				
	Weakly d-d		✓			✓
	d-i				✓	
b) fishery d-d model			✓	✓		
Hydrodynamics						
	Use detailed hydrodynamic model	✓	✓		✓	✓
Model approach						
	Use fisheries catch data		✓	✓	✓	
	Use detailed y-o-y sampling data	✓	✓			
Adult impact assessment						
	Use Leslie matrix	✓	✓	✓		✓

well known fact that plants using closed cycle cooling systems are not likely to have significant impact on larval densities.

The one system where impacts are likely to be significant--the Hudson River--has an order of magnitude difference between PR predictions in two sets of models presented by groups having different interests in demonstrating significant impact. That the potential for significant impact on Hudson River striped bass populations is high is clear from results of our simulation studies with these models. Table 5.2 summarizes some of these studies made with our simulators. The most striking result is the ability to demonstrate insignificant impact (low PR) through the use of d-d mortality functions with parameters as used in the LMS models. In the high CM case PR is reduced by 75-80 percent from predictions of a d-i model. About 50 percent of this reduction is due to having d-d mortality in the later life stages (J-II and J-III) well after Chadwick (1977) demonstrated for San Joaquin striped bass that compensation no longer exists.

The sensitivity of PR predictions to the CM function makes investigation of the effects of other model differences relatively unimportant. However, there are other factors which taken together can approach the d-d mortality function in importance. These include the number of segments the river is divided into by the model, the choice of entrainment factors, and the choice of advection avoidance factors. In all these three cases the LMS parameter values worked to reduce PR over ORNL values. For example, the LMS 2-D model had 29 segments versus 10 in our simulator. Reducing the number of segments in our simulator from 10 to 5 served to reduce PR by 33 percent in the d-i case for the ORNL approach.

Many of the other differences between the Hudson River models were insignificant in their effects on PR. These include the sex ratio difference, the use of a linear vs. third order density-dependent mortality function, the adult annual survival fractions, and the lengths of age class stages in the y-o-y model.

Another difference, the use of a d-d fishing model by ORNL did significantly reduce predictions of PR on adult populations by up to 50 percent after 20 years from the d-i case (Table 4.10). However, the effect of d-d fishing on PR in fishery yield is significantly less than on the adult population and there is a lag period after entrainment loss begins before d-d fishing mortality changes start acting. Considering the sensitivity of the models to compensation versus fishing compensatory mortality, the y-o-y compensation function with parameters as used in the LMS model is more effective at reducing PR predictions than d-d fishing mortality having parameter values as used by ORNL. Several parameter values in the ORNL fishing mortality model have very high variances and an LMS review of this model suggests parameter values that would result in less compensation than the equivalent ORNL values (Table 4.10, part D).

Despite our pessimism on the use of these models for predictive purposes, our conclusion is not that these models are worthless. They have focused attention on two very sensitive areas in fisheries biology--the need for further study of compensation in fisheries and the need to use and more

Table 5.2. Summarized results of simulator investigations of differences in assumptions between Hudson River models.

Base case PR = 10

LMS 1-D parameters

Factors altered	Cases	% change over base case		
		PR (actual value)	20 yr PR in adult biomass	20 yr PR in yield
compensation	K_o/K_e = 0.5 (high CM)	-76% (3.85)	-80% (4.3)	-80% (4.3)
	K_o/K_e = 0.8 (low CM)	-52% (7.71)	-46% (11.8)	-46% (4.3)
spatial resolution	reduce number of segments to half	-33%	---	---
entrainment factors	33% increase in f (high CM)	-70% (4.86	-73% (5.88)	-73% (5.82)
	33% decrease in f (low CM)	-85% (2.38)	-86% (3.0)	-86% (2.96)
life stages for CM	juvenile stages only (high CM)	-73% (4.4)		
	larvae & J-1 only (high CM)	-43% (9.1)		
egg production CM interaction	x 1/2 (high CM)	-74% (4.1)		
	x 5 (high CM)	-88% (2.0)		

rigorously examine fisheries catch and effort data. Compensation studies need to examine the sources of compensation possibly within the predator-prey multiple food web context. We cannot be content with anecdotal evidence or year averaged data. Cushing's (1971) critical period hypothesis needs to be further examined by studies on larval and juvenile fish in situ. The nature of predation, cannibalism, and predator switching must be studied by more intensive sampling during the critical first three months of fish life.

Catch and effort data are our only long-term data for estimating population parameters of most commercially important fish species. The current trend in impact models (LMS 1977) seems to be in the direction of using these data in a stock-progeny context much as URI did (Sissenwine et al. 1974). This trend indicates an abandonment of the previous movement toward ever increasing hydrodynamic detail. That previous trend seems to be a result of the operators doing the modeling being trained primarily in an engineering rather than a bilogical approach to problems. In this sense they were just doing what they knew how to do well--staying away from biological areas perhaps not so amenable to an engineering approach. But these biological areas make all the difference in the world to model predictions and being able to make a highly detailed physical flow model to fit observed larval spatial distributions is clearly not related to being able to predict impact as the people who made those models seemingly now know.

Our hindsight thoughts about the hydrodynamic models are that they are largely a side issue to the question of plant impact. While some measure of entrainment loss is needed, this measure is obtainable from calculations based on sampling data in the neighborhood of the plant as easily as from a hydrodynamic model. Furthermore, the data estimates used as a validation measure for these hydrodymanic models are highly variable with gear selectivity and patchiness being serious impediments to the improvement of them. The biological parameters in these models are too important, too vaguely known, and the biological equations too simple to mesh with hydrodynamic detail used in many of them. In some ways the modelers are at fault for not realizing this at the start. Would an engineer build a bridge around a calculation as problematical as the LMS d-d mortality function?

Another criticism of the hydrodynamic models is that while they may give a good prediction of a particular year's spatial distribution of fish they are virtually inapplicable to another year. Data must be collected on a year-to-year basis since freshwater flow varies from year to year and such factors as advection avoidance probably need year-to-year calibration. In this sense the models are trapped in their great spatial detail into needing substantial calibration data. Finally, these models do not utilize, except peripherally (as in the ORNL d-d fishing model or the URI stock-progeny model), the catch and effort data for the fishery.

If some way were developed to tie these hydrodynamic models to some inexpensively sampled parameters such as freshwater flow, such models might eventually be used in lieu of an intensive sampling of young fish to calculate entrainment loss. Until that time, these models can have little use.

Another approach to entrainment loss calculation is to use the spatial distribution data directly to simulate spatial movement as was done in our simulator. The simulator then is a bookkeeping model for tracing when the fish are in the neighborhood of the plant. Different scenarios based on multiple years' sampling can be used to generate a range of PR values. If compensation is included in this model a stock-progeny curve can be developed from simulations with and without the plants operating. This can be used in a life cycle model to simulate the effect on adult population and fisheries yield of plant operation, with surviving y-o-y computed from egg production (a function of the adult population) and the stock-progeny curve. This approach represents a significant saving of computer expense over the detailed hydrodynamic computations employed in some of the life cycle models reviewed. Also it allowed us the flexibility of cheaply testing the effects of differences in model assumptions on long-term adult populations and fishery yield. While results of our simulator did not correspond exactly in the "base" case with the LMS model (Table 3.13), we think, the differences are primarily due to the number of segments in the model and in the spatial distributions where our approach is closer to the real data than the LMS model. Also we think the results of changes in parameter values which we investigated using the simulator also hold for the original LMS models.

As mentioned above the trend in impact models is now away from hydrodynamics and toward more classical fisheries stock-progeny models (Ricker 1954, Beverton and Holt 1957) with parameters estimated by comparison with fisheries catch data. While we see this approach as a step in the right direction, indications are (Deriso, in prep.) (1) that the striped bass catch data are not as well recorded and may be less accurate that data from other marine fish stocks, (2) that the data are highly variable and fits to stock-progeny models are poor, and (3) the application of stock progeny models developed for semelparous (single spawning) species must be modified for application to iteroparous (multiple age class spawning) species like striped bass.

Our recommendations for future modeling are (1) focus research toward understanding processes controlling compensation in mortality and growth rates, (2) begin a more rigorous collection of catch and effort data on impacted fisheries including age estimates for iteroparous species, and (3) develop impact models utilizing catch and effort data as well as local entrainment calculations. These models should include age-dependent fecundity and growth and a biologically meaningful compensation model, if any, and should fit parameters using catch and effort data as well as mark-recapture data if the latter are available.

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7.0 APPENDIX A. ACRONYMS

AA = advection avoidance (factor)

BL = body lengths

C & D = Chesapeake & Delaware (canal)

CDF = convective defect factor

CE = crowding effect parameter

CM = compensatory mortality

CT = closed cycle coding

d-d = density-dependent (-ence)

d-i = density-independent (-ence)

FES = final environmental statement

IP = Indian Point

JHU = Johns Hopkins Univ. Appl. Phys. Lab.

J-I = juvenile of life stage I
J-II = juvenile of life stage II
J-III = juvenile of lift stage III

LMS = Lawler, Mutusky, and Skelly Engrs.

MPPSP = Md. Pow. Plant Siting Program
NRC = Nuclear Regulatory Commission
NRI = Nat. Resources Inst.

ORNL = Oak Ridge Nat. Lab.

OT = open cycle cooling

PR = percentage reduction

QLM = former name of LMS

SF = scaling factor
SE = shoaling effect parameter
SP = shoaling parameter (values)

S - R (curves) = spawner recruit

TCM = thousand cubic meters

TDF = transport defect factor

TI = Texas Instruments, Inc.

UEC = United Engineers & Constructors

URI = Univ. Rhode Island

USDI = United States Dep. of the Interior

U.S. NRC = U. S. Nuclear Regulatory Commission

Y-O-Y = Young of the year

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Eight models predicting the impact of power plant operation upon economically important fish species are compared. The paper focuses on the effect differences between the models have on model predictions. Generalized model simulators were developed for the young-of-the-year and life-cycle submodels. Criteria used to evaluate model predictions are percentage of reduction in young-of-the-year and annual loss in yield to the fishery due to plant operation. Major differences between the models include the life stage lengths, density-dependent or density-independent young-of-the-year fish to age class 1. Major differences in parameter values include entrainment factors, total egg production, equilibriaum population size, and survival probabilities for the life-cycle models. Recommendations are made regarding our preference for model approaches. Our conclusion is that no presently existing impact model can be used to make quantitative predictions due to the large year-to-year variability in young-of-the-year densities and spatial distribution and the sensitivity of results to parameters in the density-dependent mortality function which are not well estimated.

17. KEY WORDS AND DOCUMENT ANALYSIS

17a. DESCRIPTORS

density dependence, density independence, life-cycle model, model predictive ability, model simulations, parameter values, percentage reduction, regression equation, scaling factor, striped bass, young-of-the-year model

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